Dissertations   Electronic Theses and Dissertations

Summer 5-2014

Development of an Integrated Incident and Transit Priority Management Control System

Faisal Ahmed

Follow this and additional works at: https://scholarworks.uaeu.ac.ae/all_dissertations

Part of the Civil and Environmental Engineering Commons

United Arab Emirates University

College of Engineering

Development of an Integrated Incident and Transit Priority Management Control System

Faisal Ahmed

This dissertation is submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Under the direction of
Professor Yaser E. Hawas

May 2014

DECLARATION OF ORIGINAL WORK

I, Faisal Ahmed, the undersigned, a graduate student at the United Arab Emirates University (UAEU) and the author of the thesis/dissertation entitled " Development of an Integrated Incident and Transit Priority Management Control System ", hereby solemnly declare that this thesis/dissertation is an original work done and prepared by me under the guidance of Prof. Yaser E. Hawas, in the College of Engineering at United Arab Emirates University (UAEU). This work has not been previously formed as the basis for the award of any degree, diploma or similar title at this or any other university. The materials borrowed from other sources and included in my dissertation have been properly acknowledged.

Student's Signature................................... Date.......................

COPYRIGHT

Approved by

Ph.D. Advisory Committee:

1)   Advisor : Dr. Yaser E. Hawas

        Title: Professor

        Department: Civil and Environmental Engineering

        Institution: United Arab Emirates University (UAEU)

        Signature:.................... Date:..........................

Ph.D. Examining Committee:

1)   Advisor : Dr. Yaser E. Hawas

        Title: Professor

        Department: Civil and Environmental Engineering

        Institution: United Arab Emirates University (UAEU)

        Signature:.................... Date:..........................

2)   Member : Dr. Kamran Ahmed

        Title: Assistant Professor

        Department: Civil and Environmental Engineering

        Institution: United Arab Emirates University (UAEU)

        Signature:.................... Date:..........................

3)   Member : Dr. Younes Hamdouch

        Title: Associate Professor

        Department: Department of Business Administration

        Institution: United Arab Emirates University (UAEU)

        Signature:.................... Date:...........................

4)   External Examiner : Dr. Peter T Martin

        Title: Professor

        Department: Civil Engineering

        Institution: New Mexico State University.

        Signature:.................... Date:...........................

Accepted by

Dean of the College :

Signature:.................... Date:...........................

Dean of the College of Graduate Studies :

Signature:.................... Date:...........................

Copy ....of ....

.

ABSTRACT

The aim of this thesis is to develop a distributed adaptive control system which can work standalone for a single intersection to handle various boundary conditions of recurrent, non-recurrent congestion, transit signal priority and downstream blockage to improve the overall network in terms of productivity and efficiency.

The control system uses link detectors' data to determine the boundary conditions of all incoming and exit links. Four processes or modules are deployed. The *traffic regime state module* estimates the congestion status of the link. The *incident status module* determines the likelihood of an incident on the link. The *transit priority module* estimates if the link is flagged for transit priority based on the transit vehicle location and type. Finally, the *downstream blockage module* scans all downstream links and determines their recurrent blockage conditions.

Three different urban incident detection models (General Regression Model, Neuro-Fuzzy Model and Binary Logit Model) were developed in order to be adopted for the *incident status module*. Among these, the Binary Logit Model was selected and integrated with the signal control logic. The developed Binary Logit Model is relatively stable and performs effectively under various traffic conditions, as compared to other algorithms reported in the literature.

The developed signal control logic has been interfaced with CORSIM micro-simulation for rigorous evaluations with different types of signal phase settings. The proposed system operates in a manner similar to a typical pre-timed signal (with split or protected phase settings) or a fully actuated signal (with split-phase arrangement, protected phase, or dual ring phase settings).

The control decisions of this developed control logic produced significant enhancement to productivity (in terms of *Person Trips* and *Vehicle Trips*) compared with the existing signal control systems in medium to heavily congested traffic demand conditions for different types of networks. Also, more efficient outcomes (in terms of *Average Trip Time/Person* and delay in *seconds/vehicle*) is achieved for relatively low to heavy traffic demand conditions with this control logic (using Split Pre-timed).

The newly developed signal control logic yields greater productivity than the existing signal control systems in a typical congested urban network or closely spaced intersections, where traffic demand could be similarly high on both sides at peak periods. It is promising to see how well this signal control logic performs in a network with a high number of junctions. Such performance was rarely reported in the existing literature.

The best performing phase settings of the newly developed signal control were thoroughly investigated. The signal control logic has also been extended with the logic of pre-timed styled signal phase settings for the possibility of enhancing productivity in heavily congested scenarios under a closely spaced urban network. The performance of the developed pre-timed signal control signal is quite impressive.

The activation of the *incident status module* under the signal control logic yields an acceptable performance in most of the experimental cases, yet the control logic itself works better without the *incident status module* with the Split Pre-timed and Dual Actuated phase settings. The Protected Pre-timed phase setting exhibits benefits by activating the *incident status module* in some medium congested demands.

ملخص الرسالة

تهدف هذه الرسالة إلى تطوير نظام تحكم آلي موزع (غير مركزي) للإشارات المرورية الضوئية يمكن أن يعمل بذاته عند التقاطعات الفردية وذو قدرة على التعامل مع الظروف المختلفة للازدحام المروري المتكرر والغير متكرر، وإعطاء الأولويات لمركبات النقل العام و كذلك التعامل مع الحالات المرورية الناتجة عن الإختناقات المرورية في مصبات المرور وذلك بغرض تحسين إنتاجية وكفاءة الشبكة العامة .

ويستخدم نظام التحكم البيانات من المجسات على جميع الطرق لتحديد الحالة المرورية من وإلى التقاطعات. ويتضمن النظام أربع وحدات مختلفة يتم تفعيلها. وتقوم وحدة حساب حالة المرور بتحديد حالات الاختناق المروري من وإلى التقاطعات. أما وحدة الحوادث فتحدد احتمال وجود حوادث على الطرق. وتقوم وحدة أولوية مركبات النقل العام بحساب درجة الأولوية للطرق تبعا لنوع المركبة ومكانها على الطريق. أما وحدة انسداد المصب فتقوم بمسح جميع الطرق الخارجة من التقاطعات و تحديد ظروف الإنسداد المروري المتكررة عليها.

وانتهى البحث إلى أن النظام المقترح يمكن أن ينتج عنه زيادة كبيرة في الإنتاجية (من حيث عدد رحلات الأفراد والمركبات) بالمقارنة بأنظمة التحكم الموجودة حاليا وخاصة في الحالات المرورية متوسطة الكثافة وأيضا المزدحمة منها وذلك في الشبكات المرورية المختلفة. ويحقق النظام المقترح أيضا كفاءة أفضل (من حيث متوسط زمن الرحلة لكل شخص و التأخير في صورة عدد الثواني للمركبة) و ذلك الحالات المرورية منخفضة الكثافة وأيضا المزدحمة منها نسبيا (باستخدام النظام مع التوقيت المسبق).

وقد تم التحقيق في ماهية أفضل الإعدادات لنظام التحكم بإستفاضة. وأيضا تطوير النظام أيضا للعمل مع الإشارات الضوئية التي تعمل بنظام التوقيت المسبق لتحسين مؤشرات الإنتاجية في حالات الإزدحام المروري وفي شبكات المدن الحضرية التي تتضمن تقاطعات متقاربة نوعا ما. وباختصار فإن أداء نظام التحكم مع مع الإشارات الضوئية التي تعمل بنظام التوقيت المسبق جاء بنتائج جيدة للغاية.

الكلمات الرئيسية : الازدحام المروري، الكشف عن الحوادث في الشبكات الحضرية، نموذج الانحدار العام ، النموذج العصبي- الضبابي ، النموذج الثنائي اللوغاريتمي ، الأولوية لمركبات النقل العام، نظام التحكم المتكيف للإشارات المرورية ، نظام التحكم المتكيف الثنائي للإشارات المرورية ، نظام التحكم المتكيف المقسم للإشارات المرورية.

ACKNOWLEDGEMENTS

Finally, I would like to thank my family and friends for their support in completing this research. Very special gratitude to my wonderful wife Taslima Parvin for spending her time in cross-checking numerous modeling inputs and calculations for this study. My father, mother and my wife are the main sources of inspiration for me to complete this degree. I would also like to thank my siblings and in-laws for their constant encouragements. I am really grateful to all of them for their emotional support.

DEDICATION

Dedicated to my parents and my wife

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF NOTATIONS

Intersection:

i: Intersection i of the urban road network.

Time Index Related:

t: Current time index t:

which is the based on:

(1) the current detector data aggregation time interval (Δt) for

both *traffic regime state module* and *downstream blockage*

module;

(2) the current incident detection time interval (θ) for *incident*

detection module;

(3) the current time instant (in second) or simulation clock's second

for *transit priority module*;

Δt: Detector data aggregation time interval (in seconds) for *traffic*

regime state module, and *downstream blockage module* on

downstream exit link.

θ: Incident detection time interval (in seconds) for the *incident status*

module on the upstream approach link.

Vehicle Types:

c: Private cars.

b: Normal-priority busses.

p: High priority busses.

Detector Index:

s: Index of sensor or detector;

d: Index of the downstream detector;

m: Index of the midblock detector;

u: Index of the upstream detector;

Link Index:

$u^/$:   Upstream approach.

$d^/$:   Downstream approach.

Generic Phases:

ϕ_j: Abbreviation of *individual* phase j, $j=1....8$.

ϕ_1	ϕ_6	ϕ_3	ϕ_8
ϕ_5	ϕ_2	ϕ_7	ϕ_4
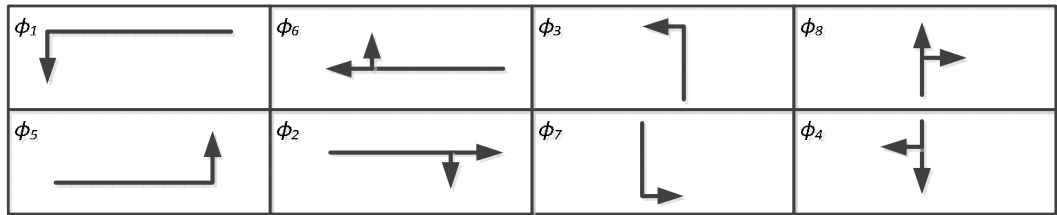
Phase Set Related:

Φ_k: Abbreviation of a candidate phase set k, $k=1,.....,8$, where $\Phi_1 = \{\phi_1 \cup \phi_5\}$, $\Phi_2 = \{\phi_1 \cup \phi_6\}$, $\Phi_3 = \{\phi_2 \cup \phi_5\}$, $\Phi_4 = \{\phi_2 \cup \phi_6\}$, $\Phi_5 = \{\phi_3 \cup \phi_7\}$, $\Phi_6 = \{\phi_3 \cup \phi_8\}$, $\Phi_7 = \{\phi_4 \cup \phi_7\}$, $\Phi_8 = \{\phi_4 \cup \phi_8\}$

$\phi^{k,1}$:   Abbreviation to denote the *1st* concurrent *individual phase* of the candidate phase set,Φ_k, where $\Phi_k = \{\phi^{k,1} \cup \phi^{k,2}\}$.

$\phi^{k,2}$:   Abbreviation to denote the 2nd concurrent *individual phase* of the candidate phase set, Φ_k, where $\Phi_k = \{\phi^{k,1} \cup \phi^{k,2}\}$.

Φ_c: Current phase set Φ_k running green.

g_{i,Φ_k}:   The total green time allocated to the candidate phase set Φ_k at intersection i for the pre-timed type signals, where $g_{\Phi_{i,k}} = g_{i,\Phi_k}^{min} = g_{i,\Phi_k}^{max}$.

g_{i,Φ_k}^{min}:   The minimum green time allocated to the candidate phase set Φ_k at intersection i.

g_{i,Φ_k}^{max}:   The maximum green time allocated to the candidate phase set Φ_k at intersection i.

$\Delta g_{i,\Phi_k}$:   The extension green time allocated (or to be allocated) for phase ϕ_j, of the candidate phase set Φ_k at intersection i.

Approach Link and Exit Link Related:

$L_{i,\phi_j,u'}$:   The ID of the upstream approach, u', of phase ϕ_j at intersection i.

$L_{i,\phi_j,d'}$:   The ID of the downstream exit link, d', of phase ϕ_j at intersection i.

$l_{i,\phi_j,u'}$:   The length of the *upstream* approach, u', of phase ϕ_j at intersection i.

$l_{i,\phi_j,e,u'}$:   The length of the through lanes of the *upstream* approach, u', of phase ϕ_j at intersection i.

$l_{i,\phi_j,o,u'}$:   The length of left-turn pocket lanes of the *upstream* approach of phase ϕ_j at intersection i.

$l_{i,\phi_j,e,d^/}$:   The length of the through lanes of the *downstream* exit link, $d^/$, of phase ϕ_j at intersection i.

$l_{i,\phi_j,o,d^/}$:   The length of left-turn pocket lanes of the *downstream* exit link, $d^/$, of phase ϕ_j at intersection i.

$n_{i,\phi_j,e,u^/}$:   Number of the through lanes of the *upstream* approach, $u^/$, of phase ϕ_j at intersection i.

$n_{i,\phi_j,o,u^/}$:   Number of the left-turn pocket lanes of the *upstream* approach, $u^/$, of phase ϕ_j at intersection i.

$n_{i,\phi_j,e,d^/}$:   Number of the through lanes of the *downstream* exit link, $d^/$, of phase ϕ_j at intersection i.

$n_{i,\phi_j,o,d^/}$:   Number of the left-turn pocket lanes of the *downstream* exit link, $d^/$, of phase ϕ_j at intersection i.

$v^0_{i,\phi_j,u^/}$:   Free-flow speed of the *upstream* approach link of phase, ϕ_j, of intersection i.

$\bar{v}^t_{i,\phi_j,u^/_{u,m}}$:   The mean speed on the link segment between the *upstream* and *midblock* detectors by all the vehicles, at time t on the *upstream* approach of phase, ϕ_j, of intersection i.

$\bar{v}^t_{i,\phi_j,u^/_{m,d}}$:   The mean speed on the link segment between the *midblock* and *downstream* detectors by all the vehicles, at time t on the *upstream* approach of phase, ϕ_j, of intersection i.

Detector Data Related:

C: Accumulative detector count;

$C_{i,\phi_j,u',s}^{\theta,t}$:   The accumulated vehicle counts of the corresponding sensor s ($s=$ d, m or u) on approach link of the phase ϕ_j of intersection i at incident time index $(t-1)$, *where* the operating incident time-step is θ.

$C_{i,\phi_j,u',1}^{V,t}$:   The vehicle counts by the *downstream* detector *1* at detector time index *(t- 1)* on the *upstream* approach, u', relevant to even phase, ϕ_j, of intersection i.

$C_{i,\phi_j,u',2}^{V,t}$:   The vehicle counts by the *downstream* detector *2* on a left-storage lane at detector time index $(t-1)$ on the *upstream* approach, u', relevant to odd phase, ϕ_j, of intersection i.

$C_{i,\phi_j,u',3}^{V,t}$:   The vehicle counts by the *midblock* detector *3* at detector time index *(t-1)* on the *upstream* approach, u', relevant to phase, ϕ_j, of intersection i.

$C_{i,\phi_j,u',4}^{V,t}$:   The vehicle counts by the *upstream* detector *4* at detector time index *(t-1)* on the *upstream* approach, u', relevant to phase, ϕ_j, of intersection i.

$C_{i,\phi_j,u',5}^{V,t}$:   The vehicle counts by the *upstream* detector 5 of the left-storage lane at detector time index $(t-1)$ on the *upstream* approach, u', relevant to odd phase, ϕ_j, of intersection i.

$C_{i,\phi_j,d^/,1}^{V,t}$:   The vehicle counts by the *downstream* detector *1* at detector time index $(t-1)$ on the *downstream* exit link, $d^/$, relevant to even phase, ϕ_j , of intersection i.

$C_{i,\phi_j,d^/,2}^{V,t}$:   The vehicle counts by the *downstream* detector *2* the left-storage lane at detector time index $(t-1)$ on the *downstream* exit link, $d^/$, relevant to odd phase, ϕ_j , of intersection i.

$C_{i,\phi_j,d^/,3}^{V,t}$:   The vehicle counts by the *midblock* detector *3* at detector time index $(t-1)$ on the *downstream* exit link, $d^/$, relevant to phase, ϕ_j , of intersection i;

$C_{i,\phi_j,d^/,4}^{V,t}$:   The vehicle counts by the *upstream* detector *4* at detector time index $(t-1)$ on the *downstream* exit link, $d^/$, relevant to phase, ϕ_j , of intersection i.

$C_{i,\phi_j,d^/,5}^{V,t}$:   The vehicle counts by the *upstream* detector 5 of the left-storage lane at detector time index $(t-1)$ on the *downstream* exit link, $d^/$, relevant to odd phase, ϕ_j , of intersection i.

v: Speed in kph;

$v_{i,\phi_j,u^/,s}^{\theta,t}$:   The average speed of the corresponding sensor *s (s= d, m or u)* on approach link $u^/$ of the phase ϕ_j of intersection i at incident time index$(t-1)$, where the operating incident time-step is θ.

$v_{i,\phi_j,u^/,1}^{V,t}$:   The average speed recorded by the *downstream* detector *1* at time index $(t-1)$ on the *upstream* approach, relevant to even phase, ϕ_j , of intersection i.

$v_{i,\phi_j,u/,2}^{V,t}$:   The average speed recorded by the *downstream* detector *2* on the left-storage lanes at time index $(t-1)$ on the *upstream* approach, relevant to odd phase, ϕ_j , of intersection i.

$v_{i,\phi_j,u/,3}^{V,t}$:   The average speed recorded by the *midblock* detector *3* at time index $(t-1)$ on the *upstream* approach, relevant to any phase, ϕ_j , of intersection i.

$v_{i,\phi_j,u/,4}^{V,t}$:   The average speed recorded on by the *upstream* detector *4* at time index $(t-1)$ on the *upstream* approach, relevant to any phase, ϕ_j , of intersection i.

$v_{i,\phi_j,u/,5}^{V,t}$:   The average speed recorded by the *downstream* detector 5 on the left-storage lanes at time index $(t-1)$ on the *upstream* approach, relevant to odd phase, ϕ_j , of intersection i.

Traffic Regime State Module Related:

$r_{i,\phi_j,u/}^{V,t}$:   The *ratio of the vehicle queue length* over the physical capacity of the corresponding link length, $l_{i,\phi_j,u/}$.

$T_{i,\phi_j,u/}^0$:   Free-flow travel-time of the *upstream* approach link of phase, ϕ_j , of intersection i.

$\bar{T}_{i,\phi_j,u/}$:   Average travel-time based on the recorded speeds of detectors on the *upstream* approach link of phase, ϕ_j , of intersection i.

$TTI_{i,\phi_j,u/}^t$:   Travel Time Index of the *upstream* approach link of phase, ϕ_j , of intersection i.

$l_{i,\phi_j,u^/}$: The length of the *upstream* approach, $u^/$, of phase ϕ_j at intersection i.

$V_{i,\phi_j,u^/}^t$: The estimated vehicular queue (in terms of number of vehicles), estimated from the detector counts, currently present at time index $(t-1)$ on the respective turning movement lanes (i.e. either on left-storage lanes for any odd phase or on through and right lanes for any even phase) assigned to the individual phase ϕ_j. It is equal to either $V_{i,\phi_j,u_o^/}^t$ for odd phase or $V_{i,\phi_j,u_e^/}^t$ for even phase.

$V_{i,\phi_j,u_L^/}^t$: The estimated total vehicular queue (in terms of number of vehicles), estimated from the detector counts, currently present at time index $(t-1)$ on the approach link $L_{i,\varphi_j,u^/}$ relevant to phase, ϕ_j, of intersection i.

$V_{i,\phi_j,u_o^/}^t$: The estimated total vehicular queue (in terms of number of vehicles), estimated from the detector counts, currently present at time index $(t-1)$ only on the left-storage lanes of the approach link $L_{i,\varphi_j,u^/}$ relevant odd phase ϕ_j.

$V_{i,\phi_j,u_e^/}^t$: The estimated total vehicular queue (in terms of number of vehicles), estimated from the detector counts, currently present at time index $(t-1)$ only on the through and right-turning lanes only of the approach link $L_{i,\varphi_j,u^/}$ relevant to the even phase ϕ_j.

V_{i,ϕ_j,u'_L}^{max}:   Maximum number of vehicular spaces, *in number of vehicles*, that could be accommodated under jamming condition on *upstream* approach $L_{i,\varphi_j,u'}$ relevant to the phase ϕ_j at intersection *i*.

$S_{i,\phi_j,u'}^{V,t}$:   The standing vehicle adjustment factor for the *downstream* detectors 1 and 2, on the *upstream* approach link of phase, ϕ_j, of intersection *i* at time index *t*.

$S_{i,\phi_j,u'_o}^{V,t}$:   The standing vehicle adjustment factor for the *downstream* detectors 1 and 2, on the left-turning lanes of the *upstream* approach link of phase, ϕ_j, of intersection *i* at time index *t*.

Transit Priority Module Related:

$b_{i,\phi_j,u'}$:   The bus ID on the *upstream* approach of phase ϕ_j, of intersection *i*.

$C_{i,\phi_j,u'}^{B,t}$:   The total counts of the all *buses*, *B*, at time *t* on the *upstream* approach, u', relevant to phase, ϕ_j, of intersection *i*.

$l_{i,\phi_j u'}^{b}$:   The distance to the stop-line from the current bus location of the bus $b_{i,\phi_j,u'}$ detected by the *bus sensor* on the upstream approach, u', associated with the individual phase ϕ_j at intersection *i*.

l_{i,ϕ_j,u'_m}^{b}:   The distance to the mid-block detector from the current bus location of the bus $b_{i,\phi_j,u'}$ detected by the *bus sensor* associated with the individual phase ϕ_j at intersection *i*.

$P_{i,\phi_j,u'}^{b}$:   A binary variable indicating the that the bus of ID, $b_{i,\phi_j,u'}$ is a high priority bus, on the approach link of ID, $L_{i,\phi_j,u'}$.

$T^b_{i,\phi_j,u/}$:   The estimated travel time to stop-line of the signal i from the current location of the bus, $b_{i,\phi_j,u/}$.

Downstream Blockage Module Related:

$d^t_{i,\phi_j,u/}$:   The demand (in terms of number of vehicles) to be served green on the *upstream* approach of phase ϕ_j at intersection i at time t, if the associated phase set extends (or starts) green for $\Delta g_{i,\Phi_k}$ (for actuated type signals) or starts the green interval g_{Φ_k} (for pre-timed type signals);

$C^{V,t}_{i,\phi_j,d/,1}$:   The vehicle counts by the *downstream* detector *1* at detector time index $(t-1)$ on the *downstream* exit link, $d/$, relevant to even phase, ϕ_j , of intersection i.

l^c: The average length of a private car unit (assumed 20 ft as the bumper to bumper distance under jam condition).

$V^{max}_{i,\phi_j,d/}$:   Maximum number of vehicular spaces, *in number of vehicles*, that could be accommodated under jamming condition on *downstream exit link* approach $L_{i,\varphi_j,d/}$ relevant to the phase ϕ_j at intersection i.

$V^{max}_{i,\phi_j,u/_o}$:   Maximum number of vehicular spaces, *in number of vehicles*, that could be accommodated under jamming condition on the left-storage lanes only of the approach link $L_{i,\varphi_j,u/}$ relevant odd phase ϕ_j.

$q_{i,\phi_j,e}$:   The vehicular discharge flow, *in number of vehicles per hour per lane*, from the *upstream* through and right turning lanes to the

$downstream$ link of even phase, ϕ_j, of intersection i at time t. It is pre-selected as the saturation flow rate in 1900 vehicles per hour green per lane.

$q_{i,\phi_j,o}$: The vehicular discharge flow, *in number of vehicles per hour per lane*, from the *upstream* left-storage lanes to the *downstream* link of odd phase, ϕ_j, of intersection i at time t. It is pre-selected as the saturation flow rate in 1900 vehicles per hour green per lane.

$S_{i,\phi_j,d/}^{V,t}$: The standing vehicle adjustment factor for the *downstream* detectors 1 and 2, on the *downstream* exit link of phase, ϕ_j, of intersection i at time index t.

$S_{i,\phi_j d/,}^{t}$: The estimated supply level, *in number of vehicles* (with average bumper to bumper spacing in traffic jam conditions) units, on the *downstream* link of phase, ϕ_j, of intersection i at time index *(t-1)*.

$V_{i,\phi_j,u/}^{s}$: The maximum number of vehicles that could be served green practically on the *upstream* approach of phase ϕ_j at intersection i if the associated phase set extends (or starts) green for $\Delta g_{i,\Phi_k}$ for actuated type signals or starts green g_{Φ_k} for pre-timed type signals.

Incident Status Module Related:

$C_{i,\phi_j,u/,s}^{0,t}$: Accumulative vehicular counts by the corresponding sensor $s(s= d, m$ or $u)$ on approach $u/$ for phase ϕ_j at time step t *extracted from the corresponding no incident base model* while the time-step (θ) is set equal to the cycle time.

$\Delta C^{\theta,t}_{i,\phi_j,u',s}$: The deviation of the corresponding sensor s $(s= d,\ m$ or $u)$ vehicular count on the upstream approach link of the individual phase, ϕ_j, at incident time index $(t-1)$ with operating time-step θ from the mean value $\bar{C}^{0,t}_{i,\phi_j,u',s}$ (estimated over all simulated time steps extracted from the no incident corresponding model of a specific hourly volume, signal cycle and link length combination) of intersection i at time t.

$v^{0,t}_{i,\phi_j,u',s}$: Average speed by the corresponding sensor $s(s= d,\ m$ or $u)$ on approach u' for phase ϕ_j at time step t *extracted from the corresponding no incident base model* while the time-step (θ) is set equal to the cycle time.

$\Delta v^{\theta,t}_{i,\phi_j,u',s}$: The deviation of the corresponding sensor s $(s= d,\ m$ or $u)$ average speed on the approach link of the individual phase, ϕ_j, at incident time index $(t-1)$ with operating time-step θ from the mean value $\bar{v}^{0,t}_{i,\phi_j,u',s}$ (estimated over all simulated time steps *extracted from the no incident corresponding model* of a specific hourly volume, signal cycle and link length combination) of intersection i at time t.

N: Total number of simulated time steps (cycle times) of the simulation model run, N is equal to 30, 23, and 18 for the models of cycle times of 60, 80 and 100 seconds, respectively;

X^t_{1,i,ϕ_j}: An independent variable of the incident detection model which represents the deviation of the downstream detector counts from its corresponding base value over the analysis time step (either cycle

xxx

time or incident detection time interval) for phase, ϕ_j , of intersection i at any time index t.

X_{2,i,ϕ_j}^t : An independent variable of the incident detection model which represents the deviation of the mid-block detector counts from its corresponding base value over the analysis time step (either cycle time or incident detection time interval) for phase, ϕ_j , of intersection i at any time index t.

X_{3,i,ϕ_j}^t : An independent variable of the incident detection model which represents the deviation of the upstream detector counts from its corresponding base value over the analysis time step (either cycle time or incident detection time interval) for phase, ϕ_j , of intersection i at any time index t.

X_{4,i,ϕ_j}^t : An independent variable of the incident detection model which represents the deviation of the downstream detector speed from its corresponding base value over the analysis time step (either cycle time or incident detection time interval) for phase, ϕ_j , of intersection i at any time index t.

X_{5,i,ϕ_j}^t : An independent variable of the incident detection model which represents the deviation of the mid-block detector speed from its corresponding base value over the analysis time step (either cycle time or incident detection time interval) for phase, ϕ_j , of intersection i at any time index t.

X_{6,i,ϕ_j}^t : An independent variable of the incident detection model which represents the deviation of the upstream detector speed from its

corresponding base value over the analysis time step (either cycle time or incident detection time interval) for phase, ϕ_j , of intersection i at any time index t.

X_{7,i,ϕ_j}: An independent variable of the incident detection model which represents the link length (in meter) of the approach link for phase, ϕ_j , of intersection i.

X^t_{8,i,ϕ_j}: An independent variable of the incident detection model which represents the analysis time step (either cycle time or incident detection time interval) for phase, ϕ_j , of intersection i at any time index t.

X^t_{9,i,ϕ_j}: An independent variable of the incident detection model which represents the expected arrival traffic flow (in vehicle/hour) over the analysis time step (either cycle time or incident detection time interval) for phase, ϕ_j , of intersection i at any time index t.

Candidate Phase Sets:

Ψ_c: Set of candidate phase sets if the current *green* phase set is Φ_c. The number of elements in any set Ψ_c varies and depends on the mode of operation of the controller (dual, split or protected) as shown below for every operation mode:

For *Pre-timed Split Phase* operation setting:

$\Psi_2 = \{\Phi_3, \Phi_6, \Phi_7\}$, $\qquad$ $\Psi_3 = \{\Phi_2, \Phi_6, \Phi_7\}$,

$\Psi_6 = \{\Phi_2, \Phi_3, \Phi_7\}$, $\qquad$ $\Psi_7 = \{\Phi_2, \Phi_3, \Phi_6\}$

For *Actuated Split Phase* operation setting:

$\Psi_2 = \{\Phi_2, \Phi_3, \Phi_6, \Phi_7\}$, $\qquad$ $\Psi_3 = \{\Phi_2, \Phi_3, \Phi_6, \Phi_7\}$,

$$\Psi_6 = \{\Phi_2, \Phi_3, \Phi_6, \Phi_7\}, \qquad \Psi_7 = \{\Phi_2, \Phi_3, \Phi_6, \Phi_7\}$$

For *Pre-timed Protected Phase* operation setting:

$$\Psi_1 = \{\Phi_4, \Phi_5, \Phi_8\}, \qquad \Psi_4 = \{\Phi_1, \Phi_5, \Phi_8\},$$

$$\Psi_5 = \{\Phi_1, \Phi_4, \Phi_8\}, \qquad \Psi_8 = \{\Phi_1, \Phi_4, \Phi_5\}$$

For *Actuated Protected Phase* operation setting:

$$\Psi_1 = \{\Phi_1, \Phi_4, \Phi_5, \Phi_8\}, \qquad \Psi_4 = \{\Phi_1, \Phi_4, \Phi_5, \Phi_8\},$$

$$\Psi_5 = \{\Phi_1, \Phi_4, \Phi_5, \Phi_8\}, \qquad \Psi_8 = \{\Phi_1, \Phi_4, \Phi_5, \Phi_8\}$$

For *Actuated Dual Ring Barrier* operation setting:

$$\Psi_1 = \{\Phi_1, \Phi_2, \Phi_3, \Phi_4\}, \qquad \Psi_2 = \{\Phi_2, \Phi_4\},$$

$$\Psi_3 = \{\Phi_3, \Phi_4\}, \qquad \Psi_4 = \{\Phi_4, \Phi_5\},$$

$$\Psi_5 = \{\Phi_5, \Phi_6, \Phi_7, \Phi_8\}, \qquad \Psi_6 = \{\Phi_6, \Phi_8\},$$

$$\Psi_7 = \{\Phi_7, \Phi_8\}, \qquad \Psi_8 = \{\Phi_8, \Phi_1\}$$

Actuation Module Related:

Φ_{c*1}: The most deserving candidate phase set to be allocated green in the next time interval, given that the current *green* phase set is Φ_c and the set of candidate phase sets, Ψ_c, where $Z^t_{i,\Phi_{c*1}} = \text{Max}\{Z^t_{i,\Phi_k}\}, \forall\, \Phi_k \in \Psi_c$.

Φ_{c*2}: The second most deserving candidate phase set to be allocated green in the next time interval, given that the current *green* phase set is Φ_c and the set of candidate phase sets, Ψ_c, where $Z^t_{i,\Phi_{c*2}} = \text{2nd Max}\{Z^t_{i,\Phi_k}\}, \forall\, \Phi_k \in \Psi_c$.

Φ_o: Optimum phase set (either Φ_{k*1} or Φ_{k*2}) which should start (or continue) green.

Φ_n: The next phase set to be allocated green following the current phase set Φ_c.

Φ^{k,Ψ_c}: The associated phase set of the kth position under Ψ_c when the current *green* phase set is Φ_c.

$\beta^N_{i,\phi_j,u^/}$: A coefficient for *incidents* on the upstream approach, $u^/$, of phase ϕ_j, at intersection i.

$\beta^p_{i,\phi_j,u^/}$: A coefficient for *transit priority* for high priority buses on the upstream approach, $u^/$, of phase ϕ_j, at intersection i.

$\beta^b_{i,\phi_j,u^/}$: A coefficient for *transit priority* for normal priority buses on the upstream approach, $u^/$, of phase ϕ_j, at intersection i.

$\beta^B_{i,\phi_j,d^/}$: A coefficient for *blockage* on the *downstream exit link* of phase ϕ_j at intersection i;

$\beta^V_{i,\phi_j,u^/}$: A coefficient for *virtual queue of vehicles* on the *upstream approach link* of phase ϕ_j at intersection i;

$C^{b,t}_{i,\phi_j,u^/}$: The total counts of the *normal priority buses*, *b*, at time *t* on the *upstream* approach, $u^/$, of phase, ϕ_j, of intersection i.

$C^{c,t}_{i,\phi_j,u^/}$: The total counts of the car*s*, *c*, at time *t* on the *upstream* approach link, $u^/$, relevant to phase, ϕ_j, of intersection i.

$C^{p,t}_{i,\phi_j,u^/}$: The total counts of the high *priority buses*, *p*, at time *t* on the *upstream* approach, $u^/$, of phase, ϕ_j, of intersection i.

$O^b_{i,\phi_j,u^/}$: Average passenger *occupancy* for the normal *priority buses* on the *upstream* approach, $u^/$, of phase ϕ_j at intersection i.

$O_{i,\phi_j,u^/}^c$: Average passenger *occupancy* for the *private cars* on the *upstream* approach, $u^/$, of phase ϕ_j at intersection i.

$O_{i,\phi_j,u^/}^p$: Average passenger *occupancy* for the high *priority buses* on the *upstream* approach, $u^/$, of phase ϕ_j at intersection i.

$I_{i,\phi_j,d^/}^{B,t}$: The indicator of the presence of *blockage* at time index $(t-1)$ on the *downstream* link, relevant to phase, ϕ_j, of intersection i.

$I_{i,\phi_j,u^/}^{N,t}$: Indicator of the presence of *incidents* at time index $(t-1)$ on the *upstream* link, relevant to phase, ϕ_j, of intersection i.

$I_{i,\phi_j,u^/}^{P,t}$: Indicator of the presence of *high priority transi*t buses on the *upstream* approach of phase ϕ_j, at intersection i at time t.

$I_{i,\phi_j,u^/}^{R,t}$: Indicator of the presence of *recurrent congestion status* on the *upstream* approach of phase ϕ_j, at intersection i at time index $(t-1)$.

$J_{i,\phi_j}^{/,t}$: The base *congestion indicator of an individual phase* , ϕ_j in terms of *the total virtual queue of passengers*, without adjusting for the *incident status* on the approach link of the intersection i at time t for the individual phase, ϕ_j (equal to $\phi^{k,1}$ or $\phi^{k,2}$) of the candidate phase set Φ_k out of all feasible candidate phase sets of Ψ_k.

J_{i,ϕ_j}^{t}: The *congestion indicator of an individual phase* , ϕ_j in terms of *the total virtual queue of passengers*, adjusted for the *incident status* on the approach link of the intersection i at time t for the individual

phase, ϕ_j (equal to $\phi^{k,1}$ or $\phi^{k,2}$) of the candidate phase set Φ_k out of all feasible candidate phase sets of Ψ_k.

A^t_{i,ϕ_j} : The *actuation index of an individual phase ϕ_j* , in terms of adjusted *virtual queue of passengers*, of intersection *i* at time *t*, assuming that the individual phase ϕ_j (equal to $\phi^{k,1}$ or $\phi^{k,2}$) of the candidate phase set Φ_k would be running *green* and the remaining candidate phase sets in Ψ_k would be flagged with *red*.

Z^t_{i,Φ_k} : The *actuation index of phase set* ,Φ_k , in terms of adjusted virtual queue of passengers, of intersection *i* at time *t*, assuming that phase set Φ_k is running *green* while the remaining candidate phase sets of Ψ_k would be flagged with *red*. It is the summation of $A^t_{i,\phi^{k,1}}$ and $A^t_{i,\phi^{k,2}}$ of the respective two concurrent individual phases $\phi^{k,1}$ and $\phi^{k,2}$ of the candidate phase set, Φ_k.

Z^t_{i,Φ_c} : The *actuation index of the current phase set*, Φ_c.

Z^t_{i,Φ_o} : The *actuation index of the optimum phase set*, Φ_o.

$Z^t_{i,\Phi_{k*1}}$: The *actuation index of the first best candidate phase set* ,Φ_{k*1}.

$Z^t_{i,\Phi_{k*2}}$: The *actuation index of the second best candidate phase set* , Φ_{k*2}.

P^y_{i,Φ_c} : The binary pending status of yellow transition of the relevant phase(s) of currently running the candidate phase set Φ_c at intersection *i*. It is 1 (or Yes) if the relevant phase(s) of the current phase set is yet to continue with green and the yellow transition has not started yet. It is 0 (or No) if the relevant phase(s) of the current phase set has just finished the yellow transition.

P_{i,Φ_c}^r: The binary pending status of red transition of the relevant phase(s) of currently running the candidate phase set Φ_c at intersection i. It is 1 (or Yes) if the relevant phase(s) of the current phase set is yet to continue with green or yellow and red transition has not started yet. It is 0 (or No) if the relevant phase(s) of the current phase set has just finished the red transition.

r_{i,Φ_k}:   The all-red time to be allocated to the relevant phase(s) of the candidate phase set Φ_k while transitioning at intersection i.

t_{i,Φ_c}^g: The green timer of the currently running the candidate phase set Φ_c at intersection i.

t_{i,Φ_c}^y: The yellow timer to the relevant phase(s) of the currently running the candidate phase set Φ_c while transitioning at intersection i.

t_{i,Φ_c}^r: The red timer to the relevant phase(s) of the current phase set Φ_c while transitioning at intersection i.

y_{i,Φ_k}:   The yellow time to be allocated to the relevant phase(s) of the candidate phase set Φ_k while transitioning at intersection i.

Network Traffic Demand Related:

O: Origin;

O_{Ej}:   Origin j on the eastern boundary.

O_{wj}:   Origin j on the western boundary.

O_{Nj}:   Origin j on the northern boundary.

O_{Sj}:   Origin j on the southern boundary.

D: Destination;

D_{Ej}:   Destination j on the eastern boundary.

D_{wj}:   Destination j on the western boundary.

D_{Nj}:   Destination j on the northern boundary.

D_{Sj}:   Destination j on the southern boundary.

CHAPTER 1:   INTRODUCTION

1.1   Research Problem

Traffic congestion has become a critical issue at peak hours for every road-users in big cities round the world. Recurrent traffic congestion in urban road networks of major cities have already increased travel time for commuters at peak times and even at non-peak hours. Non-recurrent incidents just make the situation even worse. On one side, transit signal priority (TSP) is encouraged by transport planning professionals to reduce congestion on the urban roads.

According to the 2012 Urban Mobility Report (Lomax et al, 2012), the amount of delays endured by average commuters has increased considerably and the cost of congestion amounted to $120 billion in the USA. Lomax et al. (2012) also highlighted that congestion has emerged as a problem outside of rush hours, as 40% of delays occur during the mid-day and overnight hours.

According to Mahmassani et al. (1998), traffic incidents are major contributors to delay and these have significant consequences for safety, congestion, pollution, and the cost of travel. The United Arab Emirates (UAE) police reports [UAE MOI (2007, 2008)] reveal that the total number of traffic accidents was 10135 in 2008, compared with 8828 in 2007, and 8843 in 2006. The increase in the number of traffic accidents is approximately 15% from 2007 to 2008, and 4% between the years 2006 and 2007. Statistics also indicated that the UAE loses about AED 5 billion a year to road congestion [DPE Abu Dhabi (2008)]. A significant amount of mobility operational cost savings can be achieved with an efficient incident management system coupled with early

detection models. Also, a significant reduction in transit travel times is possible with the TSP systems and strategies.

A review of the literature indicated that there are very few integrated network control systems (for example, SCOOT and SCATS) that considers both recurrent and non-recurrent traffic management simultaneously, as well as transit signal priority. The potential benefits of having such integrated system are many including instantaneous real-time detection of incidents, clearance and management of incident locations, and priority of transit vehicles on urban arterial roads, while maintaining optimum signal control policy of the local operator. All together can help avoiding losses in network productivity, enhance mobility, efficiency and effectiveness of operation at the network level.

To develop an integrated system, this study has set one primary research question to be addressed throughout the various phases of the study, which is:

"Is it possible to develop a new integrated control system logic that will allow reactive strategies to non-recurrent congestion (i.e. incidents), recurrent congestion on both approach link and downstream exit link and transit signal priority along with the objective of enhanced throughput under various traffic demand conditions and, if possible, then up to what extent?"

In order to address this primary research question, this study also addresses relevant deficiencies in the existing state of the art adaptive traffic control systems, deficiencies in the existing urban incident detection models and the potential for improvement in the existing signal isolated control logic (actuated or pre-timed) with different phase settings for different boundary conditions. This study also attempts to correlate the status of signal phases with incident status.

Therefore, the possibility of using simple analytical models (like regression or binary logit) or heuristic models (like Neuro-Fuzzy) for incident status forecasting is investigated.

The boundary conditions refer to the different traffic demand scenarios combining all the recurrent congestion, non-recurrent congestion, transit signal priority and downstream blockage due to potential spill back that will be handled by the proposed integrated signal control system.

At the network level, while some network links might be experiencing a specific boundary condition (e.g. incident condition), other links might be experiencing other boundary conditions (e.g. a call for TSP). Handling such conditions locally might result in a degradation of the performance at other intersections, and this necessitates developing a tool (such as a simulation tool) to assess the effectiveness and efficiency of such systems at the network level. This leads to the question of the hierarchy of such control systems and whether it should be centralized or distributed, taking into consideration the pros and cons of each, and the trade-offs and ease of deployment and integration with readily available and functioning traffic control systems.

The primary motivation behind this study is to bridge the research gap between readily available actuated or pre-timed control systems, and to boost their functional capabilities so as to handle the various potential boundary conditions, at a network level and in real time. The most promising solution that will be amenable for immediate deployment at minimal cost would be for the envisaged integrated system to act like a distributed adaptive controller with knowledge of the traffic conditions of the neighboring junctions. It should be able to handle all possible traffic conditions with (or without) the presence of the relevant boundary

conditions. Thus, along these lines, this research aims to further enhance the productivity and efficiency of existing actuated and pre-timed signal control systems.

1.2   Research Objectives

The aim of this thesis is to devise, manage, deliver and document a research on a newly developed distributed adaptive control system logic, which can work standalone for a single intersection to handle all boundary conditions of recurrent, non-recurrent congestion, transit signal priority and downstream blockage in order to improve the overall network productivity and efficiency.

This study, consistently with the problem statement, has set the following specific objectives:

- To carry out a detailed literature review to identify the specific research gaps in existing traffic signal control systems, incident detection methodologies and transit priority systems.

- To formulate an overall control system to integrate the interactions of all the boundary conditions handling modules at the network level in order to maximize network throughput and enhance the efficiency of operation.

- To formulate urban incident detection model(s), which could be used to predict the incident conditions for a link (or associated phase) of an intersection and in turn could be integrated with the proposed adaptive signal control logic

- To develop a rationale and methodology for each of the system's boundary condition modules based on the online detector data

- To develop an integrated signal control system which has the characteristics of actuation ability in terms of green extension for a phase (or phase set) and which also incorporates each of the recurrent congestion, incident condition, transit signal priority and downstream blockage conditions within a specific module.

- To conduct comprehensive tests on the efficiency and effectiveness of the devised control mechanism of integrated signal control logic with different phase settings in a simulation-based environment.

- To conduct the sensitivity analyses of the integrated signal control logic with different phase settings to identify critical parameters for significant impact on system performance.

- To recommend the prospective application(s) and further enhancement of the proposed integrated system logic.

1.3   Thesis Outline

This thesis is organized into seven chapters. Chapter 2 presents a detailed literature review of the existing adaptive signal control systems, incident detection systems and transit signal priority (TSP) systems. The formulation of the integrated signal control logic is discussed in Chapter 3. It also incorporates all the relevant details of the modules for the recurrent congestion detection, transit signal priority and downstream blockage management. Chapter 4 presents three different types of incident detection models developed through this research study. It also discusses the structure and the effectiveness performance measures of each type. Finally, it provides a discussion on how to adopt the most effective incident detection model for integration with the signal control logic. Chapter 5 briefly

discusses the interfacing of the proposed signal control logic with the micro-simulation environment utilized for on-line testing. It also details the experimental set-ups with different traffic demand and supply conditions. The results of the extensive case studies with different control settings are presented and discussed in Chapter 6. This study also includes the sensitivity analyses of the proposed control system parameters. Finally, a synthesis of the major findings, contributions and the proposed direction of future research are presented in Chapter 7.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

This chapter reviews the existing methodologies of adaptive traffic signal control systems as presented in literature. Some background on adaptive control methodologies, along with *transit signal priority systems* and *incident detection models*, both in practice and in theory, will be briefly introduced. Section 2.2 introduces some background on practicing adaptive control systems (ATCSs). Section 2.3 discusses the general characteristics and features that distinguish between commonly used ATCSs. Section 2.4 presents a review of the research on *transit signal priority systems*. Section 2.5 discusses research studies on *urban incident detection models.* Section 2.6 describes general research trends and state-of-the art practice on signal control systems. Section 2.7 identifies the research gaps on adaptive control systems. Finally, section 2.8 identifies the expected research contribution of this study based on the research gaps identified.

2.2. Background of Adaptive Signal Control Systems

A recent comprehensive review of the history of developments and field implementations of some practicing adaptive signal control systems can be found in Stevanovic (2010), which is a NCHRP (National Cooperative Highway Research Program) report on the state of the art practices on *Adaptive Traffic Control Systems* (ATCSs). This section also includes some of the most important

review findings of Stevanovic (2010), relevant to the development of adaptive traffic control systems.

At a typical signalized intersection, traffic signals run in one of three different control modes: pre-timed control, semi-actuated and full-actuated control (Wilshire, et al. 1985). For pre-timed control, all of the control parameters are kept fixed and pre-set off-line, but for actuated (both semi and full), the base parameters are kept fixed, but the controller itself responds to the fluctuation of the traffic flows in the network in accordance with a "closed-loop, on-line" control strategy (Yu & Recker, 2006). Existing pre-timed and purely actuated traffic signal control systems typically operate on a pre-defined signal timing plans for some specific interval of the day. Although existing signal control systems can handle the recurrent congestion efficiently, they do not have the ability to cope with non-recurrent congestion and sudden fluctuations of traffic demand levels within a short period of intervals. This, in turn, leads to lower efficiency (and/or lower productivity) of the existing traffic control systems in these conditions. Therefore, to overcome these limitations, *Adaptive Traffic Control Systems* (ATCSs) emerged to adjust signal timing plans in real time based on the current traffic conditions, demand and system capacity. The ATCS needs broader surveillance and a communication infrastructure for the purpose of communication between the central and/or local controllers.

According to the Stevanovic (2010) report, initial ATCSs were developed on the basis of traffic responsive pattern-matching systems. These systems used several timing plans covering various traffic-demand scenarios and a good selection process triggers the replacement of these timing plans. However, several experiments, such as ones by Fehon (2005), one of the most prominent

pieces of research, indicated that traffic control based on traffic-responsive pattern-selection is not very efficient. This is because the traffic demand may change during the transition time of the timing plans, and the newly introduced pattern may not reflect or suit the current traffic conditions. Furthermore, because of frequent transitions due to the changing traffic conditions, the system may spend most time in transitioning, and that may cause a continuous disruption of traffic. In order to overcome these issues, the two most widely used ATCSs: the Sydney Coordinated Adaptive Traffic System (SCATS) (Lowrie, 1982) and the Split Cycle Offset Optimization Technique (SCOOT) (Hunt, et al. 1981) were developed in Australia and the United Kingdom, respectively. A series of other new ATCSs were also developed. Some of these new ATCSs ignored the conventional signal timing structures constrained by cycle lengths and offsets. Various techniques based on mathematical programming were used such as OPAC (the Optimization Policies for Adaptive Control) (Gartner 1982), and PRODYN (Programming Dynamic), (Henry 1983).

The OPAC, PRODYN, and SPOT (System for Priority and Optimization of Traffic) (Donati, et al. 1984) mostly deal with the operation of single intersections. The coupling of UTOPIA (Urban Traffic Optimisation by Integrated Automation) with SPOT emerged to cope with changes at the network level (Mauro & Di Taranto 1990). Later on, RHODES (Real-Time Hierarchical Optimized Distributed and Effective System) (Head, et al. 1992, Mirchandani & Head, 2001) and LA DOT (Los Angeles Department of Transportation) were developed in the United States.

Stevanovic (2010) states that although there were significant benefits of deploying OPAC and RHODES over fixed-time and actuated traffic control in early tests, these two systems had increased operation costs and maintenance because of the complexity of the logics, the extensive detection requirements, and the necessary hardware upgrades.

A new ATCS called ACS Lite was developed to be more simplistic, user-friendly and compatible with existing infrastructure. The ACS Lite was tested for further enhancement (Shelby, et al. 2008). Stevanovic (2010) indicated that many other ATCSs were deployed, and some showed some operational benefits in various cases, yet some professionals also claimed that the systems are no better than good time-of-day (TOD) actuated-coordinated plans. Crenshaw (2000) and Hicks & Carter (2000) identified other issues like detector maintenance and communication problems, expense and the complexity of the systems, which are unfavorable to the wide spread deployment of ATCSs.

A survey among practitioners conducted by Stevanovic (2010) indicated several advantages of implementing ACTS such as handling high day to day and within-a-day traffic variability, significant operational savings and high benefit/cost ratio, reducing costs of retiming signals, handling oversaturated traffic conditions, handling traffic events, and handling conflicts between vehicular traffic and other modes of travel.

2.3. General Characteristics of Commonly Used ATCSs

This section highlights some of the general characteristics to distinguish between the most commonly used ATCSs in practice. More discussion on the research trends of ATCSs are included in section 2.6. This section utilizes mainly

the comprehensive study by Stevanovic (2010) in addition to other studies that highlight the main features of such commonly used ATCSs. Initially, the main features of the various control systems are briefly presented, followed by a summary of the distinctive features of the most commonly used ATCSs in tabular form.

According to Stevanovic, each ATCS is somewhat unique. The following features can help in identifying the unique working principles of each respective ATCS.

Detection

The detector location (layout) forms the basis to develop strategies that adjust the signal control in a network. There are typically four detector location types: (1) stop-line detectors (2) near-stop-line detectors (3) mid block upstream detector and (4) far-side upstream detector.

Control Action

The adjustment of traffic control can be either proactive or reactive. A proactive adaptive control system adjusts traffic control based on the estimated traffic demand. On the other hand, a reactive adaptive control system adjusts traffic control based on the traffic measured during the previous interval. Reactive control systems typically depend on stop-line detectors. In contrast, the upstream detectors are used for proactive systems to estimate the traffic demand in advance based on some traffic flow models. Stevanovic (2010) indicated that there is no strong evidence to support that proactive systems work better than the reactive systems. Some of ACTSs operate in a mixed mode: some control decisions are estimated proactively while others are extracted reactively.

Adjustment Methods

There are three major types of adjustment methods: (1) domain-constrained optimization (2) time-constrained optimization and (3) rule-based methods. The domain constrained optimization uses very limited search domain to avoid excessive fluctuations in signal timings, thus preventing the negative transition effects. Time-constrained optimization is constrained by time boundaries set by local controller policies. Rule-based adjustment covers any method used to develop a (simple) functional relationship between the parameters describing the change of traffic conditions and the resulting signal timings.

Time-Frame of Adjustment

Typically, new signal timings are implemented every few seconds or coarsely every few minutes. Stevanovic (2010) indicated that there is no strong evidence that systems that respond faster are (always) better than the less responsive systems.

Hierarchical Levels

Most of the ATCSs typically operate on different hierarchical levels: all have a component that uses the operations of local controllers and also some tactical (or strategic) component which oversees the responsiveness of traffic control at a higher level, regardless of whether it is done in a centralized or a distributed way.

Traffic Status Estimation Models

Most of the ATCSs use some form of model to estimate current traffic status. These models can be macroscopic, mesoscopic, microscopic or heuristic analytical models.

Yu & Recker (2006) identifies three major categories of mathematical models for the representation of traffic on a signalized surface street network; (1) store-and-forward models (Hakimi, 1969; Singh & Tamura, 1974; D'Ans & Gazis, 1976), (2) dispersion-and-store models (Cremer & Schoof, 1989; Chang et al., 1994), and (3) kinematic wave models (Stephandes & Change, 1993; Lo, 2001). These models help ATCS perform more proactively, but the errors introduced by the model can be propagated (spatially and temporally) during the course of ATCS actions.

Signal Timing Parameters

Most ATCS primarily adjust three signal parameters: green splits, cycle lengths and offsets. The operations of some systems (for example, RHODES, InSync and some versions of OPAC) are acyclic; they do not use cycle lengths. On the other hand, very few ATCSs adjust or optimize phase sequencing in real-time, because frequent alterations in phase sequencing can have negative impacts on the traffic (Stevanovic 2010).

Flexible Regions

Some ATCSs divide the entire area into some regions or subsystems of intersections that need to be coordinated. A bordering intersection may leave its current subsystem and join the neighboring subsystem if required.

Actuated Operation

In an actuated operation mode, once a vehicle actuation call is received from the opposing phase, the current phase will hold the green until the maximum green time unless a gap is detected. If the time between vehicle actuations is greater than the preset unit extension or gap, a gap is detected. When a gap is

detected, the controller will start transitioning to the next phase in sequence with demand. This is called termination by gap-out. Some ATCSs transfer the responsibility of the common gap-out operation to the local controller. Some other systems do not allow this transfer of responsibility to the local controller.

Transit Signal Priority

With the emphasis on public transport priority policy in most urban areas, it is quite natural that most of ATCS controllers would support some transit priority operation. Stevanovic (2010) states that this priority is often given at the local controller's level, but not as the result of comprehensive optimization where transit travel times (or delays) for the network-wide vehicular and transit performances are integrated into the optimization model.

Pedestrian Facilities

Some of the ATCSs handle pedestrian facilities well. Others, typically provide this pedestrian operation by local field controller.

Table 2.1, sourced directly from Stevanovic (2010, pp. 20), shows a comparative summary of the working principles of ten common ATCSs.

Table 2.1: Operational characterization of ATCSs (Source: Stevanovic 2010, pp. 20)

ATCS	ACS Lite	BALANCE	InSync	LA ATCS	MOTION	OPAC	RHODES	SCATS	SCOOT	UTOPIA
Detection	SL, MB/US	NSL	NSL	SL & US	NSL	MB & SL	MB & SL	SL, NSL, MB	US & SL	US & SL
Action	P & R	P & R	P & R	P & R	P & R	P	P	R	P & R	P
Adjustment	DCO	TCO	DCO	RA, TCO, DCO	TCO	TCO	TCO	RA	DCO	TCO
Time Frame	5-10 min	5 min	Phase/Cycle/ 15 min	Cycle	5-15 min	Phase/Cycle/ 5 min	Sec by sec	Cycle	Cycle/5 min	3 sec- Cycle
Level	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L	C/L
Model	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
Timings	S, O	S, Cl, O, PS	S, Cl, O, PS	S, Cl, O	S, Cl, O, PS	S, Cl, O	S	S, Cl, O	S, Cl, O, PS	S, PS
Flexible Regions	No	No	Yes	Yes	No	No	No	Yes	Yes	Yes
Vehicle Actuated	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes
TSP	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Detection: SL= stop-line; NSL= near-stop-line; MB= mid-block; US = upstream.

Action: P= proactive; R= reactive. Adjustment: RA = rule-based adjustment; DCO = domain-constrained optimization; TCO = time-constrained optimization.

Level: L= local; C = central. Timings: S = splits; Cl = cycle length; O = offset; PS = phase sequencing.

2.4. Transit Signal Priority Systems

Transit Signal Priority (TSP) is meant for some priority services within the coordinated operation of traffic signals that can reduce delay for the transit vehicles with minimal impact on other traffic (Collura, et al., 2004).

Smith, et al. (2005) listed the typical objectives of the TSP as (a) improved schedule adherence, (b) improved transit efficiency and (c) a contribution to enhanced transit information and increased road network efficiency. They also indicated that typical active TSP priority measures are: (a) *green extension*: the extension of a current green phase for the approaching TSP equipped vehicle, (b) *early green*: earlier start of the green time phase for the approaching TSP-equipped vehicle, (c) *actuated transit phase*: when a transit vehicle is detected, an actuated transit phase is displayed, (d) *phase insertion*: special priority phase is inserted within the normal signal phase sequence, and (e) *phase rotation*: the order of the normal signal phases is rotated to provide TSP.

Zhou, et al. (2007) stated that the basis of TSP with adaptive signal control systems is to provide priority while simultaneously trying to optimize some given traffic performance criteria. The control strategies are continuously adjusted with the continuous monitoring of traffic conditions. Thus, early detection of transit vehicles is essential to allow more time to adjust the signals to provide priority while minimizing traffic impacts.

Active priority strategies mandate transit vehicles detection using sensors. Three known different categories of transit vehicles detection technologies exist. These are: "infrastructure equipment only", "on-bus and local infrastructure", and

"on-bus and central infrastructure" (Hounsell, et al., 2004). Such detection technologies act as the communication link between the approaching transit vehicle and the signal controller. Primarily, a detection sensor consists of a message conveyer. Detection technologies should serve the purposes of: (a) the detection of the transit vehicle and (b) the reception of this information on time (the earliest) by the signal controller.

Recent TSP research focuses on the signal control settings integrated with the intermittent use of dedicated transit lanes. The effectiveness of the traffic control system commonly deteriorates (when the TSP is active) in heavy traffic conditions because the signals have to accommodate, not just the transit vehicle, but also the traffic in which it is embedded (Viegas & Lu, 2001; Viegas & Lu, 2004; Eichler & Daganzo, 2006). Viegas & Lu (2001, 2004) and Eichler & Daganzo (2006) developed models of transit signal priority with intermittent bus lanes. Dion & Hellinga (2002) developed a traffic-responsive model named Signal Priority Procedure for Optimization in Real-Time (SPPORT) that incorporates the interference caused to the general traffic by transit vehicles stopping in the right of way to board and discharge passengers. The model is based on a multi-objective optimization process and is rule based.

Zhou, et al. (2007) developed a parallel genetic algorithm (PGA) based on adaptive Transit Signal Priority (TSP) strategy to optimize the phase plan, cycle length, and green splits at isolated intersections for the enhanced performance of both transit and the general vehicles. Muthuswamy, *et al.* (2007), in coordination with Southeastern Pennsylvania Transportation Authority, developed an adaptive TSP

algorithm in a case study that investigated several issues including the optimization of signal timing, the impact of TSP on side street traffic and on heavily congested intersections, as well as an bus and non-bus travel times. Liu, et al. (2008) developed an analytical approach for the design and evaluation of a TSP system with the early green and extended green operations to quantify an induced delay.

Stevanovic, et al (2008) introduced a Genetic Algorithm (GA) based optimization tool (VISAGOST) that incorporates transit priority settings on roads with both private and transit traffic. It is based on VISSIM platform. This program optimizes all four basic signal timing parameters: cycle length, green splits, offsets, and phase sequences. The study showed that optimization of the transit priority settings has significant impact on travelers' delays in corridors with mixed traffic and transit operations.

Ghanim, et al. (2009) presented an integrated real-time traffic signal controller with a Genetic Algorithm (GA) based traffic signal timing optimization technique and an Artificial Neural Networks (ANN) based TSP control. The study showed that a GA-based real-time traffic signal control with TSP is a very useful method. Toledo, et al. (2010) developed a mesoscopic simulation for modeling the operation dynamics of large-scale transit systems, taking into account the stochasticity due to interactions with road traffic, to support evaluation of operations, planning and control of transit operations.

On the other hand, transit priority is also applied with exclusive transit lanes with more frequent transit routes. Typically, the optimization of transit priority is addressed with a localized focus on the subject intersection only. Mesbah, et al (2011)

developed an optimum combination of exclusive transit lanes on a network basis. The model, which uses a bi-level optimization programming, has been tested on a grid network of 38 nodes and 98 one directional links. The model was tested using 20 pairs of origin and destination nodes with a total demand of 38000 passengers /hour. However, it is not a real-time control strategy with transit signal priority, rather a design problem with exclusive transit lanes to facilitate transit priority.

Recently, Hawas (2011a) developed a simulation based-integrated Fuzzy Logic model for the real-time traffic signal control. The model incorporates the traffic stream composition, the downstream approach congestion in terms of blockage percentage, predicted queues at the approach, approach speed as the fuzzy inputs. The model generates some weights for the green time allocation for each candidate phase. The extension of this fuzzy-model was made to incorporate transit signal preemption in Hawas (2011b). However, the extended model does not consider details of transit vehicle characteristics, for example, the expected location of the transit vehicle on the approach link prior to changing the associated phase, the compliance with schedule adherence and the lateness of the transit vehicle. Moreover, these models have limitations on making proper signal control decisions in the presence of the non-recurrent congestion, like incident, explicitly.

In brief, very few TSP systems have the capability to generate an optimum or near-optimum signal timing solution incorporating both private vehicular traffic and buses as transit vehicles. More research is needed to develop more efficient algorithms, with an ability to react in a balanced way in both recurrent and non-recurrent conditions. Situations involving TSP systems in incident situations should

be investigated deeply as it may deteriorate the overall network performance quite dramatically. As such, it is quite appealing to integrate such TSP systems with incident detection capabilities and incident management strategies.

2.5. Incident Detection Systems

Non-recurring events such as accidents, disabled vehicles, spilled loads, temporary maintenance and construction activities, signal and detector malfunctions, and other special and unusual events that disrupt the normal flow of traffic and cause motorist delay are generally termed as incidents (Yuan & Cheu, 2003). In arterials, incidents require operator's attention to handle the accumulation of vehicular queues on the blocked lane(s). The travel time (as an indicator of congestion) might increase because of the severity of the incident for the associated routes and road network. Therefore, incident detection has emerged as an important function in both freeway and arterial traffic management systems.

In general, the incident detection model is essentially a pattern classification problem. Here, the traffic data during (or immediately after) the incidents is to be identified and classified from incident-free patterns. Automated incident detection algorithms have been the subject of much research in the past few decades (Yuan & Cheu, 2003).

A comprehensive review of existing incident detection systems was conducted by Parkany (2005). He indicated that the majority of accident detection automated systems could be mostly classified as point detector-data processing systems that use electronic raw data from field detectors (thus, do not require visual observation).

Different algorithms employ different data requirements, principles, and complexities.

The most notable forms of such incident detection systems using point detector data are: (a) *comparative algorithms* (Payne, 1976; Payne & Knobel, 1976; Payne & Tignor, 1978; Collins, et al, 1979; Black & Sreedevi, 2001; Balke, 1993; Masters, et al., 1991), (b) *statistical algorithms* (Dudek, et al. , 1974; Levin & Krause , 1978; Tsai & Case, 1979), (c) *time series algorithms* (Ahmed & Cook, 1977; Ahmed & Cook, 1980; Ahmed & Cook, 1982; Collins, et al., 1979), (d) *filtering/smoothing algorithms* (Adeli & Samant, 2000; Cook & Cleveland, 1974; Samant & Adeli, 2000; Stephanedes & Chassiakos, 1993a; Stephanedes & Chassiakos, 1993b; Chassiakos & Stephanedes, 1993), (e) *traffic modeling algorithms* (Black & Sreedevi, 2001; Forbes & Hall, 1990; Fambro & Ritch, 1980; Persaud, et al., 1990), (f) *artificial intelligence algorithms* (Abdulhai & Ritchie, 1999; Chang & Wang, 1994; Cheu & Ritchie, 1995; Hsiao et al., 1994; Ishak & Al-Deek, 1998; Ivan et, al., 1995; Ivan & Chen, 1997; Ivan, 1997; Ivan & Sethi, 1998) and (g) *image processing algorithms* (Michalopoulos, 1991; Michalopoulos, et al., 1993).

Comparative algorithms generally compare some traffic measurements (e.g., speed, volume and occupancy) by observing various incident and no incident patterns. The on-line traffic detection variables are compared against the estimated thresholds to recognize an incident (Persaud, et al., 1990).

Time series and smoothing algorithms use statistical models to check whether the current traffic condition is following general trends of what is expected for a particular time of the day or not. Incidents are detected from the abrupt differences

between the estimated and the observed on-line trends (Chassiakos & Stephanedes, 1993; Stephanedes & Chassiakos, 1993b).

Probabilistic algorithms estimate the probability distribution functions of the detection variables. Like comparative algorithms, these algorithms define some expected threshold by examining both historical accident and accident-free data (Jin, et al., 2002).

Traffic modeling algorithms use some traffic flow modeling approach, in the form of nonlinear differential equations or simulation to model traffic streams under normal and accident conditions, based on current data from field detectors. The emulated patterns are then matched with some predetermined patterns. These algorithms can be further classified into local (observations at a single site) or section (observations at two or more spatially adjacent sites) algorithms (Corby & Saccomanno, 1997; Shah, et al., 2008; Gursoy, et al., 2009).

Artificial neural networks algorithms detect incidents in traffic streams by differentiating them from other events, such as compression waves, traffic pulses, and equipment malfunction by mimicking human-like behaviour. Inputs to these algorithms are propagated to the output (normal or accident condition) through the weights of the links connecting the neurons of different layers (Dia & Thomas, 2011; Judicky & Robinson, 1992; Kay, 1992; Chen & Wang, 2009).

Wavelet techniques identify incidents by time–frequency location (obtaining a signal at a particular time or frequency), multi-rate filtering (differentiating the signals that have various frequencies), scale–space analysis (extracting features at

various locations in space at different scales), and multi-resolution analysis (Samant & Adeli, 2000; Teng & Qi, 2003).

Bayesian models quantitatively capture the causal dependencies between traffic events (e.g. incident or congestion) and traffic parameters. Incident probability is updated at each detection interval. The conditional probability of the incident is formed using general knowledge of the incident conditions. The incident is when the incident probability exceeds the predefined decision threshold (Zhang & Taylor, 2006).

Support vector machines detect incident using a pattern classifier constructed from a unique learning algorithm. The learning algorithm uses support vectors to construct a decision boundary that optimally separates the data (Yuan & Cheu, 2003; Chen et al., 2009).

Fuzzy based models can be used separately or combined with neural net techniques for incident detection on freeways or arterials. The fuzzy sets could be trained using the loop-detector data of occupancy, volume and speed for definite time intervals (Hawas, 2004; Srinivasan et al., 2000; Hawas, 2007).

To overcome the disadvantages of point-based detectors, such as detector malfunctions, probe-vehicle based algorithms emerged to detect incidents mainly on urban expressways (Sermons & Koppelman, 1996; Mussa & Upchurch, 2000; Nelson, 2000; Hellinga & Knapp, 2000; Petty et al., 1997; Walters, 1999). The probe-vehicle could be equipped with some GPS (Global Positioning System), AVI (Automatic Vehicle Identification), RFID (Radio Frequency Identification Device), cellular or other driver based sensor technologies.

Chen et al. (2010) indicated that collected traffic data is inevitably corrupted, and often contains data that do not comply with the general behavior of the data model. These data outliers can be due to various reasons, such as detector faults, transmission distortion, emergent traffic accident or other possible influencing factors. They also indicated the limited applicability of traffic data collected on freeways being used for incident detections on major arterials or at intersections. The ability to detect one or more multi-dimensional traffic stream incident is an important consideration for evaluating the various detection systems for integrated (freeway/surface arterials) corridor traffic management (Awadallah, 2002; Petty et al., 2002).

Castro-Neto et al (2009) emphasized the accuracy of the prediction of short-term traffic flow under some typical conditions, such as vehicular crashes, inclement weather, work zones and holidays for an effective and proactive traffic management system in the context of intelligent transportation systems (ITS).

Hawas (2007) stated that the incident detection data processing algorithms are associated with two major limitations: high false-alarm rates and threshold calibration requirements. He also emphasized significant malfunction rates as the source of false-alarm rates from these data processing algorithms. The majority of incident detection algorithms are local (or point based) in perspective and based on pre-specified empirically set threshold values for particular traffic parameters measured in real-time. The occurrence of an incident is declared when measured traffic quantities exceed such thresholds. Thus, the false-alarm rates and detection rates primarily depend on the choice of threshold values. Furthermore, the detection algorithms do

not consider other factors such as time of day, geometries, pavement and environmental conditions in interpreting traffic measurements to identify incidents.

An obvious and critical weakness of virtually all detection algorithms in current practice is they do not explicitly and systematically incorporate the prior experience gained by the TMC operators, or the historical behavior of the traffic system (Awadallah, 2002; Petty et al., 2002).

To conclude, several limitations have been pointed out from this review of existing incident detection techniques. Among the most noticeable limitations are scarcity of accurate data to calibrate generalized incident detection models; the sensitivity of the algorithms performances to the preset threshold values, the instability of performances in terms of detection accuracy and false alarms under various traffic condition., Also, there is insufficient evidence to judge the various algorithms performances (both off-line and on-line). Furthermore, there is literally no research on the testing effectiveness of such detection techniques within a system operated by some advanced ATCS, or if the signal controller is enabled for TSP. This dictates the need for more research on incident detection on urban streets, and assessing the impact of deploying such incident detection techniques as integral component of ATCS and TSP systems. More discussion and a detailed review of specific incident techniques are included in Chapter 4.

2.6. Research Trends of ATCSs

Aboudolas, et al (2009) distinguishes two principal classes of signal control strategies: (a) strategies applicable to network under-saturated traffic conditions and (b) strategies applicable to network oversaturated traffic conditions.

Typically, the objective of traffic signal control algorithms is to optimize (minimize) some disutility function, such as, travel time, delay or number of stops, or maximize a utility function such as network throughput (He et al, 2011). Kosonen (2003) indicated that there are many variables and, possibly, opposing objectives for an area signal control. The main objectives of area control are often to minimize the overall vehicular delay, to avoid stops on main streets, or to improve the public transport mobility. In coordinated control systems, smooth traffic flows cannot be guaranteed for all directions equally.

The majority of existing ATCSs aim to minimize some disutility terms (delay is the most common one) as the objective function. Some systems aim to maximize some utility terms (e.g., capacity or vehicular throughput) only. Some other systems aim to maximize some utility term while simultaneously minimizing the disutility represented by other terms. The review of ATCSs by Stevanovic (2010) indicates that OPAC aims to minimize delay, UTOPIA aims to minimize stops and delay, SCATS aims to maximize capacity, SCOOT aims to minimize stops, delay and congestion, PRODYN aims to minimize total delay and MOVA aims to minimize stops, delay and maximize capacity simultaneously. Among these, UTOPIA, SCOOT and SCATS are primarily centralized, but others are distributed control systems. The majority of these systems utilize online detector data as a data source to estimate the targeted

objective function. OPAC, PRODYN and MOVA are not cycle based control systems. Most of these systems change the current signal settings (i.e. adjust cycle, green splits, off-set and green extension) for some pre-determined set of signal phases. Some of these control systems have the ability to incorporate the transit signal priority at the local control level as discussed earlier, but none of these seem to have the explicit ability to incorporate the incident conditions of the associated road network.

Aside from the well developed and commonly used ATCSs indicated above, other researchers attempted to develop various forms of ATCSs. The remaining part of this section summarizes some of these attempts and highlights the modeling approaches, findings and limitations.

Kosonen (2003) developed a multi-objective signal control system with multi-agent fuzzy signal control model called the HUTSIG signal control system. A microscopic traffic simulator was connected to real-time detector data. The control system has the ability to incorporate TSP in the control logic. It was tested with a signalized network of 6 intersections. The evaluation criterion was typical vehicle delays. However, there was no incident modeling capability in this system.

Felici et al (2006) developed a logic programming approach for online traffic control. It was tested on a grid network of 6 intersections in simulation and a single real intersection, with a typical peak period traffic demand. However, no consideration of TSP and incident management was incorporated.

Yu, et al. (2006) proposed a stochastic adaptive control model for traffic signals which uses a Markovian Control model as a centralized control system. This

model does not account for incidents or transit priority. Also, significant limitations of the Markovian Model exit as the dimensions of this model increase dramatically with the increase in network size. This dimensionality issue is very critical for real-time implementation as it requires significant memory space and computation time, and as such this research suggested the necessity for using a distributed and parallel processing protocol.

Aboudolas et al (2009) developed an open loop quadratic-programming control which is a store-and-forward based network-wide traffic signal control strategies for large-scale congested urban road networks. The control was tested in an urban network in the city centre of Chania with 16 signalized junctions and 71 links.

Viti & Zuylen (2010) developed a probabilistic model for actuated signal control. The model estimates the expected value of queue lengths during various signal phases and determines the signal sequences dynamically. This model was tested with a maximum demand of 1000 pcu/hr for one flow stream at a signalized intersection.

Liu & Chang (2011) developed an arterial signal optimization model for intersections experiencing queue spillback and lane blockage. The objective function of the optimization problem entails minimizing the time spent by all vehicles in the control area, while maximizing the total throughput under over-saturated conditions. Genetic Algorithm based heuristics were used to solve the optimization problem. The proposed model increases the vehicle throughput for high demand conditions, but decreases the throughput for low and medium demand scenarios. Also, it can mitigate the total system queue time in all conditions. However, the model was only tested

with a protected phase setting and the network was limited to 4 intersections only. Also, the model was not tested with relatively high demand scenarios.

Xie, et al. (2012) developed a schedule-driven control strategy, which can efficiently produce (near) optimal solutions in real-time. It assumes the traffic control problem as a single machine scheduling problem. The intersection is viewed as a machine and the clusters of aggregate flow coming from different routes are viewed as jobs. The model was tested in a network of 12 intersections (reported as maximum case) in the downtown area of Pittsburgh. The model was tested with a maximum traffic demand of 4786 vehicles/hour. The evaluation of this model was reported in terms of the *average speed of the vehicles in the network.*

Zheng & Recker (2013) developed a new adaptive control algorithm for traffic-actuated signals based on modified rolling horizon scheme. The algorithm optimizes the phase sequence, maximum green, minimum green and unit extension of the traffic-actuated control system. The controller showed some significant improvement in the average travel time per vehicle during the peak period. The control algorithm was tested through the PARAMICS micro-simulation program using a signalized network of 38 intersections under existing peak demand scenario.

The integration of the signal controller with a TSP usually produces more travel times for passenger vehicles. Most of the studies on the TSPs have concluded the improvements in travel times of the transit vehicles along the corridor tested. Wahlstedt (2011) indicated that TSP results in shorter travel times for buses and longer travel times for crossing traffic and traffic following the prioritized buses in one direction. Wahlstedt (2011) also showed increases of up to 13% for the travel

time on the cross-streets because of bus priority on a network of 6 coordinated signals under a peak period traffic load for a bus headway of 5 minutes.

Recently, Slavin et al. (2013) conducted a field study to measure the impact of adaptive traffic signal control on traffic and transit performance with SCATS on a heavily used bus routes. Originally, SCATS was not designed as a tool to improve transit performance, and it is typically deployed to control corridors with public transit use. It was observed that when SCATS is already implemented, no additional benefits of TSP to transit vehicles was observed. The transit travel time showed opposing trends because of the installation of SCATS. During the peak periods, the transit travel time was decreased for only one traffic flow direction, but there was a significant increase of transit travel time in the opposite flow direction. Slavin et al. (2013) concluded that travel time changes or improvements related to SCATS seemed to depend on the direction of travel and time of day. Also, SCATS improved the congestion levels for the transit buses at the minor intersection only, but no improvement of congestion at major intersections was found.

Another recent study by Skabardonis & Christofa, (2011) confirmed that under high traffic flow conditions at a signalized intersection, the provision of transit signal priority can deteriorate the HCM based Level of Service (LOS) on cross-streets by up to two levels (e.g., from LOS C to E) based on the nature of transit priority and frequency of the transit vehicles.

The integration of both the TSP and the incident-detection and management capabilities to the ATCSs was rarely reported in literature. Other than the work done by Hawas (2011), nearly all the existing ATCSs do not account for such combined

effects of TSP and incidents, simultaneously. Table 2.2 summarizes some of the initiatives and the state-of-the-art research on traffic control systems. Such systems are characterized from the perspective of the transit priority and incident management systems. The table lists the adopted objective function, the control decision parameters, whether or not it is a cycle based control system, the online/offline traffic data source, the tested signal settings, provision of incident modeling and TSP, reported method of evaluating the control system, the size of the network (in terms of number of intersections) used in testing, the reported traffic demand level and finally the hierarchy of the control architecture. The cells marked with "-" indicate that either this information was not reported in the research paper or report, or it is not applicable.

In conclusion, it seems that the majority of the control systems and strategies are designed to minimize the vehicular delays on a traditional cycle-based operation. Very few of the developed control systems use real online field detector data for the development, calibration and testing of such control systems. Even if real field data is used for testing, it is usually limited to a single intersection data. For the purposes of model development, calibration and for post-development evaluation, most of the literature reported control models or systems which depend mainly on the use of simulation. In addition, the "centralized" control systems in the literature were only tested using small test network of limited number of intersections. Centralized systems are often biased to the main-street or the coordinated arterial as these systems mostly adjust the offset as part of the real-time change of signal plans. Most of the systems in the literature use actuated phase settings for the real-time operation of

adaptive control systems. To the best knowledge of the author, there is no prominent control system that combines the strategies of the incident management and transit signal priority.

Table 2.2: Summary of some recent research in traffic control systems and management strategies

Paper [Name of the Program]	Objective function	Decisions on signal settings and Other strategies	Cycle based operation	Traffic Data Source	Nature of Control Type (Phase Settings)	Provision of Incident Modeling / Provision of TSP	Method of Evaluation	Network Intersection(s) [Traffic flow]	Control Architecture
Dahal et al (2012). [ITCS]	Minimize the severity of incidents	Reroute through VMS	-	Detector	-	Yes / No	Simulation	3 (coordinated arterial) [Peak periods]	Centralized and Distributed
Liu and Xu (2012) [-]	Minimize the delay of vehicles	Optimized green splits and Cycle time	Yes	Offline	-	No / No	Numerical (Matlab)	1 [Peak periods]	Distributed
Liu & Chang (2011) [-]	minimize the time spent by all vehicles in the control area, maximize the total throughput	Cycle length, offset, green splits	Yes	Offline	Protected Actuated	No / No	Macroscopic flow	4 [Total network demand of 7000 vehicles/hour only]	Centralized

Paper [Program]	Objective function	Decisions on signal settings and Other strategies	Cycle based operation	Traffic Data Source	Nature of Control Type (Phase Settings)	Provision of Incident Modeling / Provision of TSP	Method of Evaluation	Network Intersection(s) [Traffic flow]	Control Architecture
Cai et. al (2009) -	Minimize delay	Dynamic allocation of green time, revision of signal plans	Yes	Detector	Split Pre-timed	No/No	Numerical Simulation (Matlab)	1 [maximum 1250 veh/hr]	Distributed
Boillot et al (2006) [CRONOS]	Minimize delay	Variable cycle and stage	Yes	Online Video	-	No/No	Field (by Control Lab.)	1 [Maximum 3300 to 2600 veh/hr]	Centralized & Distributed
Dotoli et. al (2006) [-]	Minimize the number of vehicles in queue	Green splits	Yes	Detectors	Actuated	No/Yes	Macroscopic model and numerical	2 (coordinated) [Evening peak over-saturated traffic]	Centralized
Ahn & Rakha (2006) [-]	Minimize stops, delay and congestion	Green extension and recall	Yes	Detectors	Split Pre-timed and Split Actuated	No/Yes	Simulation (Integration)	21 (arterial) [Peak periods]	Distributed

Paper [Program]	Objective function	Decisions on signal settings and Other strategies	Cycle based operation	Traffic Data Source	Nature of Control Type (Phase Settings)	Provision of Incident Modeling / Provision of TSP	Method of Evaluation	Network Intersection(s) [Traffic flow]	Control Architecture
Felici et. al (2006) [-]	Minimize congestion	Terminate the current phase and select the next phase	Yes	Sensor	Protected Actuated	No/Yes	Simulation	6 [Peak periods]	Distributed
Kosmatopoulos et al (2006) [TUC]	Minimize risk of oversaturation and queue spill back	Green splits, Cycle length, offset,	Yes	Detector	-	No/Yes	Field (by Control Lab.)	53 (coordinated arterial) [Peak periods]	Centralized
Logi & Ritchie (2001) [TCM]	Minimize demand	Traffic Diversion with VMS and ramp metering	-	Detectors	Fixed Time of Day Plans	Yes/No	Simulation (for validation)	1 [High demand (Count data)]	Centralized

Paper [Program]	Objective function	Decisions on signal settings and Other strategies	Cycle based operation	Traffic Data Source	Nature of Control Type (Phase Settings)	Provision of Incident Modeling / Provision of TSP	Method of Evaluation	Network Intersection(s) [Traffic flow]	Control Architecture
Niittymaki & Maenpaa (2001) [Fuzzy-UTC]	Minimize bus travel time	Green extension, Phase recall, Extra phase for bus	Yes	Detectors/Video camera	-	No/Yes	Field Data	1 [Peak periods]	Distributed
Wey (2000) [-]	Minimize total delay	Variable cycle length and phase sequences	-	Detectors	Permitted	No/No	Simulation	5 [1200 vphpl]	Centralized
Roberg & Abbess (1998) [-]	To disperse and control the formation of traffic queues	Reroute and gating	-	-	Fixed Time of Day Plans	Yes/No	Simulation	20×20 one way network [(with 40 entry nodes) Extremely high demands]	Centralized

2.7   Research Gaps of ATCSs

Tarnoff & Parsonson (1981) stated that actuated control (working on the principle of phase extension until a predetermined maximum value is reached) may not perform efficiently (in terms of delay minimization) when high traffic volumes approach the intersection from all directions as it extends green phases to the maximum green times on all phases. He et al (2011) indicated that actuated controller with free mode yields better throughput (in terms of number of vehicles exiting the network) than either actuated coordinated controller or transit priority coordinated systems. On the other hand, the typical pre-timed signal control systems may yield better throughputs when it works on the heavily congested traffic demand at the same time from the all competing phases. The above studies suggest that there is no strong evidence to indicate which signal control system would work more efficiently under various traffic conditions. It is also important to note that within the same controller, the arrangement of phases may also significantly affect both efficiency (in terms of delays) and throughput. As such, there is a need to devise a proposed control framework (the aim of this research) with an ability to test both pre-timed and actuated controllers.

The transit signal priority is regarded as a means to promote the use of public transit and accounts for the relatively higher number of passengers in a transit vehicle compared to that of a private car. As indicated by several researchers earlier, TSPs are commonly associated with higher delay times for cross-street traffic (Wahlstedt 2011). For situations where cross streets experience heavy congestion with no transit vehicles, the activation of TSP on major arterials is usually associated with higher delay times on cross streets and possibly more network-wide delays. On the other hand, recurrent and non-recurrent congestion

management through ATCSs is mostly driven by the objective function of delay minimization on the network or isolated intersection. These ATCSs are typically acting on the vehicular, not the passenger, delay.

While TSP systems are driven by transit vehicle throughput maximization and ATCSs are driven by vehicular delay minimization, an appealing compromise is to integrate both systems through a "passenger" delay minimization function. The use of the passenger formula would allow for favoring traffic streams of higher passenger occupancy (e.g. ones with more transit vehicles), but simultaneously preserve the delay minimization criterion. This will somehow limit significant loss to the mobility on cross streets as reported earlier.

McKenney & White (2013) indicated that previous research focusing on the use of centralized systems cannot handle city-sized problem instances and solutions because of rapidly varying volumes and complex network structures. The majority of the well-developed ATCSs are designed and proven to efficiently dedicate some sort of priority to pre-specified main streets or coordinated arterials (e.g. via signal progression, offset sitting). Therefore, the idea of having an integrated system with the ability to coordinate a network that treats various traffic streams equally and simultaneously handles TSPs efficiently in a typical urban congested road network of closely spaced intersections, especially where traffic demand could be similarly high in all directions at peak periods, and where instants of traffic incidents could be quite common, is appealing. Although it may sound quite challenging but indeed a very promising integrated solution to many of the typical daily problems in the majority of the urban networks worldwide.

In order to combine incident detection and management protocols, transit signal priority, along with the recurrent congestion management into one

integrated control system in a typical urban network, the total expected throughput (in terms of number of passengers) among all competing phases of a signal settings could be an alternative evaluation criterion as indicated earlier. The signal control system would favor the phase that is likely to contribute to higher passenger throughput, from both transit buses and private cars. Better throughput may not necessarily yield better efficiency (in terms of delay or travel times), but better throughput by a control system is essential under heavily congested traffic demand scenarios.

Incident detection can be integrated with ATCS and TSP through some management strategies or a protocol based on the assumption that the incident-induced phase should be given some priority to assist in incident clearance and the removal of potential or built-up queues. If the incident induced phase is given a priority, the quick formation of the link spill-back on that phase could be prevented. Link spillbacks may occur because of the sudden reduction of supply capacity in heavy traffic demand situations in a network of closely spaced intersections.

Centralized control systems have the disadvantage of having longer information processing times, and as such expensive network-wide data processing systems. The efficiency of such centralized systems is not always better than that of localized controllers as indicated by many researchers (McKenney & White (2013), Hawas 2011b). On the other hand, purely local controllers at isolated intersections may result in inaccurate control decisions as they do not consider downstream traffic conditions. An appealing compromise between these two extremes, in order to make the control system smarter and aware of the traffic conditions of adjacent intersections, is for the control system

to be designed to account for the traffic conditions on immediate downstream intersections only. It would prevent the control system from giving inappropriate and unnecessary green times for a phase whose downstream exit link is congested or has impending spill-back. Thus, the control system acts as a distributed control system but performs under a sub-network whose centre is the corresponding intersection of the control system. This control design may require similar sets of data collection sensors (detectors) as of the centralized systems, but it will significantly reduce the information processing time for a mega city-sized network, and as such would make the control system more suitable for real time control.

There are very few studies that report on the effect of the phase arrangement and best performing phase settings of adaptive control systems. Almost all of the developed adaptive control systems work on actuated phase settings. Moreover, studies on improving the fixed (pre-timed) control systems to act as adaptive systems are also rare. As indicated earlier, pre-timed controllers may actually perform more effectively than actuated controllers at instances of high traffic demand. As such, it is worth investigating how the efficiency and effectiveness of such pre-timed controllers will be affected if coupled with TSP and incident detection, through limited alteration of phase sequencing. Enabling limited alteration of phase sequencing of pre-timed controllers may actually contribute to positive advantages in terms of higher throughput and shorter delays at some specific traffic situations. Similarly, an adaptive signal control system (based on an actuated signal system) could be further investigated to identify the best possible signal setting configurations under different traffic demand conditions.

2.8   Expected Research Contribution of this Study

This research study strives to narrow the afore-mentioned research gaps by making contributions in the following ways:

- By developing an integrated control logic for a distributive signal system which is reactive to the both incidents and recurrent congestions on the approach link, blockage condition on the downstream exit link and transit signal priority, with the objective of maximizing the productivity (i.e. throughput) under different traffic demand scenarios

- By developing simpler formulations for using the incident condition status of the approach link with the signal control decision. Hence, some new forms of urban incident detection models have to be developed.

- By conducting thorough investigations of the productivity and efficiency outcomes of different phase settings for the developed signal control logic. Therefore, the potential areas for further enhancements for some specific phase settings under certain conditions will be revealed.

CHAPTER 3: FORMULATION AND MODULES OF THE INTEGRATED TRAFFIC SIGNAL CONTROL SYSTEM

3.1 Introduction

This chapter presents the formulation of the proposed traffic control system. The proposed method can be envisaged as an improvement on the existing typical pre-timed or actuated traffic control systems with added functionalities. It takes into consideration the boundary conditions of traffic streams; incoming and outgoing at an intersection operated by a controller that employs such integrated control method. These boundary conditions relate to the recurrent traffic congestion, occurrences of incidents, transit signal priorities on incoming approach links and the presence of blockage condition on the downstream exit links of the subject intersection.

The concept of the problem will be presented first, leading afterwards to the mathematical formulation of the proposed methodology. The methodology may be envisaged as an integration of multiple modules; each module accounts for a specific boundary condition. The overall objective function of the integrated methodology and the details of all modules are presented hereafter.

3.2 Integrated Traffic Signal Control System

This research presents a new signal control system that can account for multiple effects or boundary conditions. The boundary conditions are the aspects or events that the controller should account for once detected on the traffic streams incoming or outgoing at an intersection. For instance, a boundary condition may represent the occurrence of an incident, a request of a transit vehicle preemption, etc.

The logic and mathematical formulation of the system will be presented, under the assumption that the system is integrated within the well-known pre-timed or actuated signal controllers. The system is envisioned to operate through a new form of *actuation module*. Before making the decision to switch to a new phase(s) and/or for either green extension (or truncation) of a running green phase set by the signal controller, the *actuation module* considers all the possible impacts of the relevant boundary conditions.

The control system's overall hierarchical structure is shown in Figure 3.1. The control system uses link detectors' data to determine the boundary conditions of all incoming and exit links of the subject intersection. Namely, four processes or modules are deployed. The *traffic regime state* module estimates the congestion status of the link. The *incident status* module determines the likelihood of an incident on the link. The *transit priority module* estimates if the link is flagged for transit priority based on transit vehicle location, type, etc. The *downstream blockage module* scans all downstream links and determines their recurrent blockage conditions.
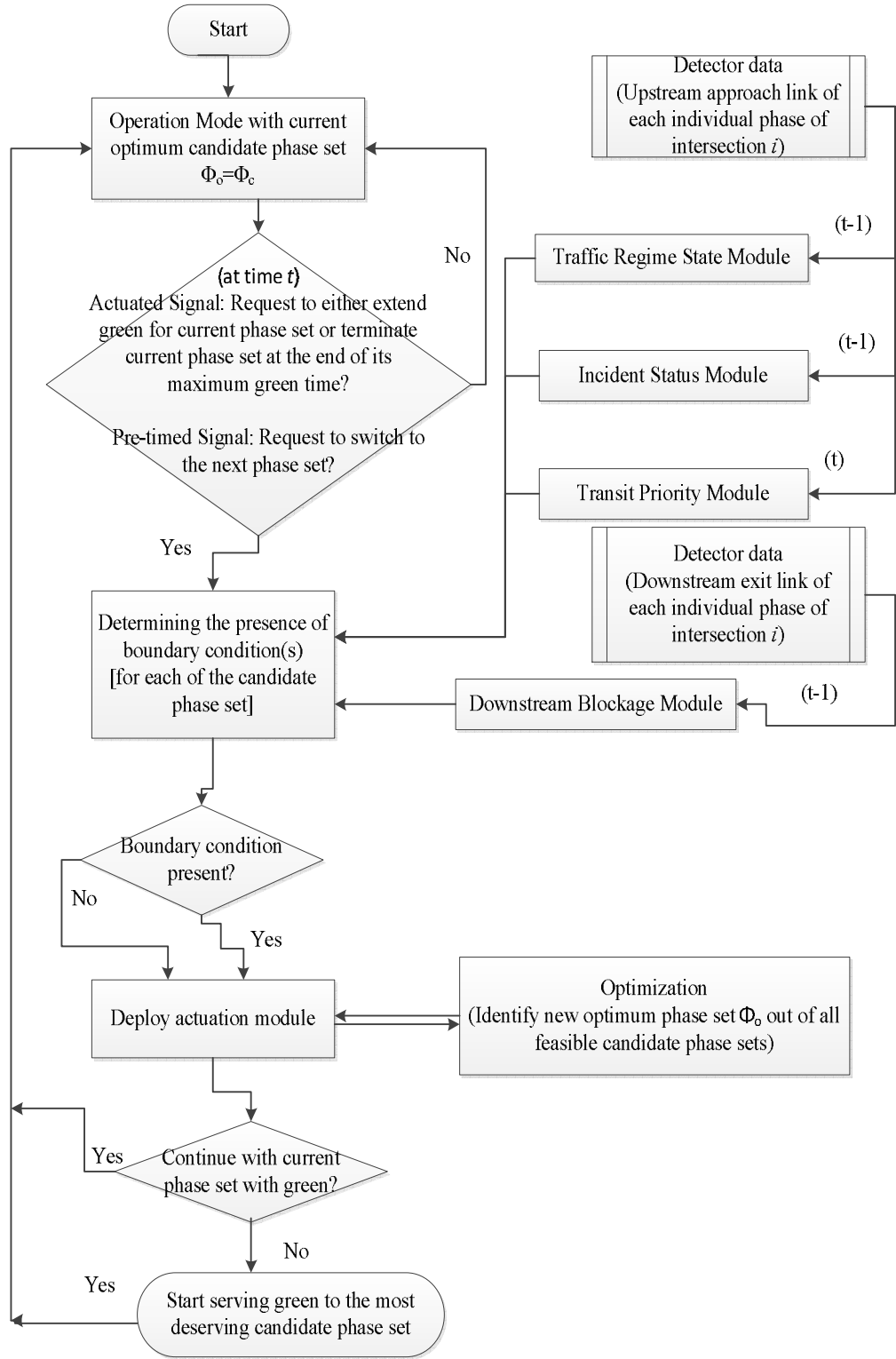
Figure 3.1: Overall hierarchical architecture of the proposed integrated signal control

The proposed system operates in a manner similar to a typical pre-timed signal (with split or protected phase settings) or fully actuated signal (with split-phase arrangement, protected phase, or dual ring phase settings). Details of the various phase arrangements will follow afterwards. The system has a continuously running *actuation module*, which decides the "most deserving" phase set to be allocated the green from the inputs of the four modules. While deploying the *actuation module*, the system also scans all feasible phase sets (including the current one). The system estimates the value of the so-called *actuation index* for all the feasible phase sets, and determines the optimum (most deserving) *candidate* phase set: the one that possesses the maximum actuation index value to be served green.

For the *actuated* controllers, the feasible phase sets include the currently running green phase set. If the *actuation module* identifies the currently running green phase set as the candidate phase set at any time *t*, then the green time is extended for a period of $\Delta g_{i,\Phi_k}$, where $\Delta g_{i,\Phi_k}$ is the adopted (pre-selected) green time extension (seconds) for the phase set Φ_k at intersection *i*. The whole control system logic is repeated (a loop) at each $\Delta g_{i,\Phi_k}$ interval, while it is constrained with some limiting conditions (e.g. maximum green allocation). If the optimum (most deserving) candidate phase set is currently red flagged, then the current green phase set is truncated to switch to the candidate phase with the maximum actuation index value. The control system logic is activated when the current phase set reaches the minimum green value, g_{i,Φ_k}^{min}.

For the pre-timed controllers, where a phase set runs with fixed green intervals, the *actuation module* scans all the feasible phase sets (excluding the currently running green phase set). At the end of the green interval of the current

phase set, the *actuation module* identifies the (most deserving) candidate phase set, with the maximum *actuation index* value from all the feasible phase sets. The controller switches the green to the most deserving candidate phase set. The control system logic is repeated only at the end of the pre-estimated green phase set. The specific details of each module (process) are presented later in this chapter.

A typical intersection with possible signal phase sets, associated approach links and exit links (as shown in Figure 3.2) is adopted herein to discuss the details of the new system and present the formulation and modules. As shown, the intersection has four incoming approach links; *A*, *B*, *C* and *D*. The intersection has four exit links; *E*, *F*, *G* and *H*. The intersection is operated with a dual ring controller of 8 phases to serve all the "Through" (with "Right") and "Left" movements. Each approach is assumed to have three detectors if the link is serving a "Through" movement or two detectors if serving a "Left" movement.

The adopted phase numbering sequence follows the phase numbering of the dual-ring barrier control system as shown in Figure 3.3. In the dual-ring operation of the actuated controller, two concurrent *individual* phases run *green* simultaneously. The two concurrently running are referred to as a phase *set*. Each individual phase of a feasible phase set is associated with one upstream and one downstream exit link (as shown in Figure 3.2).
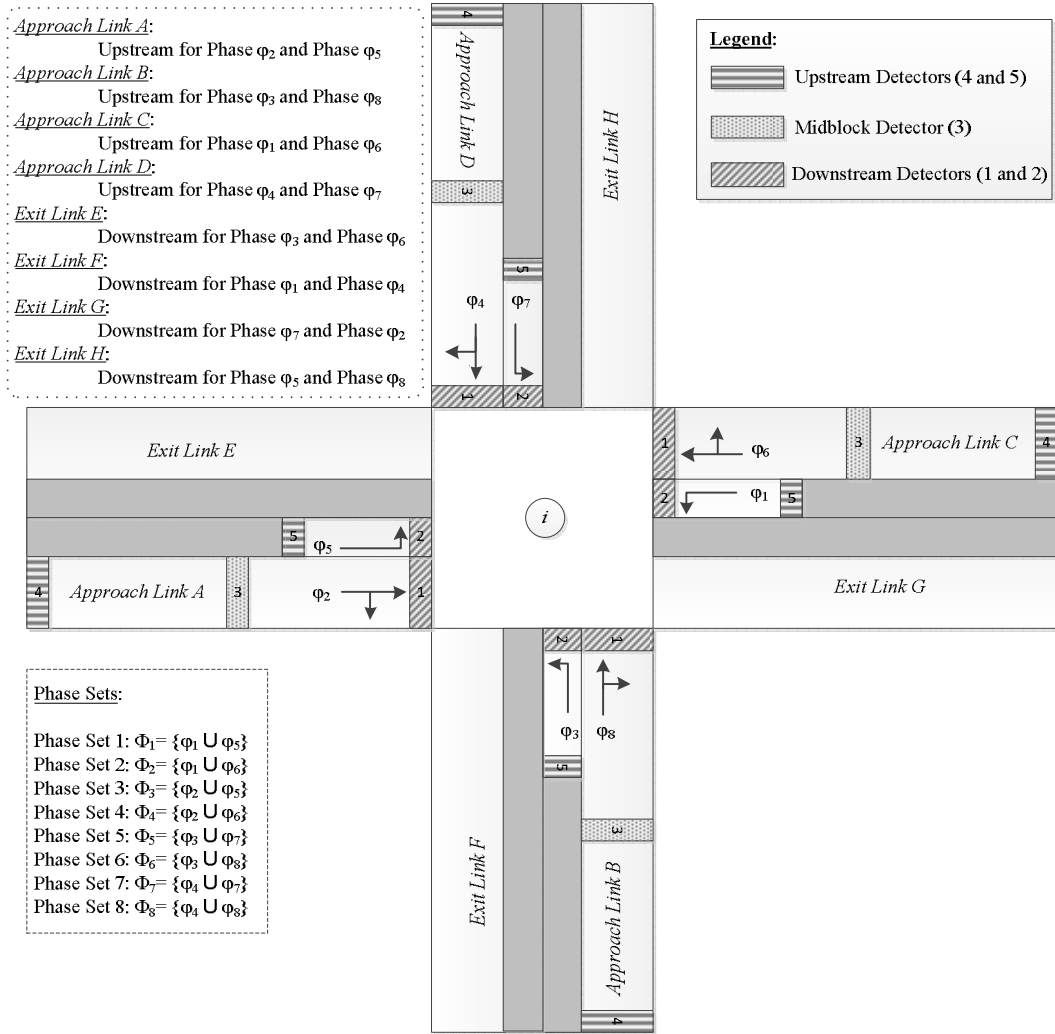
Figure 3.2: Typical phases with associated approach and exit links
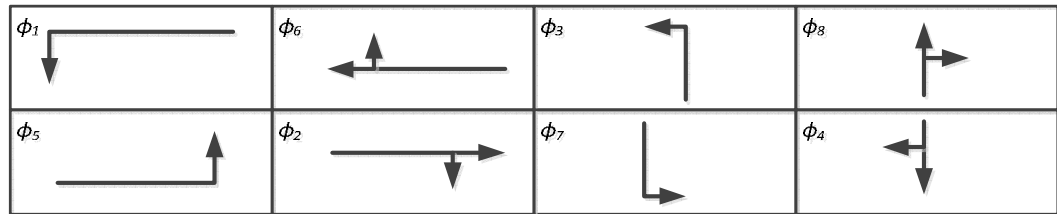
Figure 3.3: Typical phases in a dual ring operation

The proposed system applies to the two essential types of controllers; pre-timed and actuated. A typical actuated controller operates in such a way that the current phase set, if elapsed green exceeds the allocated minimum green time, it is extended by a *vehicle or unit extension* upon each actuation detected by the vehicle presence detector until the current phase set reaches its maximum allocated green time. Therefore, the important parameters of the actuated controller are the minimum green time, the pre-selected green-extension interval and the maximum green time. On the other hand, for pre-timed controllers, there is no vehicle extension. In general, pre-timed controllers can be regarded as actuated controllers with the minimum green time interval equal to the maximum green time.

Apart from the type of controllers, the proposed system can be operated with various types of phase settings. For actuated type controller, it can be applied to split phase setting, protected phase setting and dual ring barrier phase setting. For the pre-timed type controller, the system can be deployed for split phase setting and protected phase setting. In total, five different types of control system variations can be deployed as follows:

1. Pre-timed Split Phase Setting

2. Pre-timed Protected Phase Setting

3. Actuated Split Phase Setting

4. Actuated Protected Phase Setting

5. Actuated Dual Ring Barrier Setting

The details of each setting are explained below. Any of the above phase settings arrange the various phases into *sets*. Each set comprises two individual phases running green concurrently, while other phases are flagged red. The

48

adopted phase sets along with the corresponding individual phases are shown in Figures 3.4, 3.5 and 3.6 for the *Dual Ring Barrier, Split Phase* and *Protected Phase* settings, respectively. These figures also show the adopted set of candidate feasible phase sets while a specific phase set is currently running green.

With reference to Figure 3.4, Φ_k denotes a specific phase set k, where such a set comprises two individual phases. Individual phase sets are denoted here by ϕ. For instance, $\Phi_1 = \{\phi_1 \cup \phi_5\}$, $\Phi_2 = \{\phi_1 \cup \phi_6\}$, $\Phi_3 = \{\phi_2 \cup \phi_5\}$, $\Phi_4 = \{\phi_2 \cup \phi_6\}$, $\Phi_5 = \{\phi_3 \cup \phi_7\}$, $\Phi_6 = \{\phi_3 \cup \phi_8\}$, $\Phi_7 = \{\phi_4 \cup \phi_7\}$, and $\Phi_8 = \{\phi_4 \cup \phi_8\}$.

In the proposed system, the notation Ψ_c is used to refer to the set of *candidate* phase sets, if the current *green* phase set is Φ_c. In other words, if the current green set is Φ_c, then the Ψ_c set will include all the potential sets that could be served with green if a decision is to be made on extending or truncating the current phase set. Such Ψ_c will eventually vary based on the deployed mode of controller's operation (dual, split or protected). That is, the number of elements in the Ψ_c set varies and depends on the mode of operation of the controller for every operational mode as listed below:

For *Split Pre-timed* phase setting (see Figure 3.5):

$\Psi_2 = \{\Phi_3, \Phi_6, \Phi_7\}$, $\quad \Psi_3 = \{\Phi_2, \Phi_6, \Phi_7\}$, $\quad \Psi_6 = \{\Phi_2, \Phi_3, \Phi_7\}$, $\quad \Psi_7 = \{\Phi_2, \Phi_3, \Phi_6\}$

For *Split Actuated* phase setting (see Figure 3.5):

$\Psi_2 = \{\Phi_2, \Phi_3, \Phi_6, \Phi_7\}$, $\Psi_3 = \{\Phi_2, \Phi_3, \Phi_6, \Phi_7\}$, $\quad \Psi_6 = \{\Phi_2, \Phi_3, \Phi_6, \Phi_7\}$, $\Psi_7 = \{\Phi_2, \Phi_3, \Phi_6, \Phi_7\}$

Dual Ring Barrier Settings (Only for Actuated Controller)

Phase Set Φ_2

ϕ_6
ϕ_1

$\Psi_1=\{\Phi_1,\Phi_2,\Phi_3,\Phi_4\}$
$\Psi_2=\{\Phi_2,\Phi_4\}$
$\Psi_3=\{\Phi_3,\Phi_4\}$
$\Psi_4=\{\Phi_4,\Phi_5\}$

Phase Set Φ_7

ϕ_4 ϕ_7

Phase Set Φ_1

ϕ_1
ϕ_5

Phase Set Φ_4

ϕ_6
ϕ_2

Phase Set Φ_5

ϕ_7 ϕ_3

Phase Set Φ_8

ϕ_4 ϕ_8

Phase Set Φ_3

ϕ_5
ϕ_2

$\Psi_5=\{\Phi_5,\Phi_6,\Phi_7,\Phi_8\}$
$\Psi_6=\{\Phi_6,\Phi_8\}$
$\Psi_7=\{\Phi_7,\Phi_8\}$
$\Psi_8=\{\Phi_8,\Phi_1\}$

Phase Set Φ_6

ϕ_3 ϕ_8
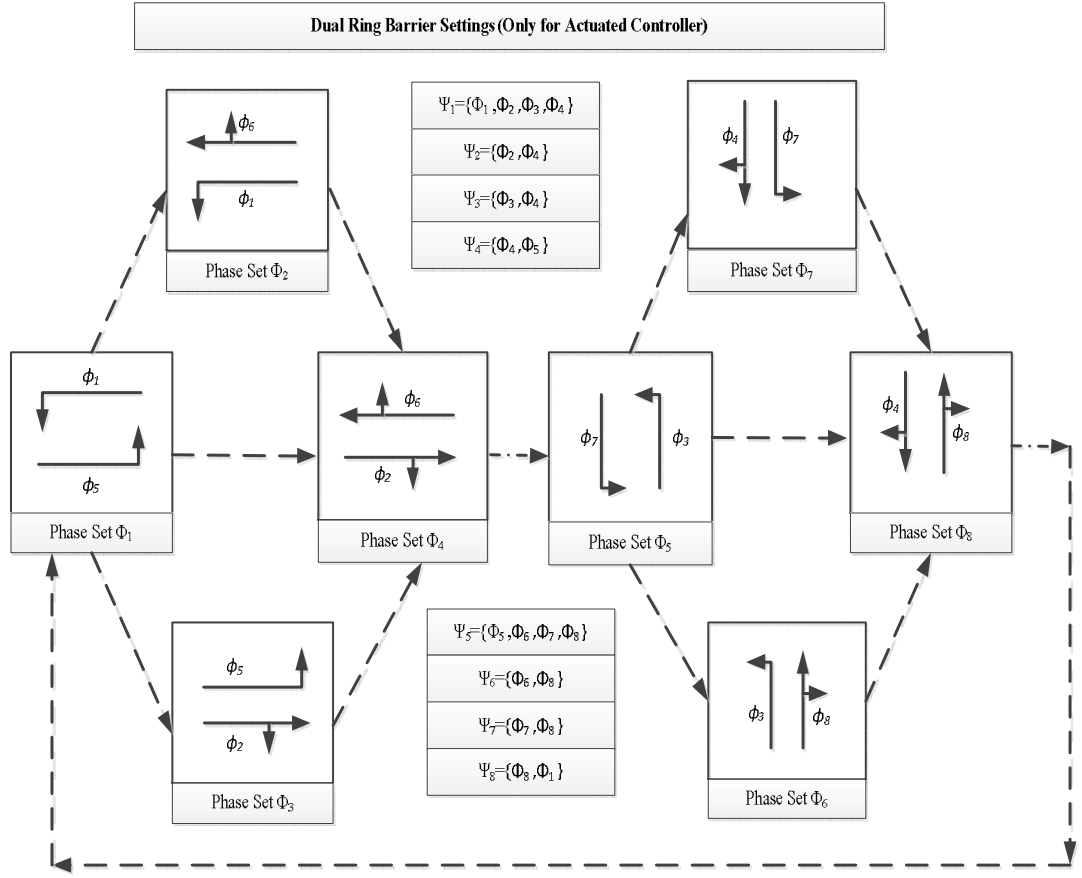
Figure 3.4: Dual Ring Barrier Mode (for Actuated Controllers only)

Split Phase Settings (For Both Actuated and Pre-timed Controllers)				
	ϕ_5 ϕ_2	ϕ_3 ϕ_8	ϕ_6 ϕ_1	ϕ_4 ϕ_7
Controller	Phase Set Φ_3	Phase Set Φ_6	Phase Set Φ_2	Phase Set Φ_7
Actuated	$\Psi_3=\{\Phi_3,\Phi_6,\Phi_2,\Phi_7\}$	$\Psi_6=\{\Phi_3,\Phi_6,\Phi_2,\Phi_7\}$	$\Psi_2=\{\Phi_3,\Phi_6,\Phi_2,\Phi_7\}$	$\Psi_7=\{\Phi_3,\Phi_6,\Phi_2,\Phi_7\}$
Pre-timed	$\Psi_3=\{\Phi_6,\Phi_2,\Phi_7\}$	$\Psi_6=\{\Phi_3,\Phi_2,\Phi_7\}$	$\Psi_2=\{\Phi_3,\Phi_6,\Phi_7\}$	$\Psi_7=\{\Phi_3,\Phi_6,\Phi_2\}$

Figure 3.5: Split Phase Mode (for Pre-timed and Actuated Controllers)

Protected Phase Settings (For Both Actuated and Pre-timed Controllers)			
Controller	Phase Set Φ_1	Phase Set Φ_4	Phase Set Φ_5	Phase Set Φ_8
Actuated	$\Psi_1=\{\Phi_1,\Phi_4,\Phi_5,\Phi_8\}$	$\Psi_4=\{\Phi_1,\Phi_4,\Phi_5,\Phi_8\}$	$\Psi_5=\{\Phi_1,\Phi_4,\Phi_5,\Phi_8\}$	$\Psi_8=\{\Phi_1,\Phi_4,\Phi_5,\Phi_8\}$
Pre-timed	$\Psi_1=\{\Phi_4,\Phi_5,\Phi_8\}$	$\Psi_4=\{\Phi_1,\Phi_5,\Phi_8\}$	$\Psi_5=\{\Phi_1,\Phi_4,\Phi_8\}$	$\Psi_8=\{\Phi_1,\Phi_4,\Phi_5\}$

Figure 3.6: Protected Phase Mode (Pre-timed and Actuated Controllers)

For *Protected Pre-timed* phase setting (see Figure 3.6):

$$\Psi_1 = \{\Phi_4, \Phi_5, \Phi_8\}, \quad \Psi_4 = \{\Phi_1, \Phi_5, \Phi_8\}, \quad \Psi_5 = \{\Phi_1, \Phi_4, \Phi_8\}, \quad \Psi_8 = \{\Phi_1, \Phi_4, \Phi_5\}$$

For *Protected Actuated* phase setting (see Figure 3.6):

$$\Psi_1 = \{\Phi_1, \Phi_4, \Phi_5, \Phi_8\}, \quad \Psi_4 = \{\Phi_1, \Phi_4, \Phi_5, \Phi_8\}, \quad \Psi_5 = \{\Phi_1, \Phi_4, \Phi_5, \Phi_8\}, \quad \Psi_8 = \{\Phi_1, \Phi_4, \Phi_5, \Phi_8\}$$

For *Dual Actuated* phase setting (see Figure 3.4):

$$\Psi_1 = \{\Phi_1, \Phi_2, \Phi_3, \Phi_4\}, \quad \Psi_2 = \{\Phi_2, \Phi_4\}, \quad \Psi_3 = \{\Phi_3, \Phi_4\}, \quad \Psi_4 = \{\Phi_4, \Phi_5\},$$
$$\Psi_5 = \{\Phi_5, \Phi_6, \Phi_7, \Phi_8\}, \Psi_6 = \{\Phi_6, \Phi_8\}, \Psi_7 = \{\Phi_7, \Phi_8\}, \Psi_8 = \{\Phi_8, \Phi_1\}$$

As an example, for an actuated dual ring barrier control system, if the current green phase set is Φ_1, ϕ_1 and ϕ_5 run concurrently with *green*, while the other competing phase sets ($\Phi_2\{\phi_1 \cup \phi_6\}$, $\Phi_3\{\phi_2 \cup \phi_5\}$ and $\Phi_4\{\phi_2 \cup \phi_6\}$) are kept with a *red* flag. On deciding whether to extend the green of Φ_1 or switching

the green to any of the potential sets (Φ_2 or Φ_3 or Φ_4), the logic scans all the sets included in $\Psi_1 = \{\Phi_1, \Phi_2, \Phi_3, \Phi_4\}$.

It is to be noted that for actuated controller, the set of feasible phase sets includes the one that is currently running green, while in the pre-timed operation, the set of feasible or candidate sets excludes the currently running green set. For example, in the *split* operation mode (Figure 3.5), if the current green phase set is Φ_2, and the signal is operated by an actuated controller, then $\Psi_2 = \{\Phi_2, \Phi_3, \Phi_6, \Phi_7\}$. Alternatively, for the pre-timed controller case, if the current phase set is Φ_2, then $\Psi_2 = \{\Phi_3, \Phi_6, \Phi_7\}$.

The newly proposed system makes the actuation decision (extension or truncation) of a currently running green phase set, in recurrent congested conditions and even in more complicated situations comprising some or all of the relevant boundary conditions. The *actuation module* incorporates the concept of balance between the demand and supply as well. The supply refers to the vehicular spaces on the downstream exit link(s) of the subject intersection. The demand refers to the vehicles (and passengers) to be served with *green* phase on the upstream approach links with a candidate phase set in order to cross the intersection. The supply side is intended to make sure that there is no restriction on the downstream exit links for the vehicles (and passengers) that are currently waiting or approaching to be served by the controller. It is intuitive that the signal controller should not allow throughput or vehicles (by extending the green) to the downstream exit link of the intersection if it does not have enough physical space to accommodate the expected number of vehicles to be dealt with.

The decision made by the *actuation module* is based on the following logical arguments:

- A benefit could be gained by serving the passengers (of a feasible phase set) who are subjected more to higher *virtual queue of passengers* on the demand side (upstream) of the intersections first.

- Even though the upstream link passengers with the highest *virtual queue of passengers* of a feasible phase set may deserve to be served *green* by the controller, restrictions may be imposed by exit links (if these do not have enough physical spaces to accommodate the expected number of vehicles, as if the exit links are flagged as physically blocked links).

The term *virtual queue of passengers* is specifically intended to represent and capture the presence of the boundary conditions on all competing phases and to account for the balance of supply and demand. To ease understanding of the term *virtual queue of passengers* on an approach link of a phase, and what exactly it is used for, some general notes have been provided below:

- The higher the number of cars on an approach link, the higher the possibility of forming queues and as such the higher the value of the *virtual queue of passengers.*

- The higher the ratio of the actual *vehicle count in queue* (in vehicles) over the corresponding maximum *link capacity (in vehicles)* of an approach link, the higher the *virtual queue of passengers.*

- The higher the number of buses (whether priority or normal ones) along the approach link of a phase, the higher the *virtual queue of passengers.* Even if there are equal numbers of small passenger cars on two competing approaches of two corresponding phases, the addition of a bus on the approach link of a phase, is likely to add a greater *virtual queue of*

passengers to that phase. This enables the treatment of transit priority of the buses as *normal* priority bus or *high* priority bus.

- The likelihood of an incident-status at some time-step is likely to generate a higher *virtual queue of passengers* on the approach link.

- In conclusion, the presence of any boundary condition on a specific phase approach (e.g., congestion in terms of longer vehicle queues, buses, and the likelihood of an incident on the approach link) is likely to yield a higher *virtual queue of passengers* for that phase compared to the absence of these boundary conditions.

To account for the downstream blockage conditions (supply), the accumulative *virtual queue of passengers* of an individual phase is adjusted by lowering its value, if, and only if, the blockage condition is present on the downstream exit link of a phase. This adjusted value is termed here as an *adjusted virtual queue of passengers.*

As any phase set consists of two individual phases (as per the dual ring operation phase settings format), the final *virtual queue of passengers* of the feasible phase set is estimated by summing the *adjusted virtual queue of passengers* of the two corresponding individual phases. The phase set incurring the highest *adjusted virtual queue of passengers* (from the corresponding two individual phases) is denoted or identified by the *actuation module* as the optimum or most deserving candidate phase.

This study adopts simple mathematical forms for the base formulations of the assumed relationships among the *adjusted virtual queue of passengers (or virtual queue of passengers)* and the input parameters in terms of number of cars,

number of normal priority buses, the ratio of the occupied link, presence of incident-status, presence of high priority buses and the presence of blockage condition on the downstream exit link.

The initial *virtual queue of passengers* of cars is estimated from the number of cars on the approach link only. Then another *virtual queue of passengers* is added to account for the normal priority buses. An extra part of *virtual queue of passengers* is also added if the bus is a high priority one. This combined value forms the base *virtual queue of passengers*.

On top of this base *virtual queue of passengers*, an extra part of *virtual queue of passengers* is also added to emphasize the growing recurrent congestion on the link. The *ratio of the vehicle queue length* over the corresponding link length is assumed as the indicator of the recurrent congestion on the link, and the higher the ratio, the higher the recurrent congestion. This combined indicator is referred to herein as the base *congestion indicator of an individual phase*.

The *base congestion indicator* on the upstream of an individual phase ϕ_j denoted by $J_{i,\phi_j}^{/,t}$ refers to the *virtual queue of passengers* on the upstream approach of that individual phase ϕ_j at time t, and could be estimated from equation (3.1). This base *congestion indicator* ($J_{i,\phi_j}^{/,t}$) is estimated without any adjustment for the incident status on the upstream approach of that individual phase ϕ_j at time t. Thus, Eq. (3.1) applies only to normal recurrent conditions; that is if no incidents are detected on the upstream approach of phase ϕ_j.

$$J_{i,\phi_j}^{/,t} = \begin{bmatrix} \left(C_{i,\phi_j,u/}^{c,t} \times O_{i,\phi_j,u/}^{c} \times 1\right) + \\ \left(C_{i,\phi_j,u/}^{b,t} \times O_{i,\phi_j,u/}^{b} \times \beta_{i,\phi_j,u/}^{b}\right) + \\ \left(C_{i,\phi_j,u/}^{p,t} \times O_{i,\phi_j,u/}^{p} \times \beta_{i,\phi_j,u/}^{p}\right) + \\ \left\{\left(C_{i,\phi_j,u/}^{c,t} \times O_{i,\phi_j,u/}^{c} + C_{i,\phi_j,u/}^{b,t} \times O_{i,\phi_j,u/}^{b} + C_{i,\phi_j,u/}^{p,t} \times O_{i,\phi_j,u/}^{p}\right) \times r_{i,\phi_j,u/}^{V,t} \times \beta_{i,\phi_j,u/}^{V}\right\} \end{bmatrix} \quad (3.1)$$

Where: $C_{i,\phi_j,u/}^{c,t}$, $C_{i,\phi_j,u/}^{b,t}$, and $C_{i,\phi_j,u/}^{p,t}$ are the total counts of cars, c, normal priority buses, b, and high priority buses, p, respectively, at time t on the *upstream approach link*, $u/$, relevant to phase, ϕ_j, of intersection i. $O_{i,\phi_j,u/}^{c}$, $O_{i,\phi_j,u/}^{b}$ and $O_{i,\phi_j,u/}^{p}$ are the average passenger occupancy of the cars, c, normal priority buses, b, and high priority buses, p, respectively. The parameters $\beta_{i,\phi_j,u/}^{b}$ and $\beta_{i,\phi_j,u/}^{p}$ are coefficients for *transit priority* for normal and high priority buses, respectively, on the *upstream approach link* of phase ϕ_j at intersection i. $r_{i,\phi_j,u/}^{V,t}$ is the *ratio of the vehicle queue length* over the physical capacity of the corresponding link length $l_{i,\phi_j,u/}$. The estimate of the $r_{i,\phi_j,u/}^{V,t}$ will be explained later in section 3.3. The $\beta_{i,\phi_j,u/}^{V}$ is a coefficient for *virtual queue of vehicles* on the *upstream* approach link, $u/$, of phase ϕ_j at intersection i.

If an incident is detected $\left(i.e. I_{i,\phi_j,u/}^{N,t} = 1\right)$, the value of the *base virtual queue of passengers* $J_{i,\phi_j}^{/,t}$ is adjusted (increased) by the incident penalty coefficient $\beta_{i,\phi_j,u/}^{N}$ to account for the potential incident on the upstream approach, $u/$, as shown in Eq. (3.2):

$$J_{i,\phi_j}^{t} = \left(1 + \beta_{i,\phi_j,u/}^{N} \times I_{i,\phi_j,u/}^{N,t}\right) \times J_{i,\phi_j}^{/,t} \quad (3.2)$$

The *virtual queue of passengers* J_{i,ϕ_j}^t (in Eq. 3.2) is further adjusted (decreased) as shown in Eq. (3.3) by applying the *downstream blockage penalty* coefficient $\beta_{i,\phi_j,d/}^B$ to account for blockage on the downstream exit link of phase ϕ_j. This applies only if the *indicator* of the downstream congestion $I_{i,\phi_j,d/}^{B,t} = 1$. If the downstream congestion indicator $I_{i,\phi_j,d/}^{B,t} = 0$, the denominator value $\left[\left(1 + I_{i,\phi_j,d/}^{B,t}\right)^{\beta_{i,\phi_j,d/}^B}\right] \to 1$, and $A_{i,\phi_j}^t = J_{i,\phi_j}^t$. The value of A_{i,ϕ_j}^t is referred to as the *actuation index of the individual phase ϕ_j*.

$$A_{i,\phi_j}^t = \frac{J_{i,\phi_j}^t}{\left[\left(1+I_{i,\phi_j,d/}^{B,t}\right)^{\beta_{i,\phi_j,d/}^B}\right]} \tag{3.3}$$

The *actuation index of a candidate phase se*t $\left(Z_{i,\Phi_k}^t\right)$ is estimated as the summation of the actuation indexes of the two concurrent individual phases of the candidate phase set Φ_k, $\Phi_k = \{\phi^{k,1} \cup \phi^{k,2}\}$.

$$Z_{i,\Phi_k}^t = A_{i,\phi^{k,1}}^t + A_{i,\phi^{k,2}}^t \tag{3.4}$$

It is to be noted that the different modules of the system run with various time intervals (resolutions), and as such the time index t of the various modules might refer to a different time interval. Table 3.1 explains the adopted time index and the time intervals of the various modules.

First, each detector's data are aggregated at a small time interval Δt (say 40 seconds). The incident detection runs at a coarser time interval θ (say 80 seconds). That is, the detector data can be collected at the beginning of each interval (40 seconds). The incident status module is only called at the beginning of each 80-second interval. The bus detectors on the other hand are assumed to be

57

able to identify the buses in the same second they arrive (continuous monitoring via some on-line GPS tracking system).

Table 3.1: Example of relevant time-indices for various system modules

Simulation seconds or controller clock time t	245 seconds						
Detector data aggregation time-interval Δt (seconds)	40	40	40	40	40	40	
Detector data extraction time index t	1	2	3	4	5	6	7
Incident detection time-interval θ (seconds)	80		80		80		
Time index t of incident detection time-step	1		2		3		4
Time index t of transit priority	245						

Modules

Time index of data used by *traffic regime state* module at clock time of 245 seconds	1	2	3	4	5	6	7
Time index of data used by *downstream blockage module* at clock time of 245 seconds	1	2	3	4	5	6	7
Time index of data used by *incident status* module at clock time 245 seconds	1		2		3		4
Time index of data used by *transit priority module* at clock time of 245 seconds							245

As such, the *transit priority module* can be called at any system clock time. The t is used interchangeably in this study to refer to either the actual clock time, or the time index at which the module is called, based on the context it is used for or the module. With reference to Table 3.1, if the current clock time (simulation seconds) is say 245, the t index would refer to the data extracted from detectors at time 240 (multiples of the Δt of 40 seconds plus 1) and that will represent the 7th time interval (if the first one starting at clock time 0 is numbered 1). Similarly, the t of the incident status module would refer to the 4th interval (multiples of 80 seconds plus 1). The *transit priority module*, given the ability for continuous

monitoring of buses, if called at the clock time of 245 seconds, the t index would actually refer to the 245th time interval.

The system has several modules (that will be explained below). Among these modules are the two known as the *traffic regime state* module and the *downstream blockage*. These two modules use the stored data of the $t - 1$ time index (of the extracted detector data). As such, these two modules (at clock time of 245 seconds) will use the detector data extracted at the 6th interval. The *incident status module* also uses the data of the $t - 1$ time index, i.e. the data of the 3rd time index. Finally, the *transit priority module* uses the data of t time index (245th second).

3.3 Traffic Regime State Module

The *traffic regime state* module is responsible for activating the so-called *congested* status if any individual phase of a competing candidate phase set is exhibiting some predefined congested traffic condition on its upstream approach link. Here, the *congested* status refers to the congestion caused by the overall vehicular traffic accounting for both recurrent and incident conditions. In order to capture the *congestion* status, a modified form of the *Travel Time Index* (*TTI*), developed by Schrank and Lomax (2005) for urban congestion at Texas Transportation Institute is adopted. *TTI* is estimated by comparing travel times both in free flow conditions and in peak hours. This index has the advantage of expressing traffic congestion in terms of both time and space.

The module of traffic regime state makes the decision each detector data time interval, Δt. The decision is simply "what is the status of congestion based on

the *TTI* index, on the associated approach link of an individual phase for a candidate phase set?"

The travel time index, $TTI^t_{i,\phi_j,u/}$ is the ratio of the actual average travel time, $\bar{T}_{i,\phi_j,u/}$ to the free flow travel time, $T^0_{i,\phi_j,u/}$.

$$TTI^t_{i,\phi_j,u/} = \frac{\bar{T}_{i,\phi_j,u/}}{T^0_{i,\phi_j,u/}} \tag{3.5}$$

The actual average travel time, $\bar{T}_{i,\phi_j,u/}$ is estimated using the average speed readings from the three detectors (u, m, and d) on the upstream link, $u/$ of phase ϕ_j as shown in Eqn. (3.6):

$$\bar{T}_{i,\phi_j,u/} = \frac{0.5l_{i,\phi_j,u/}}{\bar{v}^t_{i,\phi_j,u/_{u,m}}} + \frac{0.5l_{i,\phi_j,u/}}{\bar{v}^t_{i,\phi_j,u/_{m,d}}} \tag{3.6}$$

$$T^0_{i,\phi_j,u/} = \frac{l_{i,\phi_j,u/}}{v^0_{i,\phi_j,u/}} \tag{3.7}$$

The status of congestion index, $I^{R,t}_{i,\phi_j,u/}$ is a binary variable of a value of 1, if the upstream link associated with phase ϕ_j is flagged congested at time t, and $I^{R,t}_{i,\phi_j,u/} = 0$, otherwise.

If $TTI^t_{i,\phi_j,u/,u} \geq 5$ then, $I^{R,t}_{i,\phi_j,u/} = 1$, otherwise $I^{R,t}_{i,\phi_j,u/} = 0$; \hfill (3.8)

The traffic regime state also estimates the value of $r^{V,t}_{i,\phi_j,u/}$ which represents the ratio of the vehicle queue length, $V^t_{i,\phi_j,u/}$ to the physical capacity (in number of vehicles) of the corresponding upstream link, $V^{max}_{i,\phi_j,u/_L}$. This *congested* status of phase ϕ_j of the phase set Φ_k determines the value of $r^{V,t}_{i,\phi_j,u/}$ at each detector data time interval, Δt.

$$r_{i,\phi_j,u/}^{V,t} = \frac{V_{i,\phi_j,u_L^/}^{t}}{V_{i,\phi_j,u_L^/}^{max}} \tag{3.9}$$

The value of $r_{i,\phi_j,u/}^{V,t}$ is regarded as indicator for the growing recurrent congestions on the link because of vehicular queues. The increase of $r_{i,\phi_j,u/}^{V,t}$, or the ratio of the vehicle queue length to the corresponding link capacity, is an indication of increased virtual queues of the passengers on the approach link.

The algorithm of this *traffic regime state* module and the estimation of $I_{i,\phi_j,u/}^{R,t}$ and $r_{i,\phi_j,u/}^{V,t}$ are briefly explained with pseudo-code in Appendix A1.1. Also, the algorithm for estimating $V_{i,\phi_j,u_L^/}^{t}$ is explained in Appendix A1.2.

3.4 Transit Priority Module

The *transit priority module* determines if the coming bus on a particular link should be given priority or not for an associated individual phase. This module is supported by the appropriate technology for detection and counts of transit buses on the approach link for an individual phase, with the help of in-vehicle GPS tracking systems. This check for the *transit priority module* can be conducted at any time *t* when called by the *actuation module*. The following conditions are used to determine if the approaching bus deserves *high* or *normal* or *no* priority at all:

(1) No priority if the bus is bound to stop at some intermediate bus stop along the approach link. i.e. the bus is yet to stop

(2) If the bus has already stopped (or there is no bus stop along the approach link), we check the expected time of the bus reaching the stop-line at the

downstream end of the link. If the bus is expected to reach the stop-line within some interval, $\Delta\, g_{i,\Phi_k}$, the bus is treated as a *high* priority bus. If the bus is to reach the stop-line beyond the $\Delta\, g_{i,\Phi_k}$, the bus is treated as a *normal* priority one. $\Delta\, g_{i,\Phi_k}$ represents a pre-specified time extension period for the fully actuated signal that works with a green-extension mode. For fixed pre-timed type signals, without green time extensions, each bus, that has no pending stoppage condition along the approach link, is treated as a *normal* priority bus for the respective individual phase. It is important to note here that bus scanning applies to all approach links of all the currently running green phases. It also applies to approach links of phases running red but among the candidate phases that can be turned to green either in the next $\Delta\, g_{i,\Phi_k}$ (for the actuated type signals) or in the next g_{i,Φ_k} (for the pre-timed type signals).

The module estimates the expected travel time needed by the bus to reach the downstream stop-line, $T^b_{i,\phi_j,u/}$, by estimating the remaining distance of the bus to reach the stop-line, $l^b_{i,\phi_j u/}$ and dividing by the average approach speed in case of the actuated type signals. The speed is estimated from data extracted from the medium and downstream detectors, $\bar{v}^t_{i,\phi_j,u/_{m,d}}$, if the bus is currently located at the first half of the link; i.e. $l^b_{i,\phi_j u/} <= 0.5 * l_{i,\phi_j,u/}$. This is represented by Eqn (3.10).

If $l^b_{i,\phi_j u/} <= 0.5 * l_{i,\phi_j,u/}$ then $T^b_{i,\phi_j,u/} = \dfrac{l^b_{i,\phi_j u/}}{\bar{v}^t_{i,\phi_j,u/_{m,d}}}$

(3.10)

Alternatively, the speed is estimated from data extracted from the upstream and medium detectors, $\bar{v}^t_{i,\phi_j,u/_{u,m}}$, as well as the data extracted from the medium and

downstream detectors, $\bar{v}^t_{i,\phi_j,u'_{u,m}}$ if the bus is currently located at the second half of the link; i.e. $l^b_{i,\phi_j u'} > 0.5 * l_{i,\phi_j,u'}$. This is represented by Eqn (3.11).

If $l^b_{i,\phi_j u'} > 0.5 * l_{i,\phi_j,u'}$ then $\quad T^b_{i,\phi_j,u'} = \dfrac{(l^b_{i,\phi_j u'} - 0.5\, l_{i,\phi_j,u'})}{\bar{v}^t_{i,\phi_j,u'_{u,m}}} + \dfrac{0.5\, l_{i,\phi_j,u'}}{\bar{v}^t_{i,\phi_j,u'_{m,d}}}$ $\qquad$ (3.11)

As explained above, the module assigns the priority of the vehicle based on the remaining travel time to reach the stop-line, $T^b_{i,\phi_j,u'}$ and whether it can reach the stop-line within the pre-specified time interval, $\Delta g_{i,\Phi_k}$. The bus is treated as a high priority bus, $P^b_{i,\phi_j,u'} = 1$, and an indicator of high priority is set for the approach, $I^{P,t}_{i,\phi_j,u'} = 1$, if the bus can reach the stop-line within the interval of $\Delta g_{i,\Phi_k}$.

If $T^b_{i,\phi_j,u'} <= \Delta g_{i,\Phi_k}$ then $P^b_{i,\phi_j,u'} = 1$ and $I^{P,t}_{i,\phi_j,u'} = 1$ $\qquad$ (3.12)

The bus is treated as a normal priority bus if it cannot reach the stop line within the $\Delta g_{i,\Phi_k}$ interval.

If $T^b_{i,\phi_j,u'} > \Delta g_{i,\Phi_k}$ then $P^b_{i,\phi_j,u'} = 0$ $\qquad$ (3.13)

The module also updates the count of high priority, $C^{p,t}_{i,\phi_j,u'}$, and normal priority, $C^{b,t}_{i,\phi_j,u'}$, buses on the approach link, which are then used in estimating the link virtual queue. More details with pseudo-code for this module are included in Appendix A1.3. Also, the algorithm for car count estimation , $C^{c,t}_{i,\phi_j,u'}$ is also updated along with this module and is given with a pseudo-code in Appendix A1.4.

3.5 Downstream Blockage Module

This module declares if any downstream blockage condition exists (physical constraint on the downstream exit link(s) for an individual phase, ϕ_j). This module checks the *balance* between the *number of vehicles to be served* for the time $\Delta g_{i,\Phi_k}$ from the upstream approach link, and the *available physical spaces* on the downstream exit link. The presence of downstream blockage condition is indicated if the estimated number of vehicles to be served (from the demand side of the upstream approach link) surpasses (exceeds) the number of vehicles that could be accommodated physically (with the supply side), at the time t. It is to be noted that the available number of vehicles that could be accommodated on a downstream exit link is estimated assuming the traffic jam condition as the worst case scenario.

The demand on the approach link of any individual phase ϕ_j refers to the number of vehicles that has to be served within a specific time interval, while the controller is making the decision either for extension of the current green phase(s) or for switching to another phase(s).

For the typical fully actuated signals (with split or protected or dual ring phase settings), the anticipated demand, $d^t_{i,\phi_j,u\prime}$, of the individual phase ϕ_j, is estimated for the time interval of the interval $\Delta g_{i,\Phi_k}$ (i.e. pre-selected green extension time). On the other hand, for pre-timed signals (with split or protected phase settings), the demand of the individual phase ϕ_j is estimated for the whole time interval of the pre-selected green time g_{Φ_k} ($g_{\Phi_k} = g^{\min}_{i,\Phi_k} = g^{\max}_{i,\Phi_k}$).

In general, the demand $d^t_{i,\phi_j,u\prime}$ should be the number of vehicles in the queue, $V^t_{i,\phi_j,u\prime}$, for the individual phase ϕ_j. $V^t_{i,\phi_j,u\prime}$ are denoted further by either

V^t_{i,ϕ_j,u'_o} for odd phase or V^t_{i,ϕ_j,u'_e} for even phase. References to Figure 3.2, all

through phases are numbered even and all left phases are numbered odd. Here,

V^t_{i,ϕ_j,u'_o} accounts for the estimated number of vehicles currently on the designated

left-storage lanes only. V^t_{i,ϕ_j,u'_e} refers to the remaining number of vehicles

currently present on the through lanes and right-turning lanes along the whole link

length, out of total link vehicles, V^t_{i,ϕ_j,u'_L}.

$$V^t_{i,\phi_j,u'_e} = V^t_{i,\phi_j,u'_L} - V^t_{i,\phi_j,u'_o} \tag{3.13}$$

$$V^t_{i,\phi_j,u'} = V^t_{i,\phi_j,u'_e} \ \forall \ \phi_j \text{ is even} \tag{3.14}$$

$$V^t_{i,\phi_j,u'} = V^t_{i,\phi_j,u'_o} \ \forall \ \phi_j \text{ is odd} \tag{3.15}$$

There should be a limit on the maximum number of vehicles that can

practically be served green for the time interval of $\Delta g_{i,\Phi_k}$ (for actuated type

signals) or g_{Φ_k} (for pre-timed type signals) for any individual phase (either green

or red flagged), ϕ_j. The maximum number of vehicles that could be served

practically, during the same interval(s) for any individual phase (either green or

red flagged), ϕ_j, is $V^s_{i,\phi_j,u'}$ which based on the adopted saturation flow rate of the

respective phase.

$$V^s_{i,\phi_j,u'} = \left[\left(q_{i,\phi_j,e} \times n_{i,\phi_j,e,u'} \times \Delta g_{i,\Phi_k}\right)/3600\right] \ \forall \ \phi_j \text{ is even} \tag{3.16}$$

$$V^s_{i,\phi_j,u'} = \left[\left(q_{i,\phi_j,o} \times n_{i,\phi_j,o,u'} \times \Delta g_{i,\Phi_k}\right)/3600\right] \ \forall \ \phi_j \text{ is odd} \tag{3.17}$$

$q_{i,\phi_j,e}$ and $q_{i,\phi_j,o}$ represent the maximum practical discharge rate (in vehicles per

hour per lane) of through , $n_{i,\phi_j,e,u'}$, and left lanes, $n_{i,\phi_j,o,u'}$, respectively.

As such, the demand $d^t_{i,\phi_j,u/}$ of an individual phase is set as the minimal value of the $V^t_{i,\phi_j,u/}$ and $V^s_{i,\phi_j,u/}$ of the respective individual phase, ϕ_j.

$$d^t_{i,\phi_j,u/} = \min \{V^t_{i,\phi_j,u/}, V^s_{i,\phi_j,u/}\} \tag{3.18}$$

On the supply side, $V^{max}_{i,\phi_j,d/}$ refers to the maximum number of vehicles (in terms of vehicular length under traffic jam condition) that could be physically accommodated on the downstream exit link of the individual phase, ϕ_j. The available physical spaces (in terms of number of vehicles) on that downstream exit link can be derived as the remaining vehicular spaces (in number of vehicles) beyond the vehicles on the exit link ($V^t_{i,\phi_j,d/}$).

Thus, the number of vehicular spaces (in number of vehicles) to be accommodated as supply are denoted by $S^t_{i,\phi_j d/}$, and estimated using Eqn. (3.19).

$$S^t_{i,\phi_j d/} = V^{max}_{i,\phi_j,d/} - V^t_{i,\phi_j,d/} \tag{3.19}$$

The downstream blockage condition status is indicated with the blockage indicator, $I^{B,t}_{i,\phi_j,d/}$ as shown in Eqn. (3.20)

If $d^t_{i,\phi_j,u/} > S^t_{i,\phi_j d/}$, then $I^{B,t}_{i,\phi_j,d/} = 1$, otherwise, $I^{B,t}_{i,\phi_j,d/} = 0$. $\qquad$ (3.20)

The algorithm of this *downstream blockage module*, and the estimates of the values of $d^t_{i,\phi_j d/}$, $S^t_{i,\phi_j d/}$ and $I^{B,t}_{i,\phi_j,d/}$ is briefly explained with pseudo-code in Appendix A1.5. Also, the algorithm for estimating $V^t_{i,\phi_j,d/}$ is explained in Appendix A1.6.

3.6   Incident Status Module

An incident status would be indicated if any of the competing candidate phase sets (a set includes two individual phases running concurrently) is subjected to the likelihood of any incident condition predicted by an urban incident detection model. It is expected that the incident would block some of the roadway spaces physically, resulting in some additional delays (or vehicular queues and passenger queues) on the incident impacted approach links. However, for situations of relatively small vehicular flow on the approach link, the impact of the incident might be insignificant as vehicles might get the easy chance to bypass the incident spots on a specific lane through other lanes. Except this relatively small vehicular flow (say, 100 veh/hr) any incident is most likely to add more *virtual queue of passengers* for the incident impacted approach links. Therefore, the incident module accounts for incident cases by adding more congestion in terms of *extra virtual queue of passengers* for some specific individual phase of a candidate phase set at the subject intersection.

The *incident status* module uses the developed urban incident detection algorithm (a Binary Logistics Model) for an estimation of incident status for the associated candidate phase set. This module uses raw detector data of traffic volume and speed to estimate the independent variables for the *Binary Logit Model*. The development of the incident detection models is described in details in Chapter 3. Three different types of incident detection models are calibrated and validated using a simulation-based approach. Among these models, the so-called Binary Logit Model was found best, and as such was nominated as the basis of the *incident status* module. The *incident status* module predicts the likelihood of the

presence of incident condition on the downstream exit link(s) for any individual phase.

If an incident is detected, a binary incident indicator is set to one $\left(I^{N,t}_{i,\phi_j,u/} = 1 \right)$, the value of the *base virtual queue of passengers* $J^{/,t}_{i,\phi_j}$ is adjusted (increased) by the incident penalty coefficient $\beta^{N}_{i,\phi_j,u/}$ to account for the potential incident on the upstream approach, $u/$, as shown in Eq. (3.2):

The algorithm of this *incident status* module and how it estimates $I^{N,t}_{i,\phi_j,u/}$ is briefly explained with pseudo-code in Appendix A1.7.

3.7 Actuation Module

The *actuation module* of the proposed signal control decides on the optimum phase set to extend (or start) green.

As previously discussed in Eqn. (3.4), the *actuation index of a candidate phase se*t $\left(Z^{t}_{i,\Phi_k} \right)$ is estimated as the summation of the actuation indexes of the two concurrent individual phases of the candidate phase set Φ_k, $\Phi_k = \{\phi^{k,1} \cup \phi^{k,2}\}$.

The actuation model determines the phase set,Φ_k, with the maximum value of Z^{t}_{i,Φ_k}. This phase set is denoted by the most deserving candidate phase set. One of the following actions by the signal controller are then implemented:

- The currently running phase set should be extended green for $\Delta g_{i,\Phi_k}$ time period and flag other competing candidate phase sets as red.
- The currently running phase set should be truncated instantly with a red flag, and a green flag is given to the most deserving competing candidate

phase set (from other candidate phase sets), provided that the current phase set is not truncated before its allocated minimum green time expires.

In order to determine the optimum phase set Φ_o at any time t, the *actuation module* is formulated as an optimization (maximization) problem. At any time, t, for intersection i, while the current green phase set is Φ_c, the aim of this maximization problem is to search for the most deserving candidate phase set, Φ_k out of Ψ_c (where Ψ_c is the set of all feasible candidate phase sets while the current phase set is Φ_c).

Herein, the module seeks the two candidate sets of the highest Z_{i,Φ_k}^t values. The optimum phase set, Φ_o, will be set equal to either the set, Φ_{k*1}, of highest Z_{i,Φ_k}^t, or set Φ_{k*2}, of the second highest Z_{i,Φ_k}^t value, according to the conditions explained below.

For typical actuated type signals, any candidate phase set Φ_k operates under a pre-selected minimum green time, $g_{i,\Phi_k}^{\min}$, and a pre-selected maximum green time, $g_{i,\Phi_k}^{\max}$. The pre-selected green-extension period is $\Delta g_{i,\Phi_k}$. The currently running green phase set, Φ_c, also has a green timer t_{i,Φ_c}^g, which restarts counting green seconds instantly after the phase set turns to green status. For typical pre-timed controllers, the $g_{i,\Phi_k}^{\min}$ is set equal to $g_{i,\Phi_k}^{\max}$, and $\Delta g_{i,\Phi_k} = 0$.

At time t, when the green timer of the current green phase set, Φ_c, is t_{i,Φ_c}^g, the control decisions for actuated controllers (and also for pre-timed controllers), can be summarized as follows:

- When $\left\{g_{i,\Phi_k}^{max} \geq t_{i,\Phi_c}^g \geq g_{i,\Phi_k}^{min}\right\}$ & $\left\{g_{i,\Phi_k}^{max} \geq t_{i,\Phi_c}^g + \Delta\, g_{i,\Phi_k}\right\}$, the controller continues to serve green for Φ_c for next $\Delta\, g_{i,\Phi_k}$ time-interval, if and only if $\{\Phi_o = \Phi_{k*1} = \Phi_c\}$. Obviously, this condition does not apply to pre-timed controllers.

- When $\left\{g_{i,\Phi_k}^{max} \geq t_{i,\Phi_c}^g \geq g_{i,\Phi_k}^{min}\right\}$ & $\left\{g_{i,\Phi_k}^{max} < t_{i,\Phi_c}^g + \Delta\, g_{i,\Phi_k}\right\}$, the controller stops to serve green for Φ_c, even if $\{\Phi_o = \Phi_{k*1} = \Phi_c\}$. The controller switches to serve green to the phase set Φ_{k*2} as $\Phi_o = \Phi_{k*2}$, and the controller sets $\Phi_c = \Phi_{k*2}$.

- When $\left\{g_{i,\Phi_k}^{max} \geq t_{i,\Phi_c}^g \geq g_{i,\Phi_k}^{min}\right\}$ & $\left\{g_{i,\Phi_k}^{max} \geq t_{i,\Phi_c}^g + \Delta\, g_{i,\Phi_k}\right\}$, the controller stops to serve green for Φ_c, if and only if $\Phi_{k*1} \neq \Phi_c$. The controller switches to serve green to the phase set Φ_{k*1} as $\Phi_o = \Phi_{k*1}$ and it sets $\Phi_c = \Phi_{k*1}$.

The algorithm of the *actuation module* on how it estimates Φ_o and how the controller switches to the optimum phase set Φ_o to serve green from the current Φ_c after yellow and red transition stages is briefly explained with pseudo-codes in the Appendix A1.8.

3.8 Summary

This chapter developed the formulation of the proposed signal control logic as follows:

- Similar configurations of phases from existing dual ring, split and protected phase settings were adopted as the reference identity for the phase set(s).

- The control logic identifies the candidate phase sets for a currently running phase set

- Each of the individual phases of all candidate phase sets calls the four modules: (a) *traffic regime state* module (b) *transit priority module* (c) *downstream blockage module* and (d) *incident status* module for identifying the absence or presence of the associated boundary condition(s).

- The *traffic regime* state module and *downstream blockage module* are updated using the extracted detector data after each detector data extraction time interval. Also, the vehicular count of a phase is updated at each detector data extraction time interval.

- The *incident status* module is updated after each incident detection time interval.

- The *transit signal* module is updated at every time instant of each second. Counts of normal or high priority buses of a phase are updated each simulation second.

- Car counts are updated at each check-point of the logic using the last updated vehicular counts and last updated normal and high priority bus counts.

- For actuated control logic (i.e. dual actuated, split actuated and protected actuated), the first control decision check point is the pre-selected minimum green time of a running phase set. The next check points are after each pre-selected green extension time for this phase set (if applicable), within the limit of the maximum green time of the running phase set.

- For pre-timed control logic (i.e. split pre-timed and protected pre-timed), the only control decision check point is the pre-selected green split of a running phase set.

- At each control decision check point, the *actuation module* estimates the actuation index of all the feasible phase sets based on the currently running phase set. The actuation index of a phase set comprises of the total *adjusted virtual queue of the passengers* out of all the boundary conditions for a phase.

- The *actuation module* has an optimization program that chooses the most deserving candidate phase set which maximizes the actuation index among all of the feasible phase sets.

- At each control decision check point, if the currently running phase set is the optimum phase set, then it extends green for this phase set until the next check point. If the current check point is at the maximum green time of the currently running phase set, which is also the optimum phase set, then the control logic switches to the phase set which possesses the second highest actuation index from all of the feasible phase sets.

- At each control decision check point, if the currently running phase set is not the optimum phase set, then it truncates green for the current phase set and after a transition state, starts green for the new optimum phase set.

CHAPTER 4: DEVELOPMENT OF URBAN INCIDENT DETECTION MODELS

4.1 Introduction

Incident detection of urban road traffic is an essential element for efficient road traffic management. A significant proportion of the congestion on urban roads could be avoided with smart incident detection and management models. Incident detection algorithms for freeways have been researched extensively, but the area of urban streets incident detection systems has room for improvement. The complexity of detecting incidents on urban road networks arises from frequent interruptions at the cross-roads, entry-exit to/from the arterial link, pedestrian cross-walk and traffic control signal systems within very short space and time intervals.

Typically incident detection methodologies are formulated as pattern-recognition procedures, with different data requirements, principles, and levels of complexity (Parkany, 2005). Extensive research has been conducted on freeway-based incident detection.

For urban street incident detection, recurrent congestion makes it difficult to distinguish between the traffic flow characteristics in situations of typical congestion and the characteristics in situations of obstruction of traffic flow due to non-recurrent incidents (such as accidents or sudden breakdown of a vehicle). The research in this area still requires efficient models to enhance the applicability to urban traffic control management systems.

73

The methodologies identified in the literature include the use of neural nets (Khan & Ritchie, 1998; Dia & Thomas, 2011), probabilistic classifier [Bayesian statistics or network] (Thomas, 1998; Zhang & Taylor, 2006), non-probabilistic classifier [support vector machines] (Yuan & Cheu, 2003), fuzzy-logic (Lee, et al., 1998; Hawas, 2007; Ahmed & Hawas, 2013), probe-vehicle based techniques (Liu, et al., 2007) and GLM (General Linear Model) regression (Ahmed & Hawas, 2012).

The majority of these methodologies indicated the use of microscopic simulation models for calibration and validation. The performance of the various methodologies were compared using three primary key performance indicators: detection rate, false alarm rate and mean time to detect the incident. Most of these models used relatively longer lengths of incident duration with limited number of incidents. The majority of these models (except Ahmed & Hawas, 2012; 2013) typically do not incorporate the green time splits and the signal cycle time of the downstream signalized intersection, for incident status prediction at each unique signal setting.

To overcome the limitations of the existing urban incident detection models, this study presents new incident detection models. Three different models are discussed in detail. This chapter is structured into 8 sections. Section 4.2 discusses the methodology adopted for developing the incident detection model. Section 4.3 presents the details of the simulation models of incidents. Section 4.4 includes the data extraction procedures for the proposed model's calibration and validation. Section 4.5 discusses three model forms; General Linear Model (GLM), Neuro-Fuzzy model and Binary Logit Regression. It also reports the performance of the GLM and Neuro-Fuzzy models. Section 4.6 presents the

performance and the sensitivity analyses of the developed Binary Logit Model. Section 4.7 explains how to integrate the developed Binary Logit Model with the proposed traffic control system. Finally, section 4.8 presents the conclusions of this research with potential for further research directions.

4.2   Methodology

The methodology is built on the conceptual assumption that the average detectors' readings in the case of incidents may vary significantly from the readings in the case of no incident. The average detector's readings of no incident condition can be estimated from the recurrent congestion of an approach link. The recurrent congestion of an approach link is typically associated with some average hourly traffic flow (with some variations) for a specific link operating under specific cycle time for a typical hour of the week or weekend for a particular season. Thus, this study adopts the development of the incident detection model based on some average hourly traffic flow rates.

The steps that this study followed can be summarized as (a) development of off-line incident scenarios accounting for various network configurations, link flows and signal settings by simulation, (b) carry on detailed data analyses to capture the parameters that are likely to be affected by various incident scenarios, (c) use of simulation-based data to develop an incident-status prediction model, and (d) conducting on validation tests on the models. Figure 4.1 summarizes the overall methodology of this study. It shows that a test bed, configured with a specific *traffic flow*, *link length* and *cycle time* combination, is used to generate different incident conditions with varying start times and incident durations. Also, different test beds are generated by reconfiguring with different *traffic flow, link*

length and *cycle time* combinations to generate data. The traffic measures and independent variables were derived for the purpose of model calibration and validation along with some statistical analyses.
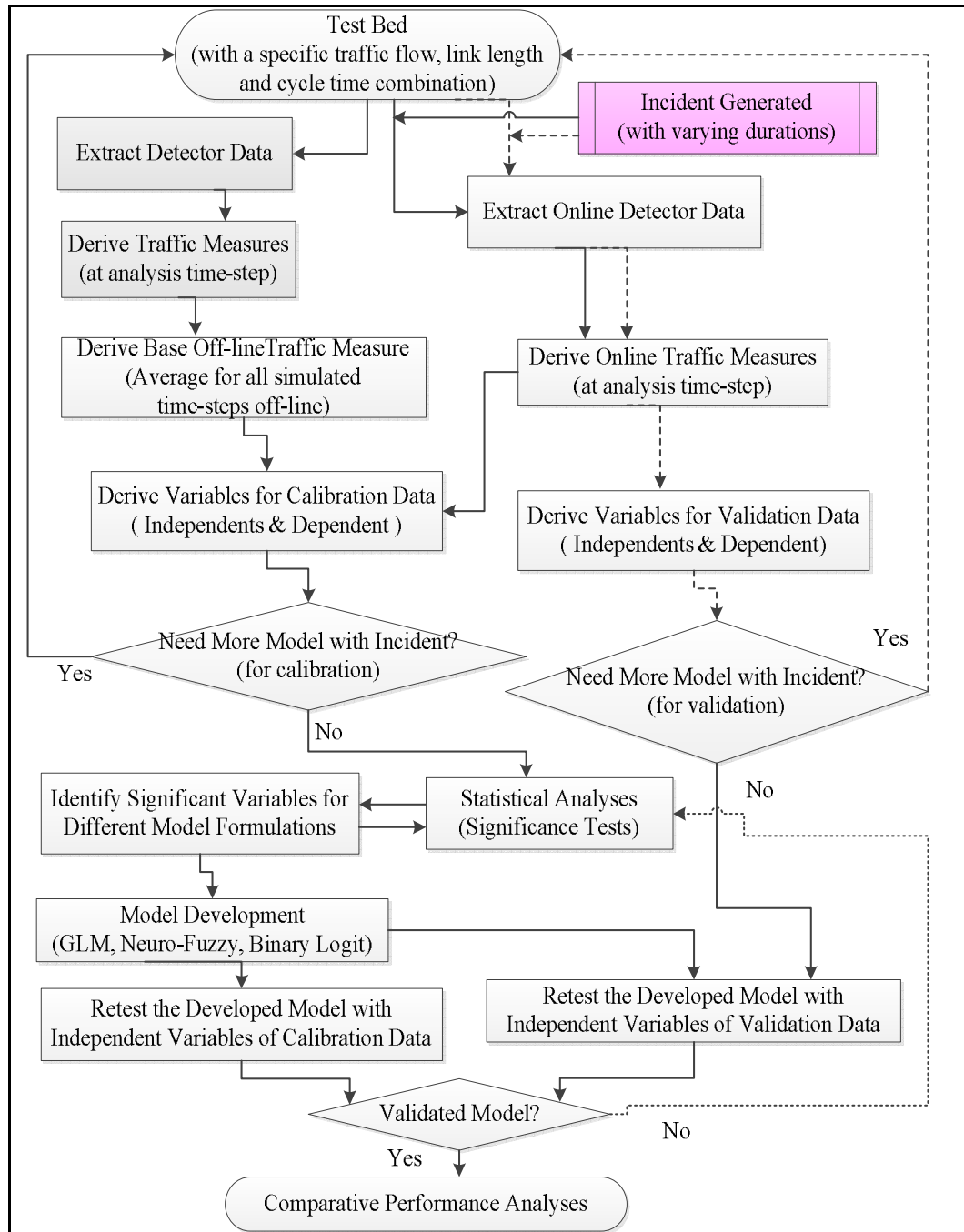
Figure 4.1: Methodology to develop some heuristics model for incident detection

4.2.1 Experimental Set Up of the Incident Modeling

A typical pre-timed urban intersection network that consists of four links of similar geometry and traffic conditions (Figure 4.2) was selected, as it represents the simplest case of a signalized urban network. Incidents were generated on one link within a specific time period. An incident is modeled here as a single lane-blocking event that persists for at least three (3) minutes on a typical three-lane urban arterial.
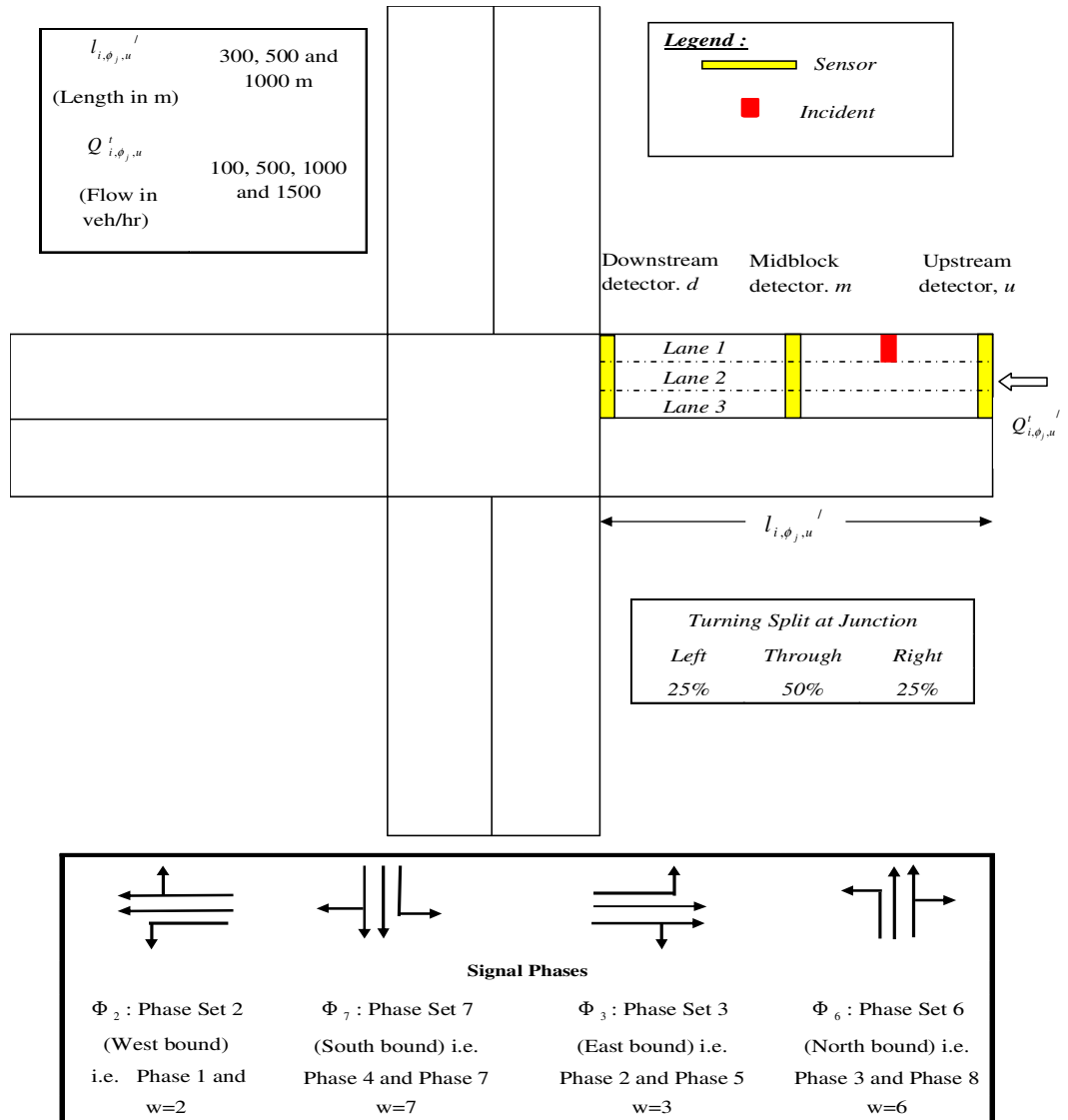
Figure 4.2: The test-bed four-leg pre-timed signalized intersection, illustrating detector positions, a sample incident location and phase arrangement with lane configurations.

4.2.2 Incident Data Development

Because of the unavailability of real-time incident data, well-validated simulation data is typically used to generate incident scenarios. Khan & Ritchie (1998) used the NETSIM micro-simulator, Thomas, et al. (2001) also used a microscopic simulator, Yuan & Cheu (2003) used the INTEGRATION mesoscopic simulator, and Zhang & Taylor (2006) used the PARAMICS micro-simulator to generate incidents. The base simulation models in those studies were calibrated using relevant field data.

This study adopted NETSIM micro simulation for its capability in simulating both short-term and long-term events on some designated lane at some specific time and for certain durations. Various types of incidents were generated at random locations on a specific lane along the west-bound approach (Figure 4.2) for different specific combinations of *cycle times, link lengths* and *traffic flows*. The differences among these incidents in terms of location, starting and clearance times are explained below.

4.2.3 Incident Data Analysis and Model Development

Each approach is assumed to be equipped with three detectors. The detector data was extracted for both incident and non-incident cases for various combinations of *cycle-time, link length* and *traffic flow.* Specific traffic measures that are likely to vary between incident and no incident cases were chosen to develop the proposed incident prediction models. Incident detection rate(s), mean time to detect and false alarm rate(s) were chosen as the measures of effectiveness (MOEs) of the calibrated models. Three different model forms were developed; a *General Linear Model* (GLM), a *Neuro-Fuzzy* model and a *Binary Logit Model*.

4.3   Incident Modeling

Incidents were generated at random locations on lanes 1, 2 and 3 along the west-bound approach of the intersection (Figure 4.2). w denotes the index of the intersection approach link, where $w=2$ for Westbound approach, $w=3$ for east-bound approach, $w=6$ for northbound approach and $w=7$ for southbound approach. t denotes the time-step. Each detector, placed perpendicularly to the direction of traffic flow, covers the three approach lanes, and is used to count passing vehicles as well as speed.

The incident is generated randomly and it lasts for multiple cycle times. It is to be noted that the incident (as a unit) consists of several incident-induced time-steps (each time step is equivalent to the cycle length of the downstream signal).

For the development of the urban incident detection model(s), different sets of incident data were generated. At the early stages of the research some incident data was generated for the GLM and Fuzzy-logic models as shown in Table 4.1. At a later stage, and to improve the generality of the proposed incident model(s), more data was generated for the Binary Logit Model as shown in Table 4.2 (a) and Table 4.2 (b).

As shown in Table 4.1, the simulation test beds were varied to reflect various signal cycle time (60, 80 and 100 seconds), approach link length (300, 500 and 1000 m) and link flows (100, 500, 1000 or 1500 veh/hr) to account for different traffic configurations. All the simulation models (whether with or without incidents) were run for around half-an-hour time intervals; 30 analysis time steps of simulation run for the 60-second cycle time models, 23 time steps

79

Table 4.1: The calibration and validation data sets of GLM and Neuro-Fuzzy Models

						Simulated		
Type	**Cycle time (sec)**	**Base models with incident-free $(l_{i,\phi_j u'}, Q^t_{i,\phi_j,u'})$ combinations**	**Types of incident durations [incident durations in cycle times]**	**Number of incident start times [cycle at which incident starts]**	**Total models with incident generated on the base $(l_{i,\phi_j u'}, Q^t_{i,\phi_j,u'})$ model**	**time-steps of each model with incident [time-steps of associated base model without incident]**	**Total simulation time-steps for the models with incidents**	**Incident-induced time-steps**
Calibration Models: (Incidents on Lane 1 Only)	60	11	1 [6]	6 [2nd,6th, 11th, 16th, 21st & 26th]	66	30 [30]	1980 (66*30)	385 (55*6+11*5)
	80	11	1 [6]	5 [2nd,6th, 11th, 16th & 21st]	55	23 [23]	1265 (55*23)	297 (44*6+11*3)
	100	11	1 [6]	6 [2nd,5th,8th, 11th, 14th & 17th]	66	18 [18]	1188 (66*18)	341 (44*6+11*5 +11*2)
Validation Models: (Some random models)	For 60 sec cycle:$(l_{i,\phi_j u'}, Q^t_{i,\phi_j,u'})$combinations of (300,530) and (300,1100) with incidents on Lane 1 and Lane 2 [2 models]							
	For 80 sec cycle:$(l_{i,\phi_j u'}, Q^t_{i,\phi_j,u'})$combinations of (300,540) and (1000,1050) with incidents on Lane 1 and Lane 2 [2 models]							
	For 100 sec cycle:$(l_{i,\phi_j u'}, Q^t_{i,\phi_j,u'})$combinations of (500,525) and (1000,1450) with incidents on Lane 1 and Lane 2 [2 models]							

GLM and Neuro-Fuzzy Models

for the 80-second cycle time models, and 18 time steps for the 100-second cycle time models, where one time step is equivalent to a cycle length. The detector placements are kept fixed: near the stop-line (downstream detector), at mid-block position (mid-detector) and at end of the link (upstream detector). The vehicle fleet composition is kept also fixed: private-cars 90% and heavy-vehicles 10%. The percentages for left, through and right turns at each approach were fixed as 25%, 50%, and 25%, respectively. The operating speed limit was fixed at 60 km/hr. The typical split phase sequencing shown in Figure 4.2 was considered.

A total of 11 basic *link length* and *link flow* $(l_{i,\phi_j u\prime}, Q^t_{i,\phi_j,u\prime})$ combinations were considered for each signal cycle. The $(l_{i,\phi_j u\prime}, Q^t_{i,\phi_j,u\prime})$ combinations, denoted by (approach link length (m), approach flow (veh/hr)), are: (300 m, 100vph), (300 m, 500vph), (300 m, 1000vph), (500 m, 100vph), (500 m, 500vph), (500 m, 1000vph), (500m, 1500vph), (1000 m, 100vph), (1000 m, 500vph), (1000 m, 1000vph) and (1000 m, 1500vph).

These 11 basic $(l_{i,\phi_j u\prime}, Q^t_{i,\phi_j,u\prime})$ models for each cycle time also serve as the basis for incident-free models. Then, incidents were generated on these base test-beds with different start-times and/or different incident durations for each incident model. The incident models were run with the same random seed number and initial warm-up period as of the corresponding base incident-free simulation models.

4.3.1 Specific Data Set for the GLM and Neuro-Fuzzy models

Initially, this study started developing incident scenarios for GLM models. Incidents were generated on lane 1 only for the calibration data set for GLM models.

As shown in Table 4.1, a total of 66 incident models were developed for the 60-second cycle time, 55 incident models for the 80-second cycle time, and 66 incident models for the 100-second cycle time. Each incident run is described by [*incident starting time step, incident duration (number of time steps)*]. The exact incident runs of the 60-second cycle time are:[2, 6], [6, 6], [11, 6], [16, 6], [21, 6] and [26, 5]. The 80-second runs are:[2, 6], [6, 6], [11, 6], [16, 6] and [21, 3]. The 100-second runs are:[2, 6], [5, 6], [8, 6], [11, 6], [14, 3] and [17, 2].Here, the incident duration is 6 time-steps in general for all calibration incident scenarios, except for the specific models whose incidents start at around 1800 seconds and the data was only extracted for around a half-an hour simulation only.

In general, the validation scenarios should reflect different settings of incident starting times, incident durations, locations and incident blocking lanes from the original runs that were used in the calibration. These different settings for the inputs also reflect the robustness of these developed models.

To validate the GLM models, another set of incident scenarios was modeled with an incident duration of 8 time steps. That is, the incident durations are 480, 640 and 800 seconds for the cycle times of 60, 80 and 100 seconds, respectively. The incidents starting and ending time steps are 9 and 16, respectively.

The incidents were not generated on lane 1 only (as in the calibration data), but also on lane 2 for around half of the scenarios to reflect a significant change in incident occurrences. The incident scenarios of lane 2 were varied in link volumes and length beyond the values used in the calibration set.

82

The calibration data set for the Neuro-Fuzzy models is exactly same as the calibration data set for the GLM models. The same validation data set was also used for the Neuro-Fuzzy models.

4.3.2 Specific Data Set for the Binary Logit Model

In order to improve the generality of the proposed model(s), more incident scenarios were added for the calibration and validation of the Binary Logit Model. Here, two different data sets were introduced as shown in Table 4.2 (a) and Table 4.2 (b).

As shown in Table 4.2 (a), the first data set was based on the incidents on lanes 1 and 2 only. The second data set, as shown in Table 4.2 (b), was based on the incidents on all the three lanes. Each set of data was further sub-divided into two sub-sets: one for the calibration and another set for the validation of the model.

For the first data set, the calibration data represent the incidents on lane 2 (middle lane) with various incident duration times. The validation data represent the incidents along lane 1 with various starting times.

For the second data set in Table 4.2 (b), the calibration data represent incidents on all the three lanes, with different incident durations and starting times. The validation data set tests the incidents on all the three lanes with varying incident starting times and durations.

For the calibration models of the 1st data set, incidents were generated on lane 2 only. Each incident run is described by [*incident starting time step, incident duration*

Table 4.2 (a):The first data set of calibration and validation data sets of the Binary Logit Model

1st Data Set								
Type	**Cycle time (sec)**	**Base models with incident-free $(l_{i,\phi_j u\prime}, Q^t_{i,\phi_j,u\prime})$ combinations**	**Types of incident durations [incident durations in cycle times]**	**Number of incident start times [cycle at which incident starts]**	**Total models with incident generated on the base $(l_{i,\phi_j u\prime}, Q^t_{i,\phi_j,u\prime})$ model**	**Simulated time-steps of each model with incident [time-steps of associated base model without incident]**	**Total simulation time-steps for the models with incidents**	**Incident-induced time-steps**
Calibration Models: (Incidents on Lane 2 Only)	60	11	4 [3, 6, 10 & 14]	2 [2nd & 4th]	88	30 [30]	2640 (88*30)	726 (3*22+6*22+ 10*22+14*22)
	80	11	4 [3, 6, 10 & 14]	2 [2nd & 4th]	88	23 [23]	2024 (88*23)	726 (3*22+6*22+ 10*22+14*22)
	100	11	4 [3, 6, 10 & 14]	2 [2nd & 4th]	88	18 [18]	1584 (88*18)	726 (3*22+6*22+ 10*22+14*22)
Validation Models: (Incidents on Lane 1 Only)	60	11	1 [6]	6 [2nd,6th, 11th, 16th, 21st & 26th]	66	30 [30]	1980 (66*30)	385 (55*6+11*5)
	80	11	1 [6]	5 [2nd,6th, 11th, 16th & 21st]	55	23 [23]	1265 (55*23)	297 (44*6+11*3)
	100	11	1 [6]	6 [2nd,5th,8th, 11th, 14th & 17th]	66	18 [18]	1188 (66*18)	341 (44*6+11*5+1 1*2)

84

Table 4.2 (b):The second set of calibration and validation data sets of the Binary Logit Model

2nd Data Set			

Calibration Models		Validation Models	
Lane 1 incident models (from the 1st data set) with the following incident start-times: 60 sec cycle: 2nd and 16th 80 sec cycle: 2nd and 16th 100 sec cycle: 2nd and 14th	Total incident models: 66 (=22+22+22)	Lane 1 incident models (from the 1st data set) with the following incident start-times: 60 sec cycle: 6th, 11th, 21st and 26th 80 sec cycle: 6th, 11th and 21st 100 sec cycle: 5th, 8th, 11th and 17th	Total incident models: 121 (=44+33+44)
Lane 2 incident models (from the 1st data set) with the incident start time at 4th cycle for the durations of 3, 6, 10 and 14 cycles for each cycle time	Total incident models: 132 (=33+33+33+33)	Lane 2 incident models (from the 1st data set) with the incident start time at 2nd cycle for the all durations of 3, 6, 10 and 14 cycles for each cycle time	Total incident models: 132 (=44+44+44)
Lane 3 incident models with the duration of 8 cycles with incident starts at 6th cycle for the 60 and 80 sec cycle-time cases and at 5th cycle for 100 sec cycle-time cases	Total incident models: 33 (=11+11+11)	Lane 3 incident models with the duration of 12 cycles with incident starts at 6th cycle for the 60 and 80 sec cycle-time cases and at 5th cycle for 100 sec cycle-time cases	Total incident models: 33 (=11+11+11)

85

(*number of time steps*)]. The exact runs are: [2,3], [2,6], [2,10], [2,14],[4,3], [4,6], [4,10] and [4,14] for each of the 60, 80 and 100 second cycle times. By accounting for every variation in link length, link flows, incident start up time and duration, a total of 88 incident models were developed for each cycle time. Here, varying incident durations of 3, 6, 8, 10, 12 and 14 cycle times were considered. Equal link length ($l_{i,\phi_j u\prime}$) and link flow ($Q^t_{i,\phi_j,u\prime}$) on all approach links (i.e. w= 2, 3, 6 and 7) were considered.

For the validation models of the 1st data set, incidents were generated on lane 1 only.

The 2nd data set was generated by some combinations of the incident models on both lanes: Lane 1 and lane 2. Also, some incidents were introduced on lane 3 to improve the generality of the proposed model. The details are briefly described in Table 4.2(b).

4.4   Data Extraction for Model Calibration and Validation

The proposed model operates with a time step resolution. That is, to detect the incident status at every cycle time. The adopted traffic measures are the *accumulated detector count* and the *average detector speed*, for all three detectors. It is to be noted that the data extraction period is equal to the green split time of one phase set. For the upstream and mid-lane detectors, the traffic measures are estimated for each cycle time, by manipulating the corresponding traffic measures over four data extraction periods. For example, the vehicle count is estimated by accumulating the vehicular counts reported during the four data extraction periods (one green phase and three red split phases) within the same cycle. The average speed is estimated as the average of the speed values reported during the four

extraction periods. For the downstream detector, only the traffic measures during the green phase(s) are used. During the red phases, it is expected that downstream detector will indicate fixed counts and zero speeds. The following notations introduce the adopted traffic measures for analysis. Equation (4.1) represents the vector of all the independent variables in developing the urban incident detection model(s). Equations (4.2) through (4.10) show the mathematical values of the independent variables. Equation (4.11) represents the vector of all corresponding co-efficient of the independent variables for the GLM or Binary Logit Model(s).

In Equation (4.1) below, X_{i,ϕ_j}^t refers the vector of independent variables measured on approach link$L_{i,\varphi_j,d/}$ of $\phi_j$at time step t and **b** (in Equation 4.11) refers to the vector of coefficients of the independent variables of the model.

$$X_{i,\phi_j}^t = \begin{bmatrix} 1 \\ X_{1,i,\phi_j}^t \\ X_{2,i,\phi_j}^t \\ X_{3,i,\phi_j}^t \\ X_{4,i,\phi_j}^t \\ X_{5,i,\phi_j}^t \\ X_{6,i,\phi_j}^t \\ X_{7,i,\phi_j}^t \\ X_{8,i,\phi_j}^t \\ X_{9,i,\phi_j}^t \end{bmatrix} \tag{4.1}$$

Where,

$$X_{1,i,\phi_j}^t = \Delta C_{i,\phi_j,u/,d}^{\theta,t} = C_{i,\phi_j,u/,d}^{\theta,t} - \overline{C}_{i,\phi_j,u/,d}^{0,t} = C_{i,\phi_j,u/,d}^{\theta,t} - \frac{\sum_{t=1}^{N} C_{i,\phi_j,u/,d}^{0,t}}{N}; \tag{4.2}$$

$$X_{2,i,\phi_j}^t = \Delta C_{i,\phi_j,u/,m}^{\theta,t} = C_{i,\phi_j,u/,m}^{\theta,t} - \overline{C}_{i,\phi_j,u/,m}^{0,t} = C_{i,\phi_j,u/,m}^{\theta,t} - \frac{\sum_{t=1}^{N} C_{i,\phi_j,u/,m}^{0,t}}{N}; \tag{4.3}$$

$$X_{3,i,\phi_j}^t = \Delta C_{i,\phi_j,u/,u}^{\theta,t} = C_{i,\phi_j,u/,u}^{\theta,t} - \overline{C}_{i,\phi_j,u/,u}^{0,t} = C_{i,\phi_j,u/,u}^{\theta,t} - \frac{\sum_{t=1}^{N} C_{i,\phi_j,u/,u}^{0,t}}{N}; \tag{4.4}$$

$$X_{4,i,\phi_j}^t = \Delta v_{i,\phi_j,u/,d}^{\theta,t} = v_{i,\phi_j,u/,d}^{\theta,t} - \bar{v}_{i,\phi_j,u/,d}^{0,t} = v_{i,\phi_j,u/,d}^{\theta,t} - \frac{\Sigma_{t=1}^{N} v_{i,\phi_j,u/,d}^{0,t}}{N}; \qquad (4.5)$$

$$X_{5,i,\phi_j}^t = \Delta v_{i,\phi_j,u/,m}^{\theta,t} = v_{i,\phi_j,u/,m}^{\theta,t} - \bar{v}_{i,\phi_j,u/,m}^{0,t} = v_{i,\phi_j,u/,m}^{\theta,t} - \frac{\Sigma_{t=1}^{N} v_{i,\phi_j,u/,m}^{0,t}}{N}; \qquad (4.6)$$

$$X_{6,i,\phi_j}^t = \Delta v_{i,\phi_j,u/,u}^{\theta,t} = v_{i,\phi_j,u/,u}^{\theta,t} - \bar{v}_{i,\phi_j,u/,u}^{0,t} = v_{i,\phi_j,u/,u}^{\theta,t} - \frac{\Sigma_{t=1}^{N} v_{i,\phi_j,u/,u}^{0,t}}{N}; \qquad (4.7)$$

$$X_{7,i,\phi_j} = l_{i,\phi_j,u/}; \qquad (4.8)$$

$$X_{8,i,\phi_j}^t = \text{Cycle time (sec)}; \qquad (4.9)$$

$$X_{9,i,\phi_j}^t = \text{Link flow (veh/hr)}, Q_{i,\phi_j,u/}^t; \qquad (4.10)$$

$$\boldsymbol{b} = [b_0 \quad b_1 \quad b_2 \quad b_3 \quad b_4 \quad b_5 \quad b_6 \quad b_7 \quad b_8 \quad b_9]; \qquad (4.11)$$

To further clarify the calculations of the independent variables, let us consider the model of the 80-second cycle time, link flow of 1000 veh/hr, and link length of 500 m. This model runs for $N=23$ time steps (half an hour = 23 cycle times). The parameters of $C_{i,\phi_j,u/,d}^{0,t}$, $C_{i,\phi_j,u/,m}^{0,t}$, $C_{i,\phi_j,u/,u}^{0,t}$, $v_{i,\phi_j,u/,d}^{0,t}$, $v_{i,\phi_j,u/,m}^{0,t}$ and $v_{i,\phi_j,u/,u}^{0,t}$ were recorded at each time step for the no incident model. The same test bed was then run introducing an incident on lane 1, starting at the 2nd cycle and ending at the 7th cycle (incident duration of 6 time steps). The incident model was also run for 23 time steps. The values $C_{i,\phi_j,u/,d}^{\theta,t}$, $C_{i,\phi_j,u/,m}^{\theta,t}$, $C_{i,\phi_j,u/,u}^{\theta,t}$, $v_{i,\phi_j,u/,d}^{\theta,t}$, $v_{i,\phi_j,u/,m}^{\theta,t}$ and $v_{i,\phi_j,u/,u}^{\theta,t}$ were also recorded at each time step for the incident model. The independent variables; X_{1,i,ϕ_j}^t, X_{2,i,ϕ_j}^t, X_{3,i,ϕ_j}^t, X_{4,i,ϕ_j}^t, X_{5,i,ϕ_j}^t and X_{6,i,ϕ_j}^t were estimated using the traffic measures of these two models. For example, the variable $X_{1,i,\phi_j}^t (= \Delta C_{i,\phi_j,u/,d}^{\theta,t})$ for a specific time step is estimated as $C_{i,\phi_j,u/,d}^{\theta,t}$ (of the incident model) subtracted by the average of $C_{i,\phi_j,u/,d}^{0,t}$ (from the incident-free models) over the $N (=23)$ time-steps.

In reality, the parameters of the incident-free scenarios can be estimated from the recorded field detector data. It is expected that the traffic flow on a specific intersection's approach is to be typically repeated (with some reasonable variations) during the same hours of a day and days of the week. That is, the hourly volume on any approach at a specific hour of the day will only vary by a value of ,say, 5 to 10% on average. It is expected that two values can be estimated for each hour/approach in reality; the average hourly traffic volume during that specific hour on a typical weekday and the average one during a typical weekend. The model will use these two values in picking up the corresponding incident-free field detector readings. Therefore, based on the prior knowledge of the average hourly volume on each approach on a typical weekday and weekend, and the associated patterns of detector readings, the model could select reasonable field detector parameters for incident-free scenarios. In real-time operation, based on the detector readings of the previous time steps (say 3 to 5 time steps), the model can identify the closest base scenario for the retrieval of the parameters.

The proposed incident detection models can also be applied practically by the using commercially available single-lane loop detectors. Single lane loop detector data could be extracted to replicate the detector covering all lanes. In the absence of real field data, the simulation-based extracted data can act as an alternative. Alternatively, an off-line detector data processing module can be deployed to update these incident-free parameters within a certain time-frame.

4.5   Development of Incident Detection Models

This section highlights the formulations of urban incident detection models. The calibrated model can be used for predicting the incident status of a single time-step. This section also includes *Statistical Significance Tests* of the

parameters of the calibrated models. In developing the incident detection model, the independent variables are the extracted traffic measures from the simulation detectors at each time step *t* as shown in Equation (4.2) through (4.7).

The measures of effectiveness of the proposed incident detection model are the:

- Online Incident Detection Rate (IDR_{on}): The percentage of time-steps that the model predicts as incident-induced time-steps out of all incident-induced time-steps. The true detection of the incident status of a time step is defined as the prediction of an incident status by the model while the associated time step was truly an incident-induced simulated time-step.

$$IDR_{on}(\%) = \frac{\text{Number of detected incident time steps}}{\text{Total generated incident time steps}} \times 100 \qquad (4.12)$$

- Offline Incident Detection Rate Offline (IDR_{off}): The percentage of all incidents detected correctly by the model to the total number of actually generated incident.

$$IDR_{off}(\%) = \frac{\text{Number of detected incidents}}{\text{Total generated incidents}} \times 100 \qquad (4.13)$$

- Mean Time to Detect Offline ($MTTD_{off}$): The average of the Time to Detect (TTD) all the detected incidents. TTD refers the difference between the time-step when the incident actually occurred and the time-step it was detected by the model.

- Online False Alarm Rate (FAR_{on}): The percentage of time-steps that the model predicts as incident-induced time-steps out of all normal incident-free time-steps. The false detection of a time step is defined as the prediction of an incident status by the model while the associated time step was truly incident-free.

$$\text{FAR}_{\text{on}}(\%) = \frac{\text{Number of normal time step declared as incident induced}}{\text{Total generated normal time steps}} \times 100$$

(4.14)

- Offline False Alarm Rate (FAR_{off}): When reporting on the performance of the algorithms, most incident algorithms and research use the off-line measure (Parkany, 2005; Brydia et al., 2005). This study also checks this so-called *FAR* percentage (offline); *the average number of false detections per time step divided by the total number of time steps that the algorithm executes over the evaluation period for which the model is applied.* This *FAR* refers to the percentage of incorrect (or false) declarations of an incident condition out of all possible declarations including true incidents, false incidents and incident-free declarations. Here, the evaluation period of each specific incident model was half-an hour simulation run.

$$\text{FAR}_{\text{off}} (\%) = \frac{\text{Average number of false alarms per time step}}{(\text{number of time steps per minute}) \times \left(60\frac{\text{minutes}}{\text{hour}}\right) \times (0.5 \text{ hour})} \times 100$$

(4.15)

Apart from these measures of effectiveness, while adopting the incident detection model for the purpose of predicting incident status or non-incident (i.e. normal) status of each time-step online, this study adopts another measure of effectiveness that is termed as the *Rate of Correct Declarations* (RCD_{on}) .

$$\text{RCD}_{\text{on}}(\%) = \frac{\text{Number of correctly detected incident status and normal status}}{\text{Total time steps}} \times 100$$

(4.16)

This measure should be important for the overall online performance of an incident model as higher incident detection rates typically come up with a higher false alarm rate if a specific threshold triggers the incident status. Therefore, while

adopting an incident detection model online, it would be better to choose a model that exhibits better performance in predicting correct status, be it incident status or non-incident (i.e. normal) status, for a wide range of input variations.

4.5.1   General Linear Regression Model (GLM)

At the early stages of research, the general linear regression model was investigated as a simple model that could be used to predict the incident status, rather than using other forms, for instance, binary discrete choice regression forms.

In developing the regression model, the independent variables as indicated above in Equations (4.2) through (4.7) are the traffic measures extracted from the simulation detectors. The dependent variable of the regression model is a variable of either an incident status (yes) or a normal recurrent traffic condition (no incident). This status is estimated at each time step. To increase the goodness of fit of the devised regression models, the typical Binary values representing the incident status (0 and 1) were avoided and instead a threshold was used. If the estimated dependent variable is higher that the threshold value an incident is indicated. A dependent variable of a value lesser than the threshold value is an indication of no incident. The threshold value is chosen to maximize the incident detection rate and minimize false alarms, and it was determined through an iterative procedure. Initially, a value of 0.5000 was set as the intuitive separating point between incident and non-incident status. Then, this value was decreased (or increased) by 0.0001 units for the next iteration as long as it improves the incident detection rate and keeps the false alarm rate within a 20% margin. A too small threshold value results in almost 100% incident detections, but with excessive

high false alarm rates. On the other hand, a relatively high threshold would result in small incident detection rates but more favorable false alarm rates.

The form of linear equation that was tested to fit the predicting equation is:

$$\text{General Liner Regression Model: } y^{\theta,t}_{i,\phi_j,u/} = \boldsymbol{b}X^t_{i,\phi_j};$$

(4.17)

Where $y^{\theta,t}_{i,\phi_j,u/}$ represent the dependent variable or incident status on the upstream approach $u/$ of phase ϕ_j at intersection i at time step t. The exact details (data sets and performance assessment) of the developed GLM models are described in Ahmed & Hawas (2012) and a sample copy is included in Appendix A2.1. In brief, equations (4.18) through (4.21) were developed for various link flow (veh/hr) levels:

Flow: 100 veh/hr (threshold: 0.3952):

$$y^{\theta,t}_{i,\phi_j,u/} = 0.3579 + 0.0107X^t_{1,i,\phi_j} + 0.1606X^t_{2,i,\phi_j} - 0.0124X^t_{3,i,\phi_j} - 0.0009X^t_{6,i,\phi_j} - 0.0144X^t_{5,i,\phi_j} + 0.0007X^t_{4,i,\phi_j} \qquad (4.18)$$

Flow: 500 veh/hr (threshold: 0.4271):

$$y^{\theta,t}_{i,\phi_j,u/} = 0.3448 + 0.015X^t_{1,i,\phi_j} - 0.0219X^t_{2,i,\phi_j} - 0.0112X^t_{3,i,\phi_j} - 0.0241X^t_{6,i,\phi_j} - 0.0186X^t_{5,i,\phi_j} + 0.006X^t_{4,i,\phi_j} \qquad (4.19)$$

Flow: 1000 veh/hr (threshold: 0.4217):

$$y^{\theta,t}_{i,\phi_j,u\prime} = 0.3227 + 0.0031X^t_{1,i,\phi_j} - 0.0189X^t_{2,i,\phi_j} - 0.0237X^t_{3,i,\phi_j} - 0.0513X^t_{6,i,\phi_j} - 0.0034X^t_{5,i,\phi_j} + 0.0163X^t_{4,i,\phi_j} \quad (4.20)$$

Flow: 1500 veh/hr (threshold: 0.4207):

$$y^{\theta,t}_{i,\phi_j,u\prime} = 0.3468 + 0.0262X^t_{1,i,\phi_j} - 0.0215X^t_{2,i,\phi_j} - 0.0038X^t_{3,i,\phi_j} - 0.0315X^t_{6,i,\phi_j} - 0.0068X^t_{5,i,\phi_j} + 0.0325X^t_{4,i,\phi_j} \quad (4.21)$$

The individual threshold value (for each link flow level) was adopted on the condition that on-line false alarm rates (FAR_{on}) should not exceed 20%. This adopted upper boundary of 20% for false alarm rates was set intuitively. Due to insufficient (initial) data for calibration and validation, the GLM models resulted in relatively poor co-efficient of determination (i.e. R^2 value as less than 0.30).Yet, these GLM equations resulted in fair performance in terms of on-line incident detection rate.   In validating the GLM models with the Lane-1 incidents scenarios (indicated in Table 4.1), the resulting average online incident detection rate (IDR_{on}) was estimated to be 51% (with standard deviation of 24%) and the average on-line false alarm rate (FAR_{on}) was estimated to be 12% (with standard deviation of 8%). The use of Lane-2 incidents validation scenarios (in Table 4.1) resulted in IDR_{on} of 42% (with standard deviation of 27%) and FAR_{on} of 17% (with standard deviation of 9%).The GLM models perform worst in cases of low link flow levels (100 veh/hr). Overall, the GLM models also resulted in a 72.34% rate of correct declarations (RCD_{on}) with the validation data set.

The primary limitation of these GLM models is the need to calibrate the different threshold levels associated with different levels of input parameters (e.g.

link flows). Furthermore, the GLM models were not tested with a wide range of input parameter variations. Considerable efforts are needed to calibrate such GLM models. Due to these limitations, this study moved on to test a different heuristic model (based on the development of Neuro-Fuzzy model) in order to achieve improved performances with same set of data.

4.5.2   Fuzzy Logic Model (FLM)

A Fuzzy Logic modeling approach (FLM) was adopted to develop incident status prediction models. The aim of using the Fuzzy Logic approach is to develop a more robust incident prediction system with lesser calibration efforts. To account for the well-known limitations of the FLM with regard to the intuitive reasoning of its parameters, this study adopted the so-called Neuro-Fuzzy approach, by coupling the initial set of FLM with a neural-net training capability.

In developing the fuzzy model, the independent variables [as indicated above by Equations (4.2) through (4.7)] are the traffic measures extracted from the simulation detectors. Some comprehensive statistical significance tests were initially conducted to identify the most significant independent variables. It was observed that Y_1(a brief notation of the deviation of upstream detector speed, X_{6,i,ϕ_j}^t), X_2(a brief notation of the deviation of midblock detector count, X_{2,i,ϕ_j}^t), Y_2(a brief notation of the deviation of midblock detector speed, X_{5,i,ϕ_j}^t) and Y_3(a brief notation of the deviation of downstream detector speed, X_{4,i,ϕ_j}^t), as shown in Table 4.3, are the most significant independent variables in predicting the incident status by the GLM (discussed in Section 4.5.1). As such, these four independent variables were considered as the input independent variables for the Fuzzy Logic models.

The dependent variable of the fuzzy model is either an incident status (yes) or a normal recurrent traffic condition (no incident) of a single time-step. The membership function of this variable was considered a "continuous" index; the higher the index, the higher the possibility of an incident. The range of the "true" incident status term is allocated the central value of 1 for an incident, and the 'false' term range is allocated the central value of 0.

The software program FuzzyTECH 5.5 (INFORM 2001) was used in developing the logic explained below. In applying the fuzzy-logic model to predict the incident status, a threshold value is utilized. Initially, the value of 0.50 was used as a separation point between incident and non-incident status. The initial threshold value was then incremented (decreased or increased) by 0.01 units for the next iteration. The incremental change to the threshold value is repeated if improvement in the incident detection rate is noticed, while keeping the false alarm rate within some acceptable limits.

The connecting lines symbolize the data flow. The four input variables and the output incident status variable with the associated linguistic terms were identified for the logic as shown in Table 4.3.The range of the input variables was identified as the minimum and maximum values reported from the calibration data sets.

The Fuzzification Process:

The linear (L-shaped) membership function (MBF) was adopted for all variables. Defining the variable includes the definition of its possible linguistic terms, range of values, and membership values, μ. The membership functions are initially equally distributed over the range of all possible values. Each variable's term is defined by that single value that corresponds to a term membership value (μ) of 1.

The devised FLM structure is shown in Figure 4.3.

Fuzzification   **Inference Engine**   **Defuzzification**
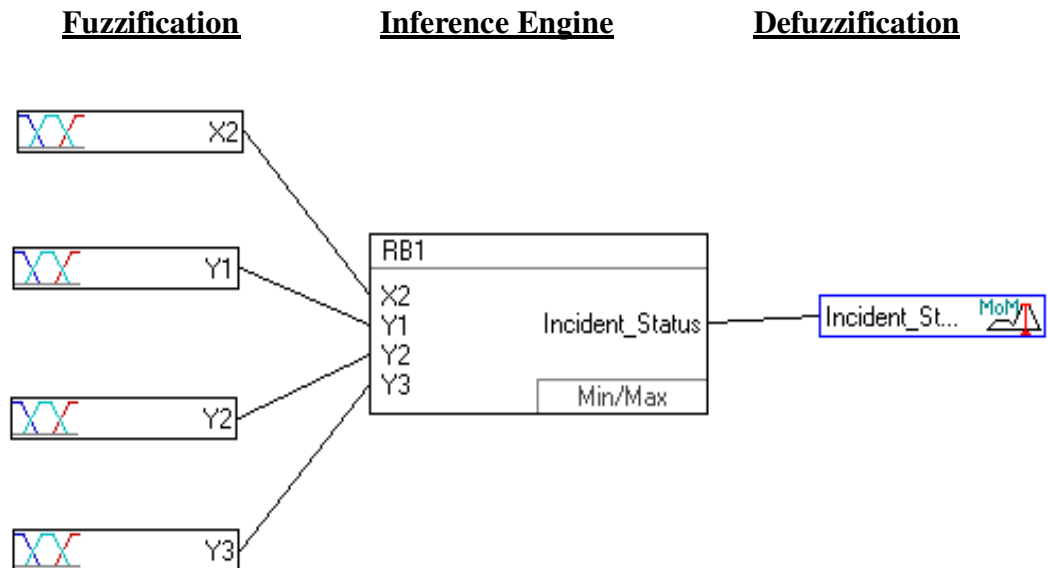
Figure 4.3: The FLM structure of the urban incident detection model.

For example, for the specific case of a 60-second cycle, 500-meter link length and the 1000 veh/hr link flow scenario, the value of Y_2 was initially set to range between -3.63 to 6.37 as shown in Figure 4.4a. The μ value (shown in the vertical axes of Figure 4.4a) represents the degree of confidence that a specific numeric value belongs to a linguistic term. For example, for the Y_2 variable, the numeric value of 1.37 has the μ value of 1.00 at the *Medium* term. This means that the Y_2 value of 1.37

Table 4.3: The FLM input and output variables, numerical ranges, and linguistic terms.

Variable category	Variable name (Denoted in FLM)	Numerical ranges		Linguistic terms
		Min	Max	
Input variables	Deviation of upstream detector speed (Y_1)	-17.96	24.11	Low, Medium, High
	Deviation of midblock detector count (X_2)	-14.56	42.28	Low, Medium, High
	Deviation of midblock detector speed (Y_2)	-31.51	21.74	Low, Medium, High
	Deviation of downstream detector speed (Y_3)	-28.75	43.53	Low, Medium, High
Output variable	Incident Status (Incident_Status)	-1	+2	False, True
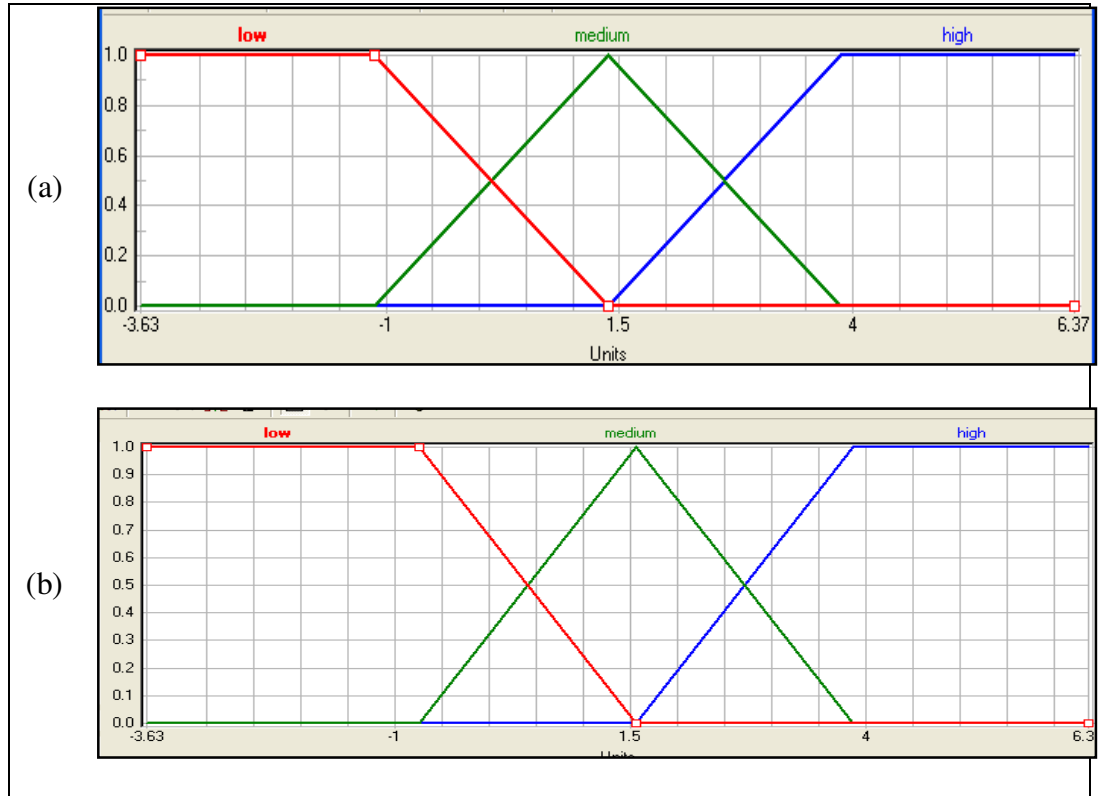
Figure 4.4: (a) The initial and (b) finally calibrated MBF of input Y_2 (60-second cycle, 500-m link length and 1000 veh/hr link flow scenario).

fully belongs to the term *Medium* with 100% confidence. A specific neural net algorithm (in FuzzyTECH) is used to optimize these confidence levels and

membership functions via data training as will be explained below. The calibrated membership function of the Y_2 variable (following the training) is shown in Figure 4.4b.

Fuzzy Inference Process:

The inference process scans and evaluates the set of the fuzzy rules. The fuzzy inference consists of three computational steps: Aggregation, Composition, and Result Aggregation [INFORM (2001)]. The fuzzy operators used for "aggregation" (namely, Minimum or Maximum) combine the preconditions of each fuzzy rule. The "composition" works generally with the PROD-Operator as fixed operator. The composition eventually combines the different rules to one conclusion. The results "aggregation" uses the MAX operator to enable maximum firing degree of all rules matching to the term.

Table 4.4 shows a sample of the IF-THEN rules included in the FLM rule block. The (IF-THEN) rules describe the logical relationship between the input variables (IF part) and the output variable (THEN part). The so-called degree of support (DoS) weighs each rule according to its importance. A "DoS" value of 0 means a non-valid rule. Initially, all the possible combinations of rules (3*3*3*3*2=162) were set initially with equal DoS of 0.5. The initial value of the DoS for each rule is adjusted through the neural net training.

Table 4.4: Sample of the "IF-THEN" rules in the FLM rule block.

IF				THEN	
Y1	X2	Y2	Y3	DoS (initial: final)	Incident_Status
low	low	low	Low	(0.50: 0.97)	false
low	low	low	Low	(0.50: 0.98)	true
low	low	high	Low	(0.50: 0.49)	false
low	low	high	Low	(0.50: 0.50)	true
low	low	high	High	(0.50: 0.45)	false
low	low	high	High	(0.50: 0.50)	true

Defuzzification Process:

The result of firing the rules (the fuzzy inference) is a fuzzy term that has to be re-transformed into a crisp numerical value. This process of transforming the fuzzy terms into a numerical value is known by the defuzzification process.
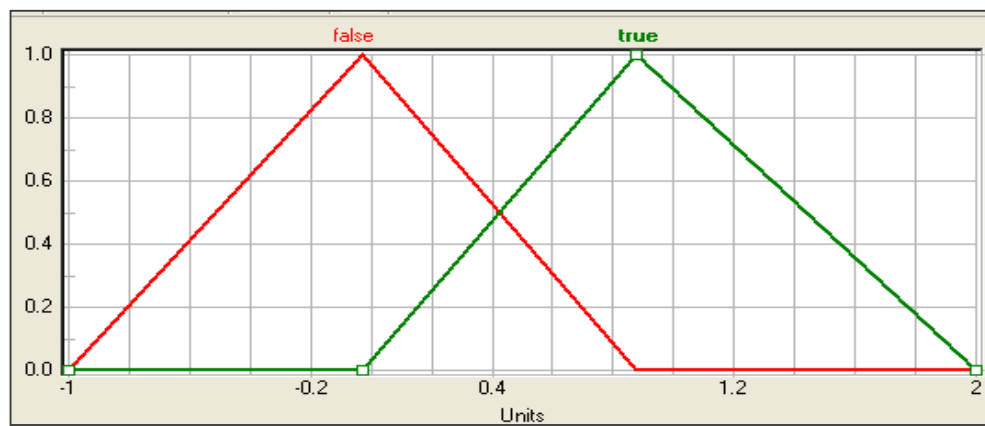
Figure 4.5: The final MBF of the *Incident_Status* output after MBF training (60-second cycle, 500-meter link length and 1000 veh/hr link flow scenario).

Among the several defuzzification methods, the adopted MoM (Mean-of-Maximum) method delivers the most plausible result that is mostly used in pattern

recognition problems. Figure 4.5 shows the final *incident_status* output variable following the training of the FLM.

Neural Net Data Training:

Neuro-Fuzzy system can be viewed as a three-layer feed forward neural network similar to the traditional fuzzy system above (Figure 4.3) with a layer of hidden neurons used to perform each process. The first layer represents the input variables of the fuzzification process, the middle hidden layer represents the fuzzy rule inference process and the third layer represents the output variable defuzzification process.

The calibration of the FLM refers to finding the optimal fuzzy membership shape and the Degree of Support (DoS) for the IF–THEN rules. In the first step, all MBFs and rules were selected for training to find the best FLM to describe the training data. Then, the parameters (step width for DoS and terms) were selected for the training. The whole Neuro-Fuzzy training was carried out for five cycles with each cycle for 1000 iterations.

The step width for the DoS values was set to 0.1 for each training cycle. The step width for the terms was set to 5% in the first training cycle, which was then increased by 5% in later cycles. The maximum and average deviations (between the model output and the training data) were observed after completion of each cycle. The cycle, for which the deviation values were less, was selected as the final FLM. After the training phase, the MBFs and the DoS values were determined as shown in Table 4.4, Figures 4.4b and 4.5.

The FLM reported measure of IDR_{on} value is 51.3%, the FAR_{on} value is 11% and RCD_{on} value is 81.86% with the calibration data set. When applied to the

validation data set, the FLM completely fails to detect any incident(s) for 9 specific combination(s) of link length, hourly volume and cycle time out of 33 base combinations for all cycle times. This makes the FLM unfavorable to be used for online detection of incident(s).The details of the developed Neuro-Fuzzy models are described in Ahmed & Hawas (2013), and a sample copy of it is included in Appendix A2.2. Based on the performance measures of the GLM and the FLM, this study was further encouraged to develop a probabilistic model, namely, a Binary Logit Model using Binary Logistics Regression.

4.5.3   Binary Logit Model (BLM)

In developing the Binary Logit Model (BLM), the independent variables summarized in Equations (4.2) through (4.10) along with the associated coefficients in Equation (4.11) were considered for calibration.

The binary logistic regression model was defined as follows:

Incident Event Probability: $p_{i,\phi_j}^t = \exp(\boldsymbol{b} X_{i,\phi_j}^t)/(1 + \exp(\boldsymbol{b} X_{i,\phi_j}^t))$ (4.22)

Where p_{i,ϕ_j}^t is the probability of an incident status on the link relevant to phase j at time step t, and $0 \le p_{i,\phi_j}^t \le 1$;

The dependent variable is either an incident status (*Yes* or binary value of *1*) or a normal recurrent traffic condition (*No* or binary value of *0*).

In applying the model to predict incident status, a threshold value is utilized. If the predicted p_{i,ϕ_j}^t is higher than the threshold value (for instance, 0.500) an incident status is indicated.   The threshold value was chosen to maximize the incident detection rate and minimize the false alarm rate by using a Brute-Force search. If this threshold is too small (for example, 0.100), almost every time step would be predicted as incident-induced. On the other end, if this

threshold is set at higher values (for example, 0.700) there would be no incident detected and no false alarms. Initially, a value of 0.500 was intuitively set as the threshold value. This value was then decreased (or increased) iteratively by 0.001 to increase the detection rate and decrease the false alarm rate. A threshold value of 0.400 was found to be the best for the incident models.

The Binary Logistic Regression models (with all 9 independent variables) were developed using both data sets, as described above in Table 4.2. In applying Binary Logistic Regression, the following hypotheses were tested:

Null Hypothesis H_0:

All coefficients in the regression equation (4.22) take the zero value.

Alternative Hypothesis H_1:

The model with predictors in equation (4.22) is accurate and differs significantly from the null of zero.

If alternative hypothesis (H_1) is true, then it indicates that the predictors (i.e., independent variables) are likely to have a significant influence on the probability of an event.

The significance of this Logit model was tested with the 'Log-Likelihood' test. When the probability (p-value) of the 'Log-Likelihood' test fails to reach the 5% significance level, the null hypothesis is retained which means that the predictor has no effect (i.e. makes no difference) in predicting the dependent variable.

This model was further tested using Pearson's Chi-squared test (ξ^2). The measures how well the observed distribution of data fits with the distribution that is expected if the variables are independent, it only tests the probability of the independence of a distribution of the data. Higher ξ^2 values and lower p-values

indicate that the model may not fit the data well. Similarly, goodness of fit tests are conducted using the 'Deviance' and ' Hosmer-Lemeshow' methods. When applied with a specific threshold value, this statistically significant logit model serves the purpose of predicting the 'incident' and 'no-incident' status which is to be integrated with the control system logic. The binary logistic regression analysis of the calibration data for the 1st data set in Minitab can be summarized as follows :

Binary Logistic Regression: 1st Data Set (Calibration Data Only)

```
Link Function: Logit

Response Information

Variable  Value  Count
Incident  1       2178   (Event)
          0       4070
          Total   6248

Logistic Regession Table:
```

Predictor	Coef.	SE Coef.	Z	P	Odds Ratio	95% CI Lower	95% CI Upper
Constant	-2.10074	0.153711	-13.67	0.000			
X3	0.558845	0.0514150	10.87	0.000	1.75	1.58	1.93
X2	-0.132018	0.0212634	-6.21	0.000	0.88	0.84	0.91
X1	-0.0556647	0.0186396	-2.99	0.003	0.95	0.91	0.98
X6	-0.0864939	0.0070379	-12.29	0.000	0.92	0.90	0.93
X5	-0.0040127	0.0053859	-0.75	0.456	1.00	0.99	1.01
X7	-0.0000245	0.0000953	-0.26	0.797	1.00	1.00	1.00
X9	-0.0000325	0.0000564	-0.58	0.565	1.00	1.00	1.00
X8	0.0187694	0.0017188	10.92	0.000	1.02	1.02	1.02
X4	0.0016468	0.0070377	0.23	0.815	1.00	0.99	1.02

```
Log-Likelihood = -3828.842
Test that all slopes are zero: G = 421.860, DF = 9, P-Value = 0.000

Goodness-of-Fit Tests:
```

Method	Chi-Square	DF	P
Pearson	5207.60	2720	0.000
Deviance	6372.58	2720	0.000
Hosmer-Lemeshow	21.94	8	0.005

Here, the P-value of the Log-Likelihood method tells us that we should reject the null hypothesis H_0, and that the alternative hypothesis H_1 is true. That is, the overall Binary Logit Model is significant. The parameters X^t_{4,i,ϕ_j}, X^t_{5,i,ϕ_j},

X_{7,i,ϕ_j}^t and X_{9,i,ϕ_j}^t were found to be non-significant with *p-values* higher than 0.500.

The goodness of fit tests show that the model may not fit all the independent data well. However, the model can be applied in conjunction with an adopted threshold value. Therefore an acceptable goodness of fit can be judged from the outcomes of the measures of effectiveness adopted. Table 4.5 summarizes the further refined BLM developed from both data sets with associated model parameters.

Table 4.5: The developed Binary Logit Model(s) for incident detection

Items		Binary Logit Model(s)	
		1st data set	2nd data set
Model Log-likelihood value		-3829.420	-3195.776
Model p-value		0.000	0.000
Significant variables		Coefficient of the variable (p-value)	
Constant		$b_0=$-2.13270 (0.000)	$b_0=$-2.22621 (0.000)
$X_{3,i,\phi_j}^t = \Delta C_{i,\phi_j,u',u}^{\theta,t}$		$b_3=$0.55277 (0.000)	$b_3=$0.60253 (0.000)
$X_{6,i,\phi_j}^t = \Delta v_{i,\phi_j,u',u}^{\theta,t}$		$b_6=$-0.08774 (0.000)	$b_6=$-0.07827 (0.000)
$X_{2,i,\phi_j}^t = \Delta C_{i,\phi_j,u',m}^{\theta,t}$		$b_2=$-0.13264 (0.000)	$b_2=$-0.22002 (0.000)
$X_{5,i,\phi_j}^t = \Delta v_{i,\phi_j,u',m}^{\theta,t}$		$b_5=$0.00000 (0.000)	$b_5=$-0.01862 (0.001)
$X_{1,i,\phi_j}^t = \Delta C_{i,\phi_j,u',d}^{\theta,t}$		$b_1=$0.05408 (0.002)	$b_1=$-0.04893 (0.018)
$X_{8,i,\phi_j}^t =$ Cycle time (sec)		$b_8=$0.01871 (0.000)	$b_8=$0.01750 (0.000)
Goodness of Fit Tests (with p-values)	*Pearson*	0.000	0.000
	Deviance	0.000	0.000
	Hosmer-Lemeshow	0.000	0.019
Threshold value		0.400	0.400
Performances against calibration data set	[IDR$_{on}$ (%);IDR$_{off}$ (%)]	[-; 79.50]	[36 ; 75.76]
	[RCD$_{on}$ (%) ; MTTD$_{off}$ (Cycle)]	[-; 2.21]	[69.8 ; 2.42]
	[FAR$_{on}$(%) ; FAR$_{off}$(%)]	[-; 0.68]	[15 ; 0.52]
Performances against validation data set	[IDR$_{on}$ (%) ;IDR$_{off}$ (%)]	[-; 82.35]	[32 ; 74.13]
	[RCD$_{on}$ (%) ; MTTD$_{off}$ (Cycle)]	[-; 1.79]	[68.52 ; 2.42]
	[FAR$_{on}$(%) ; FAR$_{off}$(%)]	[-; 0.83]	[15 ; 0.46]

4.6   Binary Logit Model performance

4.6.1 Model Performance

The refined Binary Logit Model(s) performs satisfactorily (as shown in Table 4.5) against both calibration and validation data sets. For the calibration data of the 2nd data set, an IDR_{on} of 36%., a FAR_{on} of 15% and an RCD_{on} of 69.18% were reported, On the other hand, the validation data of the 2nd data set resulted in an IDR_{on} of 32%, a FAR_{on} of 15%, and an RCD_{on} of 68.52%.This indicates a stable performance by the BLM, bearing in mind that BLM uses only one specific threshold for every combination of input variables.

The Logit model for the 1st data set performs relatively better in detecting incidents (higher IDR_{off}%). The Logit model for the 2nd data set performs relatively better with regard to false alarms (lesser FAR_{off}). The slight differences in performance could be attributed to the fact that the 2nd data set model comprises a mix of traffic dynamics for all three lanes with different lane configurations. On the other hand, incidents in lane 1 and lane 2 (using the 1st data set) might have similar traffic dynamics as these two lanes comprise mainly through and right traffic. It could be that the 2nd data set based Logit model might have improved the representation of traffic dynamics by taking into account the turning movements (i.e. left, through and right) of the vehicular flows.

4.6.2 Comparative Performance of the Binary Logit Model

The proposed Binary Logit Model can be compared against other benchmark algorithms (models). As indicated in Zhang and Taylor (2006), it may be inappropriate to compare two models even using the same data set. The reason could be that models were calibrated using different urban road network configurations and different detector placements. Nonetheless, Table 4.6 (a) (sourced from Zhang and Taylor, 2006) shows the relative performance of the model against some of state-of-the-art urban incident detection algorithms.

It should be noted that other algorithms have been tested against relatively smaller numbers of incident sample sizes than that of the current model. Moreover, other algorithms were tested against incidents of relatively longer durations. Unlike in this study where the proposed model was tested with incidents of shorter durations such as 3 minutes and 6 minutes. For example, TSC_ar (in Zhang & Taylor, 2006) was tested against incident durations ranging from 10 minutes to 35 minutes and all the incidents started 20 min after the beginning of each simulation run for congested road networks. Yuan & Cheu (2003) generated incidents of 2 to 5 cycles time durations, where the cycle time was 140 sec and the traffic volume varied from 500 to 1200 vehicles per hour per lane. In Thomas (1998), incidents occupy the first 3 intervals of the simulation run, where each interval is 7 minutes long. Although, Khan & Ritchie (1998) simulated incidents with durations between 2 to 16 minutes, the cycle time was 126 seconds for flow levels of 700 to 1100 veh/hr. Therefore, the distinctive features of the presented model is that it is capable of predicting incidents of relatively short durations with wide variations in traffic flow.

108

Table 4.6 (a): Performances of the Binary Logit Model (BLM)

(a) Comparative performances of the model against other algorithms							
					Algorithm performance (Offline)		
Algorithm	**Source**	**Data set**	**Sample size of the generated incidents**	**Step-size of analysis time-step**	**IDR (%)**	**FAR (%)**	**MTTD [Cycles] (Sec)**
Binary Logit	This study	(1st data set)	451	Cycle Time	80.7	0.75	[1.765] (130)
		(2nd data set)	517		74.8	0.47	[2.42] (190)
TSC_ar	Zhang & Taylor (2006)	Cross Road	40	Cycle Time	88	0.62	(178)
MLF	Yuan & Cheu (2003)	Ave West-Clementi	324	Cycle Time	60.2	0.24	(156)
PNN					77.2	0.89	(155)
SVM_P					88.9	0.22	(149)
MLF (modular)	Thomas et al. (2001)	Coronation	13	20 sec cycle	85	0.64	(114)
MLF (basic)	Khan & Ritchie (1998)	Dr. Anaheim	108	Cycle Time	76	1.16	[1.63]

Table 4.6 (b): Sensitivity analyses of the Binary Logit Model (BLM)

(b) Sensitivity analyses of the model with the potential contributing factors									
Cycle time-wise performance					Link length-wise performance				
Cycle (sec)	Models	Detected	IDR_{off} (%)	$MTTD_{off}$ (Cycle)	Link-length (m)	Models	Detected	IDR_{off} (%)	$MTTD_{off}$ (Cycle)
60	176	70	39.8	3.91	300	141	108	76.6	2.23
80	165	146	88.5	2.60	500	188	140	74.5	2.63
100	176	171	97.2	1.66	1000	188	139	73.9	2.36
Link flow-wise performance					Lane-wise performance				
Flow (Veh/h)	Models	Detected	IDR_{off} (%)	$MTTD_{off}$ (Cycle)	Lane ID	Models	Detected	IDR_{off} (%)	$MTTD_{off}$ (Cycle)
100	141	85	60.3	3.04	1	187	135	72.2	1.97
500	141	111	78.7	2.30	2	264	196	74.2	2.67
1000	141	113	80.1	2.15	3	66	56	84.8	2.54
1500	94	78	83	2.32					
Incident duration-wise performance					Incident placement-wise performance				
Duration (Cycle)	Models	Detected	IDR_{off} (%)	$MTTD_{off}$ (Cycle)	Incident-placement from downstream detector	Models	Detected	IDR_{off} (%)	
3	66	42	63.6	1.95	Very near	88	74	84.1	
6	253	180	71.1	2.01	Near	72	54	75	
8	33	29	87.9	2.59	Far	56	47	83.9	
10	66	52	78.8	2.92	Very far	48	35	72.9	
12	33	27	81.8	2.48					
14	66	27	86.4	3.51					

(a)

Cycle length (Seconds)	Duration (cycles)						Success of offline incident detection
	3	6	8	10	12	14	>90%
60	22.7	36.4	63.6	36.4	45.5	59.1	70-90%
80	68.2	84.4	100	100	100	100	50-70%
100	100	94.3	100	100	100	100	<50%

(a)

(b)

Cycle length (Seconds)	Link length (m)			Success of offline incident detection
	300	500	1000	>90%
60	41.7	37.5	40.6	70-90%
80	95.6	97.4	81.7	50-70%
100	93.8	96.9	100	<50%

(b)

(c)

Cycle length (Seconds)	Link flow (veh/hr)				Success of offline incident detection
	100	500	1000	1500	>90%
60	14.6	43.8	50	56.3	70-90%
80	73.3	93.3	95.6	93.3	50-70%
100	93.8	100	97.9	96.9	<50%

(c)

(d)

Link length (m)	Link flow (veh/hr)				Success of offline incident detection
	100	500	1000	1500	>90%
300	57.4	83	89.4	-	70-90%
500	68.1	72.3	83	74.5	50-70%
1000	55.3	80.9	70.2	89.4	<50%

(d)

Figure 4.6: Incident detection rates versus: (a) incident duration and cycle time (b) link length and cycle time (c) link flow and cycle times and (d) link flow and link length

4.6.3 Sensitivity of the Binary Logit Model

A detailed sensitivity analysis was conducted to determine the significant factors influencing the incident detection rates from the 2nd data set (all data for both calibration and validation- a total of 517 incident models). The detailed performance results are listed in Table 4.6 (b), separated by each of the potential contributing factors. Figure 4.6 illustrates the incident detection rates versus dual combinations of cycle time, link flow, link length and incident duration.

The incident detection ranges are termed as "excellent detection zone", "very good detection zone", "acceptable detection zone" and "low detection zone" if the corresponding detection rate is greater than 0.90, between 0.70 to 0.90, between 0.5 to 0.7 and below 0.50, respectively.

(A) Cycle time:

Incident detection rates are higher than 85% for models of the 80-and 100-second cycle times. For the 60-second cycle time models, the detection rate is below 50% as shown in Table 4.6 (b). Figure 4.6a and Figure 4.6b also show the higher detection success zone near the cycle times of 80 and 100 seconds. It is apparent that the Logit model performs better in detecting incidents at intersections operating longer cycle times. The reason might be that longer cycle times are associated with longer data extraction times that can capture significant changes in detector readings due to incidents. The $MTTD_{off}$ was also found to be relatively better for longer cycle times for the same reason.

(B) Link flow:

As indicated above, the link flow level (denoted by X_{9,i,ϕ_j}^t) emerged as an insignificant factor for the Logit model. However, there were still some recognizable patterns of relations as explained hereafter. Figure 4.6c and Figure 4.6d show the trends for the lower success levels of incident detection for the low hourly flow zones. Higher flow levels coupled with higher cycle times generate higher success levels for incident detection. As shown in Table 4.6 (b), for the 100 veh/hr hourly traffic flow, the detection rate is relatively lower and the $MTTD_{off}$ is relatively higher than the counter values of higher link flows. At such low flow levels, if one lane gets blocked (because of an incident), the incoming vehicles can bypass the blocked lane easily. As such, the detector readings do not change significantly from the average non-incident scenario. It might not be an important issue for the traffic control center to detect relatively short incidents (e.g. the sudden stopping of a vehicle on the right-most lane for 3 minutes) when the traffic flow is relatively low during off-peak hours. Better detection rates are demonstrated in the relatively higher flow scenarios. The detector readings are not expected to exhibit significant changes with higher traffic flows in recurrent congestion situations.

(C) Link length:

The link length (denoted by X_{7,i,ϕ_j}^t) also emerged as an insignificant factor for the proposed Logit model. It was observed that each type of link length has more or less a similar impact on both the incident detection rates and $MTTD_{off}$ as shown in Table 4.6 (b). Figure 4.6d also confirms that no significant recognizable pattern exists for the coupling effect of the link flow and link-length combination in detecting

113

the incident. Incident detection rates fall within the same detection zone for all link length values.

(D) Duration of the incident:

Figure 4.6a shows that the proposed model reveals better level of incident detection with incidents of relatively longer duration and longer cycle times. Shorter durations of incidents emerged with lower rates of detection. This is because it requires a time lag to capture the changes in detector readings due to incidents from the normal incident-free condition. Therefore, incidents with shorter durations (for example, 3 cycle times) are expected to exert relatively less impact on the detector readings. For all durations, except for the duration of 14 cycle times, the $MTTD_{off}$ falls below 3 cycle times as shown in Table 4.6 (b).

(E) Random incident placements from the downstream detector:

With reference to Table 4.6 (b), the link length is assumed to be divided into 4 small segments (quarters) of equal length. If an incident is placed on the 1st quarter of the link (measured from the downstream detector), it is termed as *Very Near.* Similarly, incidents were termed as *Near, Far* and *Very Far* if they were placed on the 2nd, 3rd and 4th quarters, respectively.

The sensitivity analysis for the incident placement was carried out using middle-lane incidents from the calibration data (from the 1st data set). The detection rates were found to be at least 70% for different incident placements. Relatively high detection rates could be attributed to the fact that the Logit model incorporates the readings from all three detectors. An incident at any location might affect the nearby detector(s) readings within a reasonable time delay.

114

4.7 Integration of the Developed BLM with the Control System

In line with the primary objective(s) of this research, this study applies the BLM (of the 2nd data set) to predict online incident status for each time step. BLM was chosen because of its simplicity (with a single threshold only) and its stable behavior in terms of IDR$_{on}$, IDR$_{off}$ and *Rate of Correct Declarations* (RCD$_{on}$) for a wide range of input variables. BLM is integrated with the proposed control system, as discussed in Chapter 3, in order to have a control decision by the controller while different boundary conditions are (or are not) present.

BLM (of the 2nd data set) is based on a pre-timed type split signal control system only, where the incoming traffic flow on each approach link of an intersection is similar. However, this research study integrates the BLM (as an *incident status* module) with all the proposed signal control types (pre-timed or actuated) along with split, protected and dual ring barrier phase settings. The proposed signal control system is flexible on to activating or non-activating the BLM-based *incident status* module (see Chapter 3).

In order to implement BLM-based *incident status* modules for the proposed control system, the values of $C^{\theta,t}_{i,\phi_j,u\prime,d}$, $C^{\theta,t}_{i,\phi_j,u\prime,m}$, $C^{\theta,t}_{i,\phi_j,u\prime,u}$, $v^{\theta,t}_{i,\phi_j,u\prime,d}$, $v^{\theta,t}_{i,\phi_j,u\prime,m}$ and $v^{\theta,t}_{i,\phi_j,u\prime,u}$ have to be extracted using the detector configurations (as associated with the individual phase). In chapter 3, we noted that the individual detector data extraction time step is Δt, while the incident detection time step is θ, where θ is *n* times of Δt.

To account for the different time resolutions of both detector readings and incident detection, and to extract the values of $C^{\theta,t}_{i,\phi_j,u',d}$, $C^{\theta,t}_{i,\phi_j,u',m}$, $C^{\theta,t}_{i,\phi_j,u',u}$, $v^{\theta,t}_{i,\phi_j,u',d}$, $v^{\theta,t}_{i,\phi_j,u',m}$ and $v^{\theta,t}_{i,\phi_j,u',u}$, Equation (4.23) to Equation (4.28) can be used.

$$C^{\theta,t}_{i,\phi_j,u',d} = \sum_1^n (C^{V,t-(n-1)}_{i,\phi_j,u',1} + C^{V,t-(n-1)}_{i,\phi_j,u',2}) \tag{4.23}$$

$$C^{\theta,t}_{i,\phi_j,u',m} = \sum_1^n C^{V,t-(n-1)}_{i,\phi_j,u',3} \tag{4.24}$$

$$C^{\theta,t}_{i,\phi_j,u',u} = \sum_1^n C^{V,t-(n-1)}_{i,\phi_j,u',4} \tag{4.25}$$

$$v^{\theta,t}_{i,\phi_j,u',d} = \frac{\sum_1^n (C^{V,t-(n-1)}_{i,\phi_j,u',1} \times v^{V,t-(n-1)}_{i,\phi_j,u',1} + C^{V,t-(n-1)}_{i,\phi_j,u',2} \times v^{V,t-(n-1)}_{i,\phi_j,u',2})}{\sum_1^n (C^{V,t-(n-1)}_{i,\phi_j,u',1} + C^{V,t-(n-1)}_{i,\phi_j,u',2})} \tag{4.26}$$

$$v^{\theta,t}_{i,\phi_j,u',m} = \frac{\sum_1^n (C^{V,t-(n-1)}_{i,\phi_j,u',3} \times v^{V,t-(n-1)}_{i,\phi_j,u',3})}{\sum_1^n (C^{V,t-(n-1)}_{i,\phi_j,u',3}} \tag{4.27}$$

$$v^{\theta,t}_{i,\phi_j,u',u} = \frac{\sum_1^n (C^{V,t-(n-1)}_{i,\phi_j,u',4} \times v^{V,t-(n-1)}_{i,\phi_j,u',4})}{\sum_1^n (C^{V,t-(n-1)}_{i,\phi_j,u',4}} \tag{4.28}$$

To estimate the general base values of the parameters $\overline{C}^{0,t}_{i,\phi_j,u',d}$, $\overline{C}^{0,t}_{i,\phi_j,u',m}$, $\overline{C}^{0,t}_{i,\phi_j,u',u}$, $\overline{v}^{0,t}_{i,\phi_j,u',m}$ and $\overline{v}^{0,t}_{i,\phi_j,u',u}$ (which are required to estimate the independent variables defined by Equations 4.2 through 4.10), statistical regression analyses were performed (with every data set in the BLM) to come up with a general form that can be applied to form the base(s) of the BLM.

Equations (4.29) through (4.34) summarize the generalized form of the base parameters for the adopted BLM. These generalized regression equations were found to be statistically significant for the given data.

For any level of input of link length and cycle time (=time step),

116

For$X_{9,i,\phi_j}^t > 100$ veh/hr,

$$\overline{C}_{i,\phi_j,u',u}^{0,t} = -20.8768 + 0.26X_{8,i,\phi_j}^t + 0.0222X_{9,i,\phi_j}^t \qquad (4.29)$$

For$X_{9,i,\phi_j}^t \leq 100$ veh/hr,

$$\overline{C}_{i,\phi_j,u',u}^{0,t} = 0.0147 + 0.0273X_{8,i,\phi_j}^t \qquad (4.30)$$

For any level or combination of link flow, link length and cycle time (=time step),

$$\overline{v}_{i,\phi_j,u',u}^{0,t} = 39.0144 + 0.0044X_{7,i,\phi_j}^t + 0.0027X_{9,i,\phi_j}^t \qquad (4.31)$$

$$\overline{C}_{i,\phi_j,u',m}^{0,t} = -15.7945 + 0.1970X_{8,i,\phi_j}^t + 0.0222X_{9,i,\phi_j}^t \qquad (4.32)$$

$$\overline{v}_{i,\phi_j,u',m}^{0,t} = 51.7248 - 0.0043X_{9,i,\phi_j}^t \qquad (4.33)$$

$$\overline{C}_{i,\phi_j,u',d}^{0,t} = 1.7682 + 0.0021X_{9,i,\phi_j}^t \qquad (4.34)$$

The approach link flow (in veh/hr) or the input variable$\left(X_{9,i,\phi_j}^t\right)$ can be estimated from the upstream detector count at each incident detection time-step θ as shown in Equation (4.35).

$$X_{9,i,\phi_j}^t = \frac{C_{i,\phi_j,u',u}^{\theta,t}}{X_{8,i,\phi_j}^t} \times 3600 \qquad (4.35)$$

The above variables (estimated from Equations 4.23 through Equation 4.35) are used to estimate the input variables $(X_{1,i,\phi_j}^t, X_{2,i,\phi_j}^t, X_{3,i,\phi_j}^t, X_{5,i,\phi_j}^t$ and $X_{6,i,\phi_j}^t)$ using Equation (4.2) through (4.7). X_{8,i,ϕ_j}^t refers to the pre-selected incident detection time-step θ. These input variables are then used to estimate the incident event probability using the generalized BLM shown in Equation (4.36).

Event Probability:

$$p_{i,\phi_j}^t =$$

$$\frac{e^{(-2.2262-0.0489X_{1,i,\phi_j}^t-0.22X_{2,i,\phi_j}^t+0.6025X_{3,i,\phi_j}^t-0.0186X_{5,i,\phi_j}^t-0.0783X_{6,i,\phi_j}^t+0.0175X_{8,i,\phi_j}^t)}}{1+e^{(-2.2262-0.0489X_{1,i,\phi_j}^t-0.22X_{2,i,\phi_j}^t+0.6025X_{3,i,\phi_j}^t-0.0186X_{5,i,\phi_j}^t-0.0783X_{6,i,\phi_j}^t+0.0175X_{8,i,\phi_j}^t)}} (4.36)$$

A threshold value of 0.500 was adopted to distinguish between the incident and normal status.

4.8   Conclusions

The research area of urban incident detection models has not been fully explored. This study attempts to address some of the gaps using various models :namely, GLM, FLM and BLM. The devised BLM can be used to identify single-lane blocking incidents at any time step. The BLM can be envisaged as an integral component of a broader incident management system, to respond to the likelihood of an incident condition at an intersection approach as part of integrated incident management, taking into consideration other aspects such as transit priority and recurrent congestion management. In deploying the model in real-time, an off-line mechanism is required to update the average traffic parameters that are used in calculating the input parameters. Further research should tackle these issues and would mostly focus on developing adaptive response strategies as part of the integrated incident management system.

The BLM is a relatively stable model that performs effectively under various traffic conditions. It also proved to be quite effective as compared to other algorithms reported in the literature. Furthermore, BLM was tested under variable conditions and

with several incident scenarios much higher than those of other models. This indicates the better stability of the model in detecting incidents successfully over a wide range of traffic conditions. Except for the combination of relatively low traffic flow (100 veh/hr) and the short cycle time (60 seconds), the BLM outperforms all other algorithms in terms of offline detection rates. The estimates of the IDR_{off} in every case (excluding the stated low traffic flow and cycle time, which are typically rare in urban areas), is around 93%, irrespective of the incident duration when the 2nd data set is used. Most of the peak-hour traffic conditions exhibit relatively higher traffic flow and cycle time combinations. Thus, the potential for applying this BLM to urban incident detection is promising.

The uniqueness of the BLM is that it does not necessarily require calibration for each of the specific combinations of signal cycle times, link lengths and hourly traffic flows. The calibrated threshold value also shows stability in all conditions. More importantly, the BLM can capture incidents of shorter duration with acceptable performance measures that are comparable to other benchmark procedures .

Further challenges remain in predicting the incident status with significantly wide variations of the input attributes from the base cases, with reduced traffic parameters, different geometric road networks, varying incident durations, actuated signal cycle times, varying detector placements and varying traffic flow on other links of the downstream intersection. This study also made an attempt to integrate a generalized form of BLM within the traffic signal control system. The development of the BLM form was based on data associated with pre-timed signal setting. This

could be regarded as a limitation, and suggests that other frequently used signal types

could be incorporated to improve the generality of BLM in future research.

CHAPTER 5:   EXPERIMENTAL SET UP

5.1   Introduction

This chapter summarizes the experimental set up for testing the proposed integrated signal control logic as outlined in Chapter 3. A wide variety of traffic demand scenarios were implemented in the test beds of the CORSIM micro-simulation model. Also, some specific coefficients' values associated with the main formulation of the proposed signal control logic were tested . Section 5.2 discusses the micro-simulation methodology for these experimental tests. Section 5.3 details the traffic demand scenarios for the private cars and bus transit for specific grid road network cases. Section 5.4 details the specific coefficients values associated with the formulation of the proposed signal control logic.

5.2   Use of CORSIM Micro-Simulation

Stevanovic (2010) stated that, typically, Advanced Traffic Control Systems (ATCS) are evaluated in micro-simulation environments because of the expensed field data collection. The ATCS logic is interfaced with a micro-simulation model to test its level of performance. Stevanovic (2010) indicated that there are practitioners who lack confidence in micro-simulation results. Also, there remains the complexity and cost of modeling field conditions in micro-simulation and interfacing with ATCS, in addition to licensing issues with ATCS software.

Almost all ATCSs have been interfaced with micro-simulation tools, even though these micro-simulation methodologies may have drawbacks (Stevanovic

2010). Table 5.1 summarizes the interfaces available between ATCS and micro-simulation tools as identified in Stevanovic (2010, pp. 33).

Table 5.1: Interfaces between ATCS and micro-simulation tools, identified by Stevanovic (2010).

Micro-simulation tools	ATCS
CORSIM	ACS Lite, LA ATCS, OPAC, RHODES, SCOOT
VISSIM	ACS Lite, BALANCE, InSync, MOTION, SCATS, SCOOT, UTOPIA
Q-Paramics	RHODES
S-Paramics	SCATS, SCOOT, UTOPIA
AimSun	SCATS, SCOOT, UTOPIA
NONSTOP	BALANCE

At earlier stages of this study, VISSIM was considered, but this was abandoned for its limited incident modeling capabilities and RTE support. Also, VISSIM requires additional costly add on modules for the Dual Ring Barrier Phase Control support [PTV VISSIM Manual (2012)].

This study adopts CORSIM micro-simulation to imitate the test bed conditions for the following reasons:

- CORSIM uses dual ring phase settings to base the formulation of the proposed signal control logic .

- CORSIM has the explicit ability to generate a lane-blocking incident as both short-term and long-term events. The generation of an incident is a pre-requisite of the *Incident status module* (IM).

- The CORSIM academic license was less expensive .

Extensions to CORSIM simulation using a run-time extension (RTE) interface can also be provided. Run-time extensions replace existing logic in CORSIM or supplement its logic [TSIS-CORSIM Manual (2010)]. This study has built a CORSIM RTE with Microsoft Visual C++ compiler.

The CORSIM operation manual states that TSIS-CORSIM facilitates *Dynamic Link Library* (DLL) as an interface with the windows operating system. At each simulation time step (e.g. one second), the CORSIM server calls a series of functions within CORSIM to drive the simulation event loop. When an RTE is present and enabled, the CORSIM server also calls the exported functions of the RTE based on messages it receives from CORSIM at different points in the CORSIM execution time line. The server also calls the RTE initialization function during CORSIM initialization and the RTE exit function at the end of the simulation [TSIS-CORSIM Manual (2010)]. For details, readers are referred to the manual, *RTE Developers Guide,* with the TSIS-CORSIM.

5.3   Traffic Demand and Supply Scenarios

Any proposed signal control systems must be tested in a network environment under various traffic demand and supply conditions. This study tested the proposed signal control logic, (see Chapter 3 and 4), with various demand and geometric network scenarios.

Because of the unavailability of real field detector data for some urban areas in this region, it was not an option to test this signal control logic on a real network. Thus, various traffic demand flows starting from relatively low to high traffic volume levels (corresponding to high congestion levels), have been adopted under a theoretical grid-type network of 49 intersections. This grid network topology has 7 horizontal and 7 vertical arterials, where the cross-over of each pair of arterials represents a signalized intersection as shown in Figure 5.1. The origin (O) and destination (D) are chosen from the eastern, western, northern and southern boundary link entrances and exits, respectively.

Three different geometric configurations of grid networks were considered in order to have variations in the network structures. These three configurations are:

(a) Small grid network: Both vertical and horizontal links have a lengths of 300 m.

(b) Mix grid network: This network has one short link (i.e. 300 m) and one long link (i.e. 600 m) side by side, on alternatively in both vertical and horizontal dimensions. This represents a typical grid network with a mix of non-uniform link lengths, side by side.

(c) Big grid network: Both vertical and horizontal links have a length of 600 m.
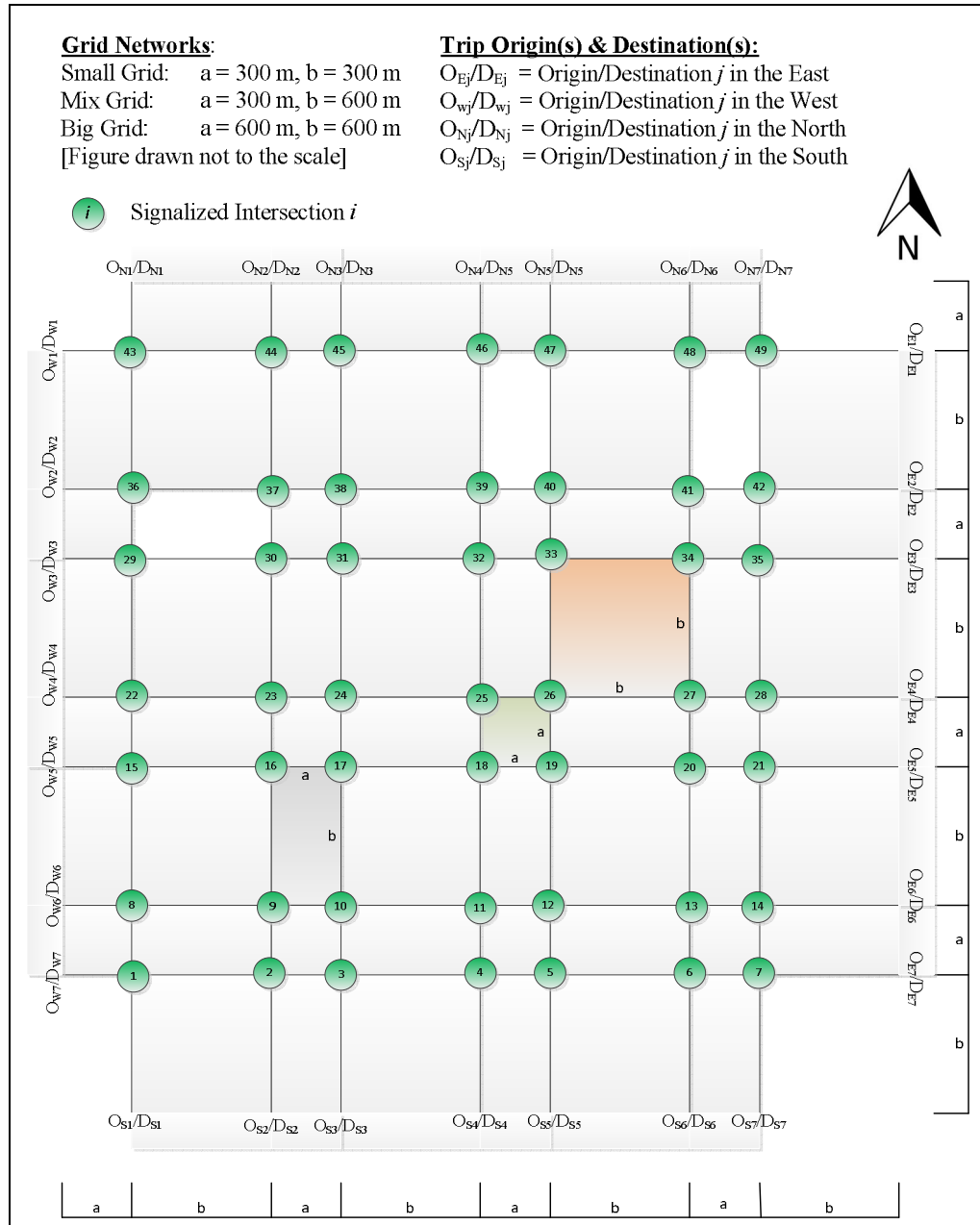
Figure 5.1: Layout of theoretical test bed network

As discussed in Chapter 3, each of the signalized intersection has four approach links (from the east, west, north and south) and four exit links. Also, each approach link has three continuous lanes and two additional left-storage lanes of 80 m each.

The network has seven (7) origins and seven (7) destinations at each of the four boundaries as shown in Figure 5.1. The adopted "car" trip distribution for any demand case is as follows:

- From any origin j on the eastern boundary (O_{Ej}), 60% of the total trips are split equally among the destinations on the western boundary (i.e. D_{W1} to D_{W7}). Furthermore, 20% of the total trips are split equally among the destinations on the northern boundary (i.e. D_{N1} to D_{N7}). Finally, the remaining 20% of the trips are split equally among the destinations on the southern boundary (i.e. D_{S1} to D_{S7}).

- From any origin j on the western boundary (O_{wj}), 60% of the total trips are split equally among the destinations on the eastern boundary (i.e. D_{E1} to D_{E7}). Furthermore, 20% of the total originated trips are split equally among the destinations on the northern boundary (i.e. D_{N1} to D_{N7}). Finally, the remaining 20% of the total originated trips are split equally among the destinations on the southern boundary (i.e. D_{S1} to D_{S7}).

- From any origin j on the northern boundary (O_{Nj}), 60% of the total trips are split equally among the destinations on the southern boundary (i.e. D_{S1} to D_{S7}). Furthermore, 20% of the total originated trips are split equally

among the destinations on the eastern boundary (i.e. D_{E1} to D_{E7}). Finally, the remaining 20% of the total trips are split equally among the destinations on the western boundary (i.e. D_{w1} to D_{w7}).

- From any origin j on the southern boundary (O_{Sj}), 60% of the total trips are split equally among the destinations on the northern boundary (i.e. D_{N1} to D_{N7}). Furthermore, 20% of the trips are split equally among the destinations on the eastern boundary (i.e. D_{E1} to D_{E7}). Finally, the remaining 20% of the total trips are split equally among the destinations on the western boundary (i.e. D_{w1} to D_{w7}).

For the assignment of car trips, the Federal Highway Administration (FHW) impedance function (supported by CORSIM) was chosen. The two parameters of impedance in the formula of FHW are fixed as a=0.60 and b=4.0 in CORSIM. The static user equilibrium assignment procedure was carried out to determine the link flows and movements. This represents typical traffic flow conditions.

A fixed bus route network comprising 18 directional routes was introduced for every the demand case scenario. Figure 5.2 shows the detailed bus network map adopted for this study. This is a static bus demand model with uniform headways. According to the demand of car trips, proportionate levels of bus trip headway and bus occupancy were considered. As shown in Figure 5.2, the origins and destinations on the eastern and western boundaries were considered as the bus flow directions. Some of the network links are parts of several overlapping bus routes. Some intersections have both left- and right-turning bus routes on their associated approach links.

127

Different levels of traffic demand were configured into different cases (based on the origin nodes traffic volumes and the characteristics of the bus routes). The traffic demand conditions adopted here are the demand cases "A", "B", "C", "D", "E" and "F".

Here, the demand case for "A" corresponds to relatively low traffic volume. Demand case "B" has a higher traffic volume than "A", demand case "C" has higher traffic volume than "B", etc.

The "E" demand scenario was tested twice (with two different phase maximum green intervals), and are termed as "E1" and "E2". Similarly, the "F" demand case is also tested twice as "F1" and "F2".

Each demand case has a pre-specified bus occupancy rate (based on car demand levels). The bus occupancy rate is used to estimate the number of *Person Trips* completed on buses, from the output of the number of *Bus Trips* in CORSIM.
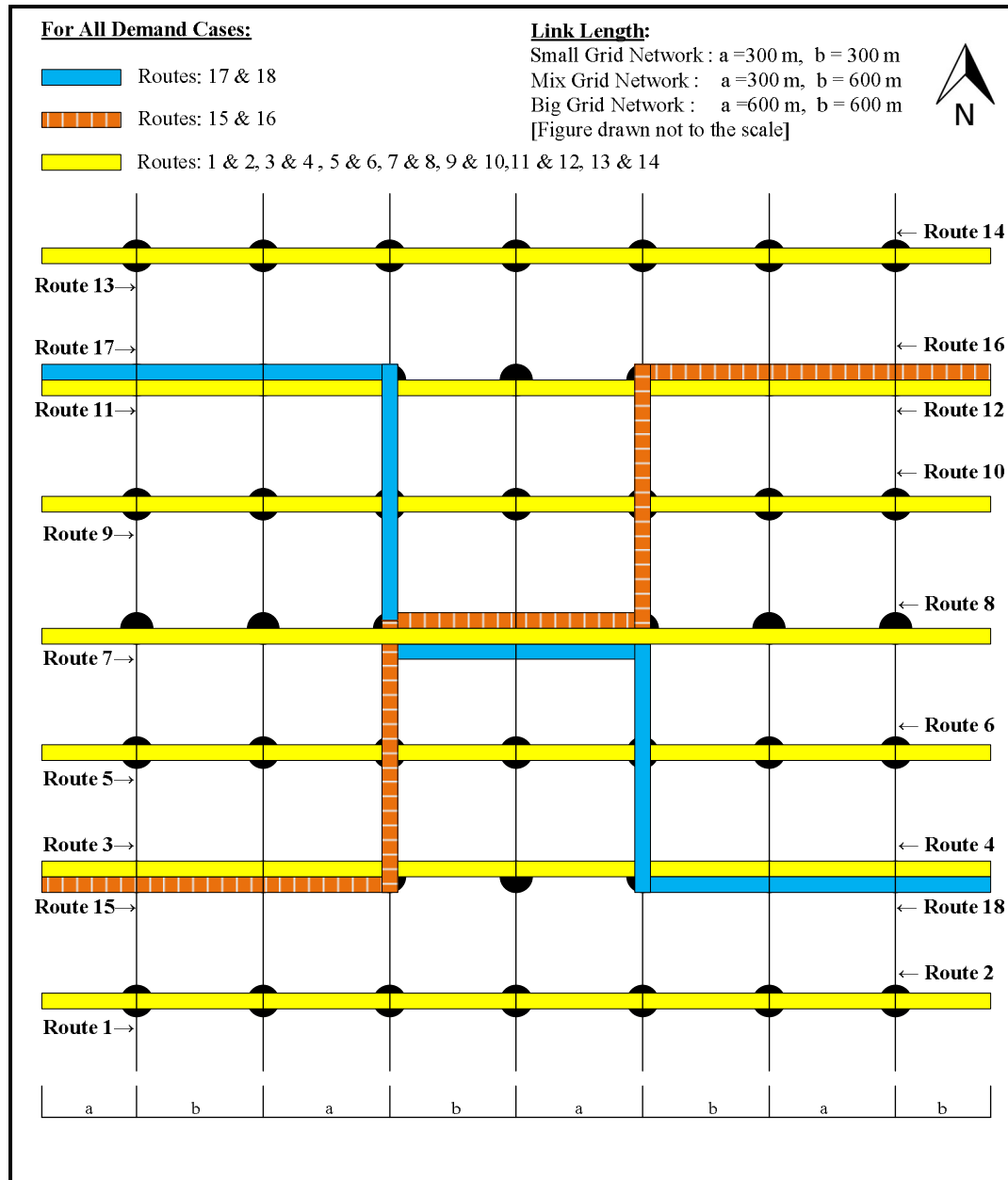
Figure 5.2: Layout of bus route network

All the demand cases and network configurations, except for the two demand cases of "E2" and "F2", were tested using the maximum green time parameter of 30 seconds. The demand cases of "E2" and "F2" were tested using the maximum green time of 45 seconds.

Demand Case "A":

This demand scenario represents very low traffic demand conditions. From any origin j along the eastern (O_{Ej}) or western (O_{wj}) or northern (O_{Nj}) or southern (O_{Sj}) boundaries, the hourly traffic volume is set as 100 cars/hour as shown in Figure 5.3. For 28 origin nodes (with 100 cars/hour each), the total demand is 2,800 cars per hour (or 4200 per 1.5 hour). The mean headway along the bus routes is 30 minutes. The occupancy rate is 25 persons per bus for performance evaluation.

Demand Case "B":

This case has higher traffic demand condition than the previous demand case . From any origin j on the eastern (O_{Ej}) or western (O_{wj}) boundaries, the hourly traffic volume is 500 cars/hour. From any origin j on the northern (O_{Nj}) or southern (O_{Sj}) boundaries, the hourly traffic volume is 100 cars/hour, as shown in Figure 5.4. The total network demand is 8400 cars per hour (or 12600 per 1.5 hours). The mean headway along the bus routes is 20 minutes. The occupancy rate is 30 persons per bus.

Demand Case "C":

From any origin j along the eastern (O_{Ej}) or western (O_{wj}) or northern (O_{Nj}) or southern (O_{Sj}) boundaries, the hourly traffic volume is set as 500 cars/hour, as shown in Figure 5.5. The network demand for cars is 14000 per hour (or 21000 per 1.5

hours). The mean headway along the bus routes is 20 minutes, and the bus occupancy is 35 persons per bus.

Demand Case "D":

This case has higher traffic demand condition than the previous Demand Case. From any origin j on the eastern (O_{Ej}) or western (O_{wj}) boundaries, the hourly traffic volume is 1000 cars/hour. From any origin j on the northern (O_{Nj}) or southern (O_{Sj}) boundaries, the hourly traffic volume is 500 cars/hour, as shown in Figure 5.6. The network demand for cars is 21,000 per hour (or 31,500 per 1.5 hours). The mean headway along the bus routes is 15 minutes, and the bus occupancy rate is 40 persons per bus.

Demand Cases "E1" and "E2":

Both cases "E1" and "E2" are equal in demand. From any origin j along the eastern (O_{Ej}) or western (O_{wj}) or northern (O_{Nj}) or southern (O_{Sj}) boundaries, the hourly traffic volume is set as 1000 cars/hour, as shown in Figure 5.7. The network demand for cars is 28,000 per hour (or 42,000 per 1.5 hours). The mean headway along the bus routes is 10 minutes, and the bus occupancy rate is 45 persons per bus.

Demand case "E1" was tested with the maximum green time (of any individual phase or phase set) of 30 seconds, while case "E2" was tested with the maximum green time of 45 seconds.

Demand Cases "F1" and "F2":

Both cases "F1" and "F2" are equal in demand. From any origin j along the eastern (O_{Ej}) or western (O_{wj}) or northern (O_{Nj}) or southern (O_{Sj}) boundaries, the hourly traffic volume is set as 1,500 cars/hour, as shown in Figure 5.8. The network

131

demand for cars is 42,000 per hour (or 63,000 per 1.5 hours). The mean headway along the bus routes is 5 minutes, and the bus occupancy rate is 50 persons per bus.

Demand case "F1" is tested with the maximum green time (of any individual phase or phase set) of 30 seconds, while case "F2" is tested with the maximum green time of 45 seconds.

It is to be noted that CORSIM is limited in its capability to generate incidents. It can only generate a single lane-blocking incident (as a long term event) randomly on a given link for a specific start time and a specific duration. Given the extent of the adopted grid network, the opportunity for introducing an incident condition anywhere in the network is numerous. To provide consistency among the experiments conducted, a one lane incident was generated (lane number 1) on the link between intersections 26 and 25 (as shown in Figure 5.1), starting at a time of 1800 seconds, with a duration of 600 seconds.

Following the analysis of the performance of the proposed signal control logic on the above mentioned demand cases, the seemingly better performing signal control types of the proposed signal control logic were tested again to introduce incidents on lanes 2 and 3. For some medium and heavy traffic demand cases, the duration of such incidents were varied. The details are described in Chapter 6.
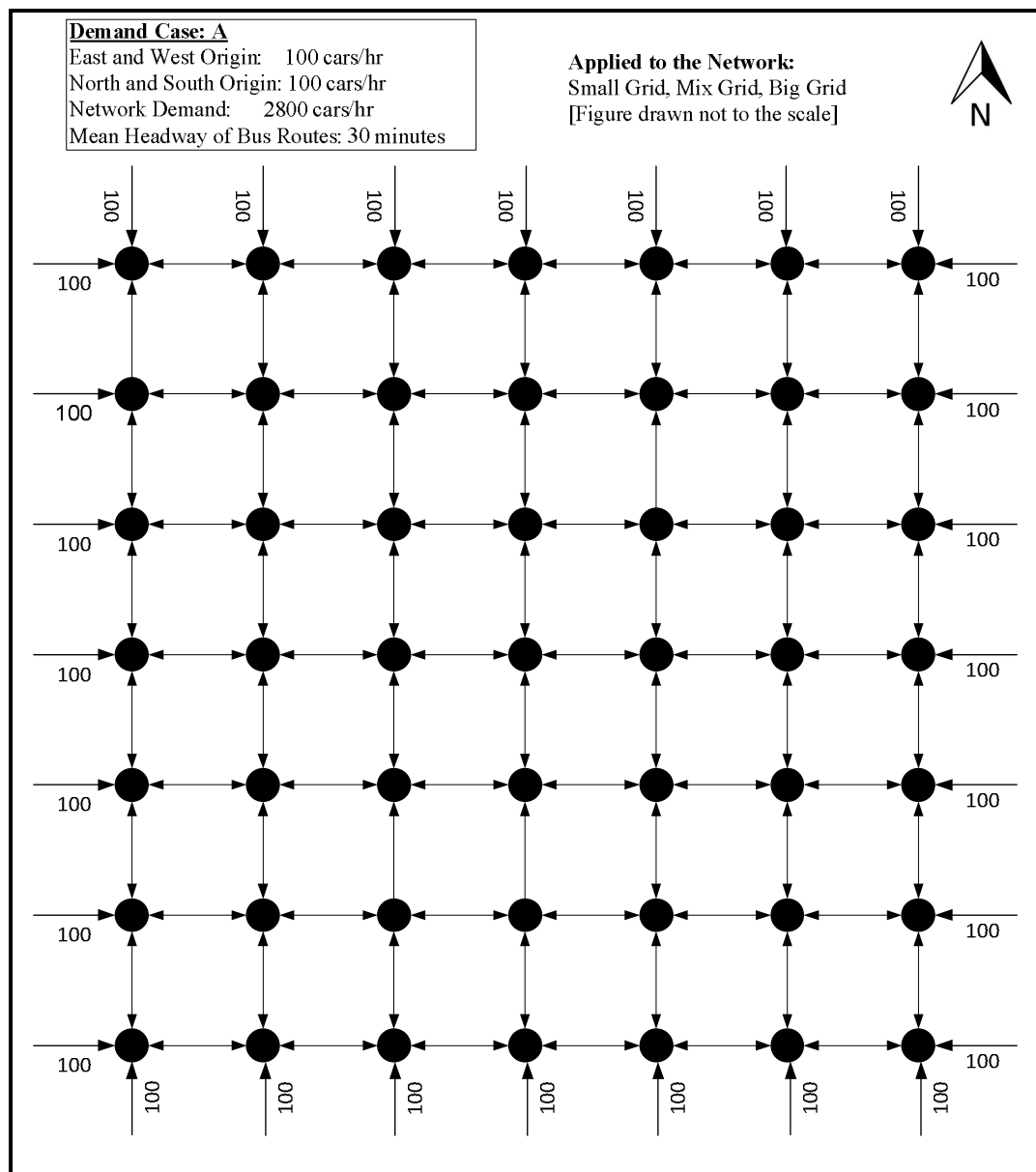
Figure 5.3: Demand Case "A"
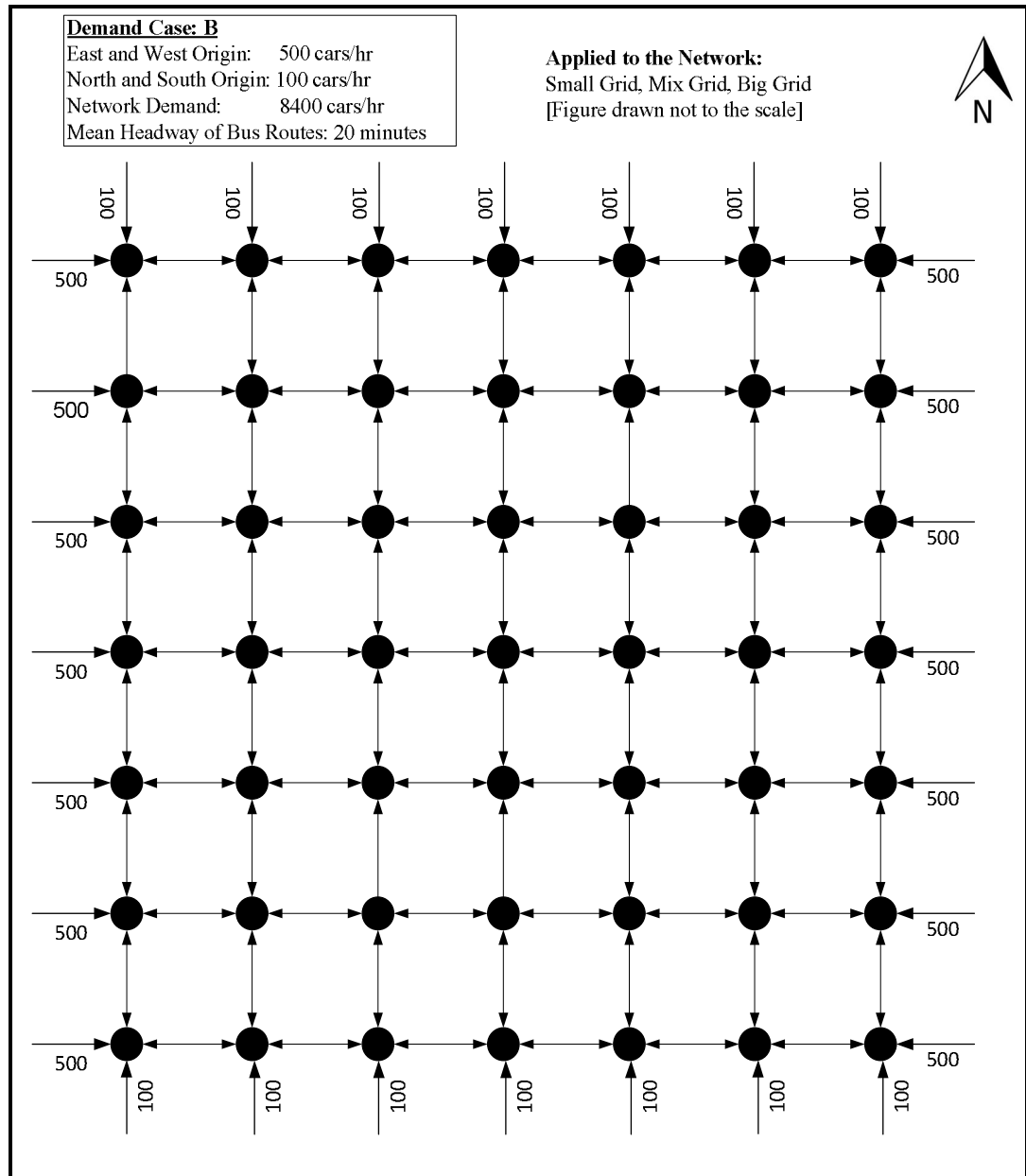
Figure 5.4: Demand Case "B"
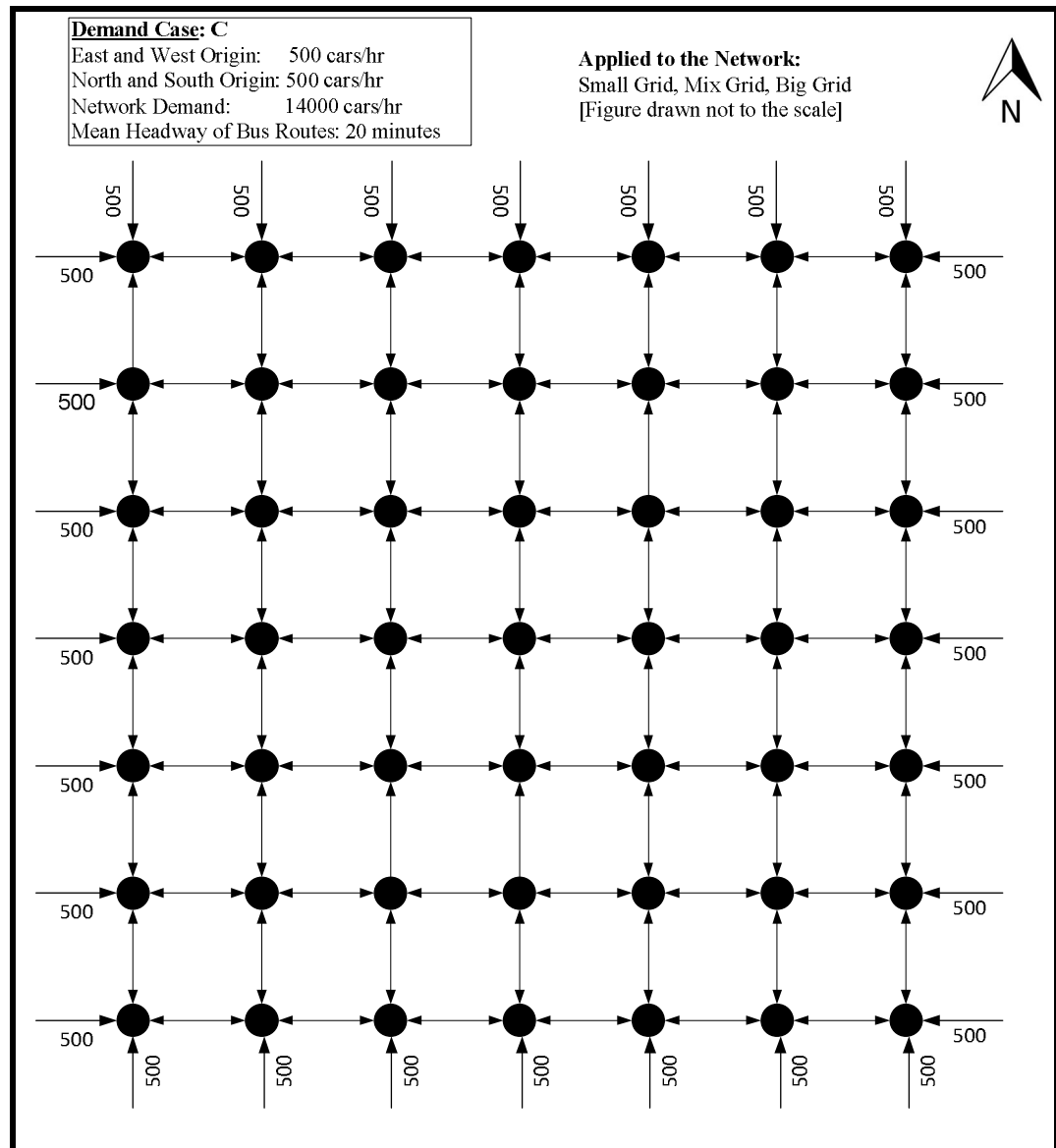
Figure 5.5: Demand Case "C"
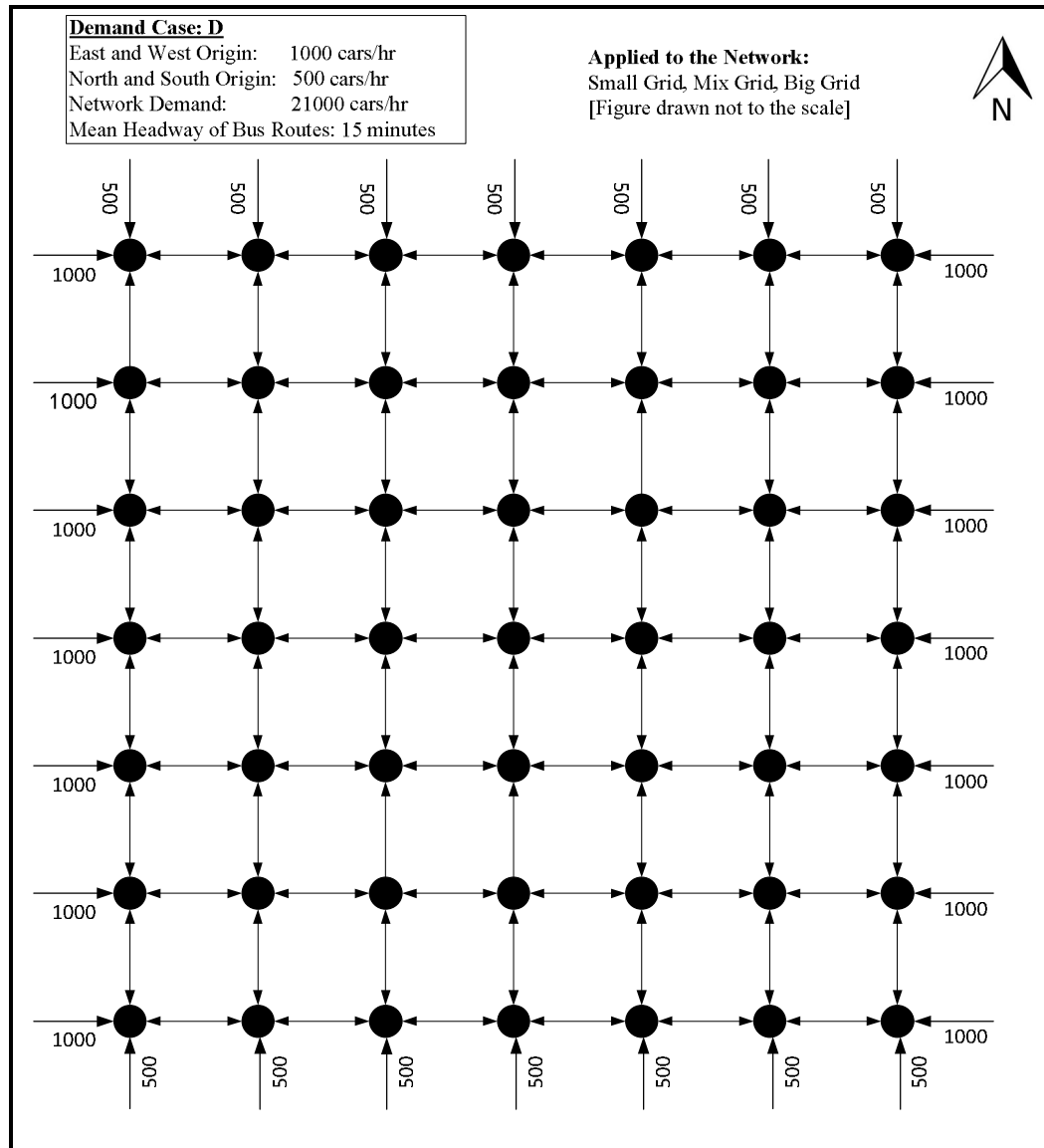
Figure 5.6: Demand Case "D"
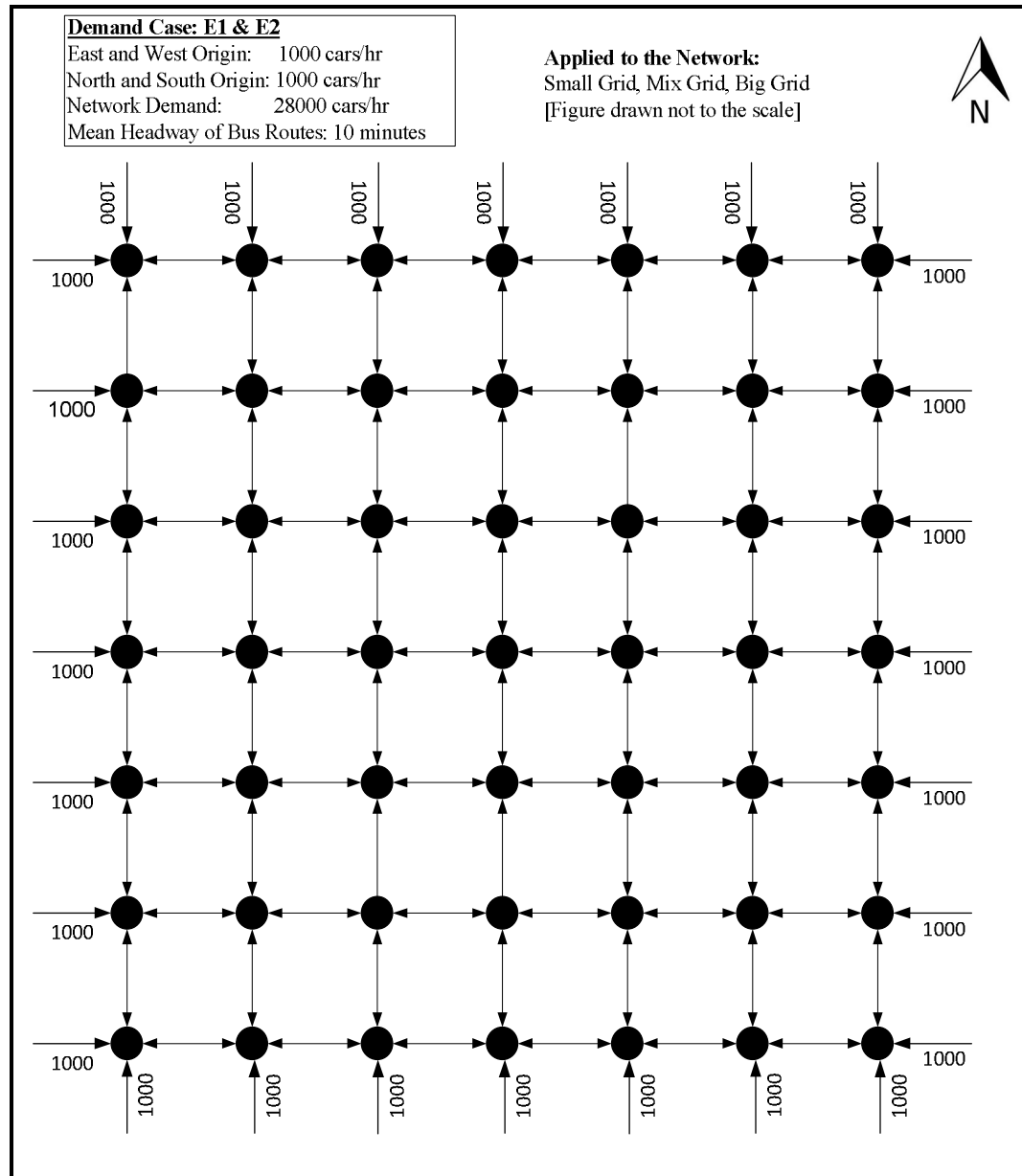
Figure 5.7: Demand Cases "E1" and "E2"
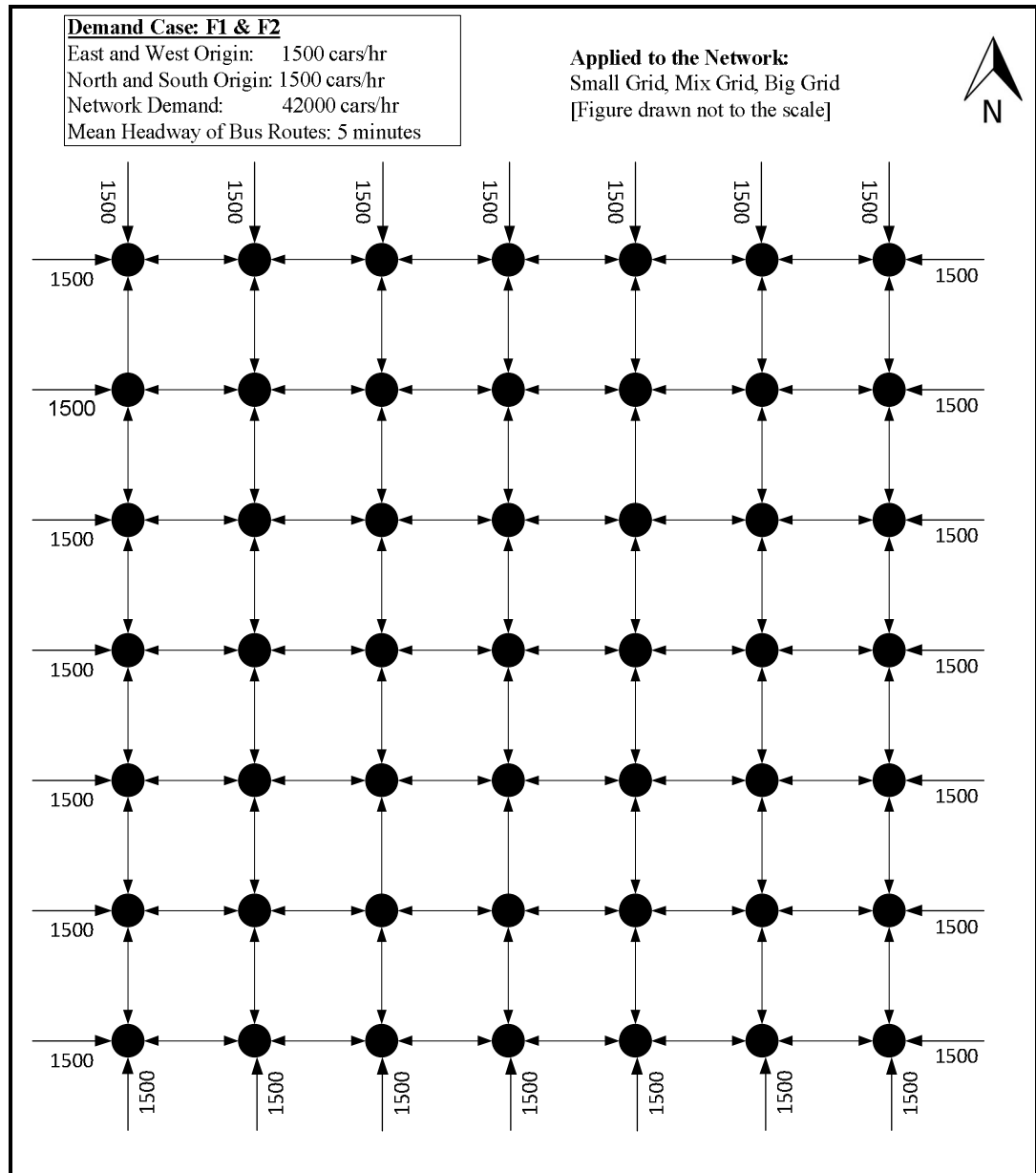
Figure 5.8: Demand Cases "F1" and "F2"

5.4 Parameters of the Proposed Control Logic

As discussed in Chapter 3, the main parameters that affect the value of the *actuation index of the individual phase* ϕ_j (A_{i,ϕ_j}^t) are:

- The coefficient for the transit priority for normal buses ($\beta_{i,\phi_j,u\prime}^b$);

- The coefficient for the *transit priority* for high priority buses ($\beta_{i,\phi_j,u\prime}^p$);

- The coefficient for the *virtual queue of vehicles* on the *upstream* approach link ($\beta_{i,\phi_j,u\prime}^V$);

- The incident penalty coefficient ($\beta_{i,\phi_j,u\prime}^N$); and

- The *downstream blockage penalty* coefficient ($\beta_{i,\phi_j,d\prime}^B$).

The other parameters for car occupancy ($O_{i,\phi_j,u\prime}^c$) and bus occupancy for normal and priority busses ($O_{i,\phi_j,u\prime}^b, O_{i,\phi_j,u\prime}^p$) are kept fixed. Even though the bus occupancies are different as indicated before for the various demand cases, due to the limited capability of CORSIM, it was not possible to flexibly adjust their values internally. As such, the RTE logic was augmented with an output post processor to account for the various occupancy rates. Below is a brief explanation of the adopted methodology accounting for the various bus occupancies.

TSIS-CORSIM does not provide a graphical user interface (GUI) option for changing the default bus occupancy rate on the bus type (either priority or no priority) within simulation runs of the "embedded" existing actuated and pre-timed signal control systems. Furthermore, no built-in specific API (Application Interface) has been developed for the transit priority option for buses .

The occupancy rate of buses can be varied only within the RTE option, through external the *Dynamic Link Library* (DLL) file. On the other hand, modeling the "embedded" existing signal control system of CORSIM is not directly supported by RTE. Therefore, it was necessary to use a fixed bus occupancy rate (default value of 25) for both types of run; existing CORSIM signal systems and the RTE proposed logic. This means that the RTE logic estimates the value of its relevant parameters based on this default occupancy rate only while making the signal control decisions in the simulations.

On the other hand, for both control systems, the CORSIM output (after simulation) such as vehicular trips, vehicular delays and total vehicular travel times are further post-processed to extract the final output in the form of passenger trips, passenger delays and passenger travel times. This passenger-based output is estimated using the occupancy rates (of private cars and buses) an indicated earlier in each demand case.

Regarding the treatment of various bus types, CORSIM does not provide any distinction between the *buses without any priority*, *normal priority buses* and *high priority buses*. Such distinction is not essential for the existing built in typical pre-timed and actuated control systems. Existing controllers consider the bus as a typical vehicle only for actuation requests. In order to implement the transit priority of the RTE logic (see Chapter 3), we considered only two types of buses: normal buses without priority and transit priority buses; i.e. no distinction was made between the "normal" and "high" priority buses. Both parameters of $\beta^p_{i,\phi_j,u\prime}$ and $\beta^b_{i,\phi_j,u\prime}$ were assumed to be equal.

140

This shrinks the five parameters listed earlier in this section to only four; $\beta_{i,\phi_j,u/}^p, \beta_{i,\phi_j,u/}^V, \beta_{i,\phi_j,u/}^N$ and $\beta_{i,\phi_j,d/}^B$. These four parameters were determined using a Brute-Force search. Initially, the RTE logic was tested in some medium and heavy traffic demand (Demand Cases of "C" and "F1") using some pre-selected values for the four parameters. The well-known Brute- Force method was applied to determine the parameters most suitable for each RTE control type. Table 5.2 shows the pre-selected values of the four parameters with the different proposed RTE control types.

Table 5.2: The pre-selected values of the coefficients for the proposed signal control logic

Control Type	$\beta_{i,\phi_j,u/}^V$	$\beta_{i,\phi_j,u/}^N$	$\beta_{i,\phi_j,u/}^p$	$\beta_{i,\phi_j,d/}^B$
Dual Actuated	1000	10	100	3
Protected Actuated	1000	100	1000	3
Protected Pre-timed	1000	100	1000	3
Split Actuated	500	10	500	3
Split Pre-timed	1000	10	500	3

Apart from the above four primary parameters, Table 5.3 also shows the other fixed parameters, used for both existing signal control systems (in CORSIM) and the proposed RTE logic.

Table 5.3: The pre-selected values of other relevant parameters for simulations

Parameter	CORSIM (Existing signal control system)	RTE Logic (Proposed signal control system)
Detectors data interval Δt	-	40 seconds
Incident detection interval θ	-	80 seconds
Pre-selected green extension time interval $(\Delta g_{i,\Phi_k})$ [for an individual phase ϕ_j or Phase Set Φ_k]	3 seconds	3 seconds
Minimum green time: g_{i,Φ_k}^{min} [for an individual phase ϕ_j or Phase Set Φ_k]	8 seconds	8 seconds [10 seconds only for RTE Dual Actuated]
Maximum green time: g_{i,Φ_k}^{max} [for an individual phase ϕ_j or Phase Set Φ_k]	30 seconds [For all demand cases: A, B,C,D,E1,F1] 45 seconds Only demand cases: E2 and F2]	30 seconds [For all demand cases: A, B,C,D,E1,F1] 45 seconds Only demand cases: E2 and F2]
Yellow Transition	3 second	3 seconds
Red (or All Red) Transition	1 second	1 second
Car Occupancy	1.27 (default)	1.27
Speed limit	60 kph	60 kph

It should be noted that the RTE logic is configured to work on a phase "set" basis, not on individual phases, as it is in typical existing signal control systems'. RTE logic is not bound to follow a cycle time. It is rather a biased system which has been formulated intentionally to give green (either by extension or by early green) to the most deserving candidate phase set as discussed in Chapter 3. Therefore, some of the base parameters were set differently from those of the existing control systems, with the assumption that these different parameters might yield better output for RTE.

The evaluation (analysis) period of all simulation runs is set for 1.5 hours. From initial runs, it was observed that the model is likely to reach equilibrium (even in heavy congestion conditions) within the first half an hour of the simulation run.

CHAPTER 6:   PEFORMANCE RESULTS AND ANALYSES

6.1   Introduction

This chapter summarizes the results and the sensitivity analyses of the proposed integrated control system for the various control types, demand cases and network topologies discussed earlier in Chapters 3 and 5. Section 6.2 describes the adopted *passenger-based* measures of effectiveness (MoEs) for comparing the performance of the proposed RTE control system against frequently used signal control systems. Section 6.3 details the comparative performance results of the proposed RTE control system. Section 6.4 briefly analyzes the performance measures. Section 6.5 presents the sensitivity analyses of the relevant coefficients of the proposed RTE control system Section 6.6 shows the performance results of the proposed control system logic using conventional *vehicular-based* evaluation criteria. Section 6.7 presents some conclusive remarks on the results and analyses.

6.2   Measures of Effectiveness

The typical measures of effectiveness to test signal control systems are *number of vehicles exited the network* (as a measure of productivity of the controller in easing network mobility), *vehicle's average travel time*, *average delay per vehicle* and *average network speed*. These measures are based on vehicles only, not on passengers or persons. Therefore, in line with the essentials of the proposed control system, passenger-based measures (particularly associated with the network "passengers") are deemed necessary. Keeping in mind that the proposed system includes a bus priority module, it is essential to assess the system using passenger-based criteria (in addition to the conventional vehicular-based ones). In brief, sections 6.3, 6.4 and 6.5 utilize passenger-based measures in evaluating the proposed system. Section 6.6 utilizes vehicular-based measures. For comparative assessment of the various control types, the following passenger-based measures of effectiveness were included.

- **Bus Trips**: Number of buses that have completely traversed the network, on a specific bus route and over all the network routes, during the evaluation (analysis) interval. This measure reflects the overall network productivity when *bus transit priority* is an important policy for the traffic control management system.

- **Person Trips**: The number of passengers that have completely traversed the network, either with private car or in a bus (along bus routes), during the evaluation interval. This measure directly reflects the overall network

144

productivity as it captures the total throughput under specific demand and supply condition for a specific evaluation period. The number of bus-based *Person Trips* (on a specific route) is estimated by multiplying the number of *Bus Trips* (along this specific route) by the bus occupancy rate (of this route), for the associated demand case. The *Person Trips* travelled in private cars are estimated as the number of cars multiplied by the car occupancy rate.

- **Average Delay per Person**: The average delay experienced by passengers that have completely traversed the network, either with private car or in a bus, during the evaluation interval. This measure reflects the efficiency of the network.

- **Average Trip Time per Person**: The average trip travel time experienced by passengers that have completely traversed the network, either with private car or in a bus, during the evaluation interval. This measure is also one of the most important network efficiency measures.

Due to the inherent complexity of interactions among road traffic variables, it is not guaranteed that efficiency will increase when there is an increase in productivity, for a specific supply system against a specific demand condition. For a control system, performance should be assessed using both productivity and efficiency measures. Typically, researchers tend to focus on using efficiency measures. It is believed that a tradeoff should be sought between productivity and efficiency. For example, under very low traffic volume condition, the typical travel

time is less than that of congested conditions. Under such low traffic volumes, vehicles can move with free flowing speed resulting in shorter travel times, and thus it is a highly efficient option, but with very low productivity. With the increase of traffic volume, one would expect a more productive but less efficient system. A good control system is one that incorporates both measures and attempts to maintain high (or at least acceptable) levels of productivity and efficiency under various operational conditions.

6.3   Comparative Performances of the Integrated Control Logic

The output of the proposed control system logic were compared against typical pre-timed and actuated traffic control systems with different phase settings. Existing pre-timed and actuated traffic control systems are generally referred as CORSIM default systems in order to distinguish them from the proposed control system logic in this chapter.

Table A3.1 and Table A3.2 in Appendix 3 summarize the comparative performance (in terms of *Bus Trips* and *Person Trips*) of the proposed system for various control types against the typical CORSIM, for the various demand levels and network topologies explained in Chapter 5. These also include information on whether or not the proposed control logic is able to produce the same or more *Bus Trips* or *Person Trips* than that of the existing controller for a specific grid network, demand conditions and phase settings.

Table A3.3 and Table A3.4 in Appendix 3 summarize the comparative performance (in terms of *Average Delay/Person* and *Average Trip Time/Person*) of the proposed control system. This also includes information on whether or not the proposed control logic is able to yield the same or less *Average Delay/Person* or *Average Trip Time/Person* than that of the existing controller for a specific grid network, demand condition and phase settings.

Of all the scenarios tested, representing various demand conditions, varying grid network, signal controller types, phase settings and maximum green time, the average performance of the proposed signal control logic is summarized in Table 6.1(a). The table shows four productivity and efficiency measures for various control

147

types (with and without the Incident Module (IM) activated). The performance measures are reported in a comparison to CORSIM for two cases: if the bus occupancy assumes a constant bus occupancy rate of 25 persons/bus, or if it is treated as variant based on the underlying demand condition as explained in Chapter 5.

Table 6.1(a): Overall average performance of the proposed signal control logic

Bus Occupancy Rate	Proposed control system	Percentage of times the proposed signal control logic either outperforms or yields similar result as of the existing signal controllers			
		Bus Trips	*Person Trips*	*Average Delay/ Person*	*Average Trip Time/ Person*
25 as Constant for both CORSIM and RTE Logic (while running the simulation only)	Logic with IM	67.5%	26.7%	25%	21.7%
	Logic w/o IM	67.5%	35.8%	41.7%	41.7%
Variant bus occupancy rate as per the individual demand case for both CORSIM and RTE Logic (while evaluating performances only)	Logic with IM	67.5%	29.2%	25.8%	25%
	Logic w/o IM	67.5%	37.5%	42.5%	43.3%

Keeping the same number of *Bus Trips* obtained for both existing control systems (i.e. CORSIM) and RTE Logic , as shown in Table 6.1(a), we can see that the overall performance of *Person Trips, Average Delay/Person* and *Average Trip Time/Person* does not change significantly even if we use varying bus occupancy rates. This chapter will proceed with the performance analyses by using the relative bus occupancy as rate in each individual demand case.

It seems that the proposed control system logic achieves significantly better throughput (in terms of *Bus Trips*) in most conditions compared to the existing CORSIM signal control systems, when applied with various signal phase settings. Other performance measures (in *Person Trips, Average Delay/Person* and *Average Trips Time/Person*) also show comparable outcomes. In general, it could be claimed that the proposed control system outperforms the productivity and efficiency measures of the typical CORSIM in about 41.6% of cases. This can be considered acceptable, keeping in mind that the proposed system has an added advantage of a bus priority system, that is likely to cause degradation in overall network's vehicular performance measures.

The following section focuses on examining the extent of variations in the performances of the signal control logic. The extent of the change in performance due to the control logic (for different control types, grid types or demand cases) is quantified using the percentage of increase/decrease of the corresponding measures from the corresponding base measures of the existing signal control logic in CORSIM. A positive change in either *Bus Trips* or *Person Trips* means improvement in productivity, and a negative change in either *Average Delay/Person* or *Average Trip Time/Person* indicates an improvement in efficiency by the signal control logic.

The general performance of the developed signal control types were estimated against the corresponding existing signal control system for each control type logic. Table 6.1(b) also shows the percentage increase in *Person Trips* and *Average Trip Time/Person* for different demand scenarios irrespective of the network grid types. The performance of the Split Pre-timed logic is outstanding in terms of a significant

enhancement in the productivity in all demand scenarios. Even, some significant reductions in trip travel time/person are achieved without the IM option in some scenarios for this the Split Pre-timed logic. On the other hand, Protected Actuated performs worst in terms of productivity. The remaining control types perform somewhere in between these two extremes.

Table 6.1(b): Overall average performance of the proposed signal control logic

% Increase of *Person Trips* (Against Existing CORSIM controllers)					
Control Type		Demand Cases (A to F2)	Demand Cases (C to F2)	Demand Cases (D to F2)	Demand Cases (E1 to F2)
Dual Actuated	Logic with IM	-0.91	-0.6	-0.57	-0.6
	Logic w/o IM	-1.06	-0.88	-0.95	-1.15
Protected Actuated	Logic with IM	-25.27	-32.98	-39.11	-45.02
	Logic w/o IM	-34.7	-45.63	-54.23	-61.18
Protected Pre-timed	Logic with IM	-9.21	-12.1	-14.76	-18.25
	Logic w/o IM	-21.56	-28.73	-34.77	-42.24
Split Actuated	Logic with IM	-3.88	-4.69	-5.42	-6.7
	Logic w/o IM	-0.99	-0.89	-0.9	-0.96
Split Pre-timed	Logic with IM	2.04	2.61	2.92	3.51
	Logic w/o IM	4.93	6.38	7.38	8.96
% Increase of *Average Trip Time/Person* (Against Existing CORSIM controllers)					
Control Type		Demand Cases (A to F2)	Demand Cases (C to F2)	Demand Cases (D to F2)	Demand Cases (E1 to F2)
Dual Actuated	Logic with IM	15.01	5.73	4.77	4.62
	Logic w/o IM	14.07	4.54	3.45	3.42
Protected Actuated	Logic with IM	45.22	45.89	50.53	55.8
	Logic w/o IM	19.46	12.62	11.17	9.67
Protected Pre-timed	Logic with IM	4.49	2.19	3.06	4.61
	Logic w/o IM	-10.16	-16.42	-18.89	-21.48
Split Actuated	Logic with IM	19.76	17.25	16.49	17.81
	Logic w/o IM	15.29	12.14	10.98	11.8
Split Pre-timed	Logic with IM	3.14	6.19	8.12	10.39
	Logic w/o IM	-2.78	-0.77	0.47	2.53

6.3.1 Performances of the Control Logic in Different Demand Cases

In comparing the performance of the various control types (See Chapter 3) under various demand cases and network topologies, the *Box and Whisker* analysis method was adopted. The *Box and Whisker* plot shows the central tendency and the extent of variations in the data points. It shows the specific central values (i.e. mean and medians) where data points are clustered. The *Box and Whisker* plots identify the mean value(s) of the data points with a circular dot inside the box. The lower boundary of the box represents a lower quartile of data, the upper boundary shows the upper quartile and the line inside the box refers to the median.

Dual Actuated Control

The Dual Actuated control type of the proposed integrated control logic does not produce better output in terms of *Person Trips* for every demand case: A to D. That is, for traffic demand of relatively low to medium levels, the Dual Actuated control underperforms against overall network productivity of the typical CORSIM Dual Actuated signal system.

Figures 6.1 and 6.2 demonstrate the performance of the proposed Dual Actuated controller in terms of *Person Trips* and *Average Trip Time/Person*, respectively, under various demand cases irrespective of the network topology/size. The plots illustrate the variability of performance whether the Incident Module (IM) is activated or not.
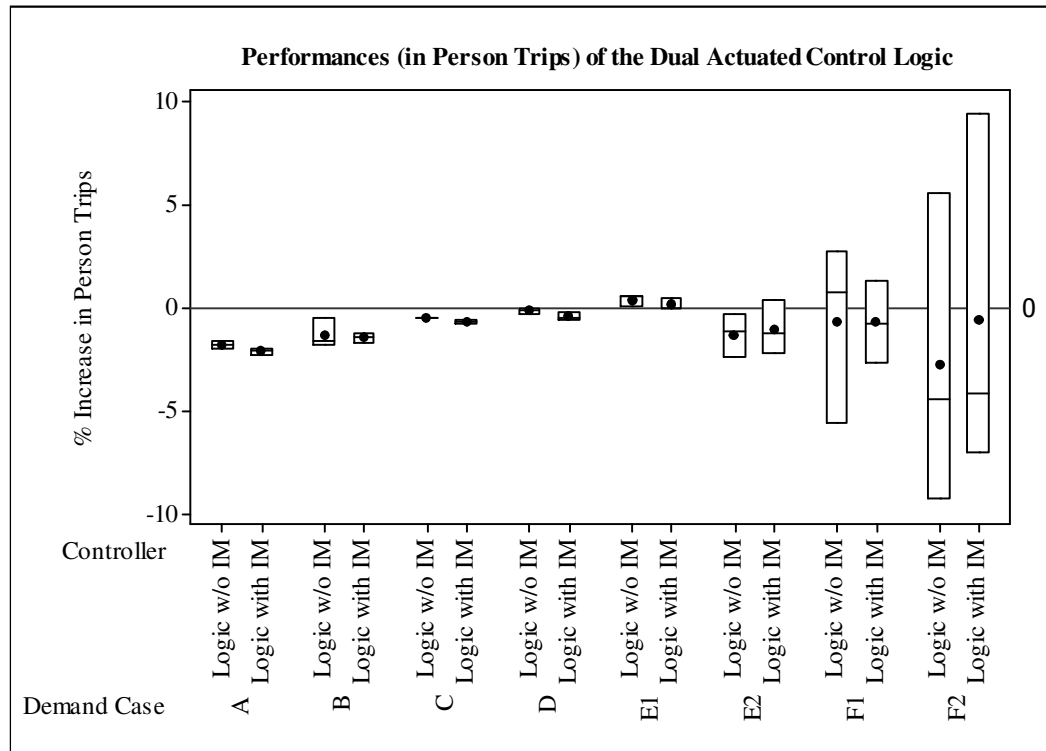
Figure 6.1: Relative productivity performance (in *% Person Trips*) of the Dual Actuated Logic

Figure 6.1 indicates an increase in productivity for demand case E1 both with and without the IM module. A detailed analysis of this control system indicates more productivity applied to specific grid networks for demand cases F1 and F2. Figures A3.1 and A3.2 (in Appendix 3) indicate that for demand cases F1 and F2, the proposed Dual Actuated logic outperforms the existing CORSIM-Dual Actuated control system in *Person Trips* in the large grid network. It also outperforms in the mix grid for demand case F2.

Figure 6.2 shows that the logic has comparable efficiency measures (in terms of *Average Trip Time/Person*) for demand cases E1 and E2, and even better measures for demand case F1. The logic without IM seems to be performing relatively well

(both in productivity and efficiency) in such high demand cases. For relatively low to medium traffic demand cases, the existing CORSIM-based system performs better.
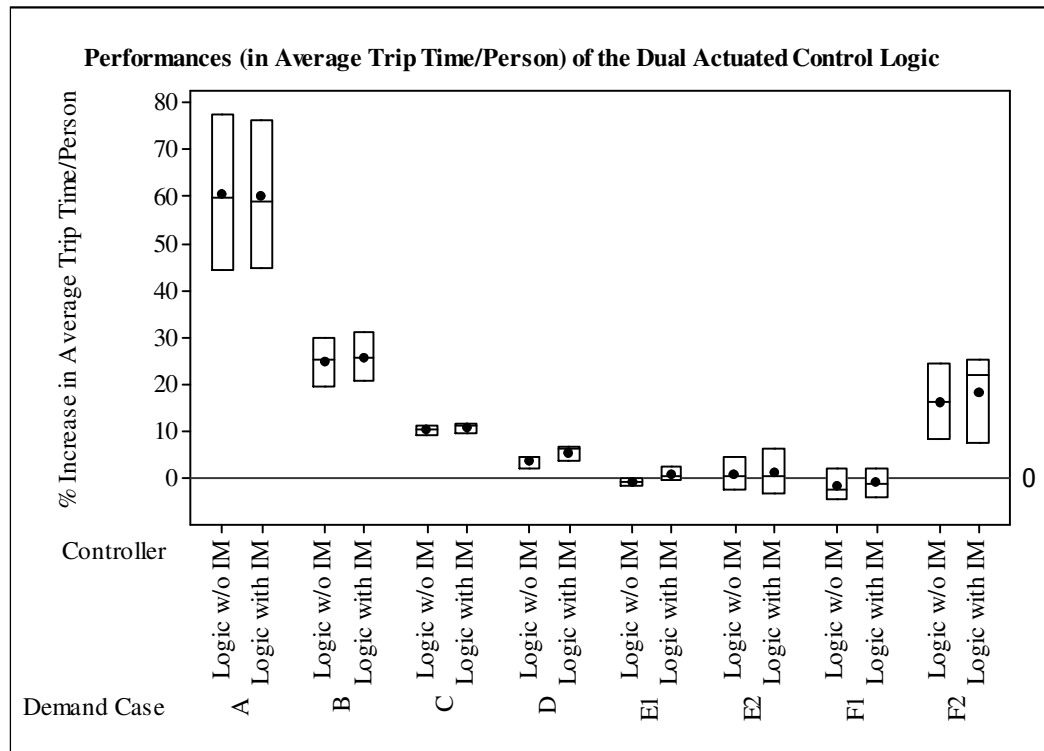
Figure 6.2: Relative efficiency performance (in *% Average Trip Time/Person*) of the Dual Actuated Logic

Protected Actuated Control

The Protected Actuated control logic shows comparable *Person Trips* for demand cases A to C. With higher traffic demand levels, the overall network productivity declines compared to CORSIM-based measures.

Figure 6.3 shows that for demand cases D to F2 (except for F1), with the increase in network demand, the productivity (in *Person Trips*) of the Protected Actuated logic decreases. This control type performs worst in heavy demand traffic conditions. F1 with the big grid (See Figure A3.3 in Appendix 3), (with IM) shows a comparable outcome of *Person Trips* with the CORSIM-based control.

153
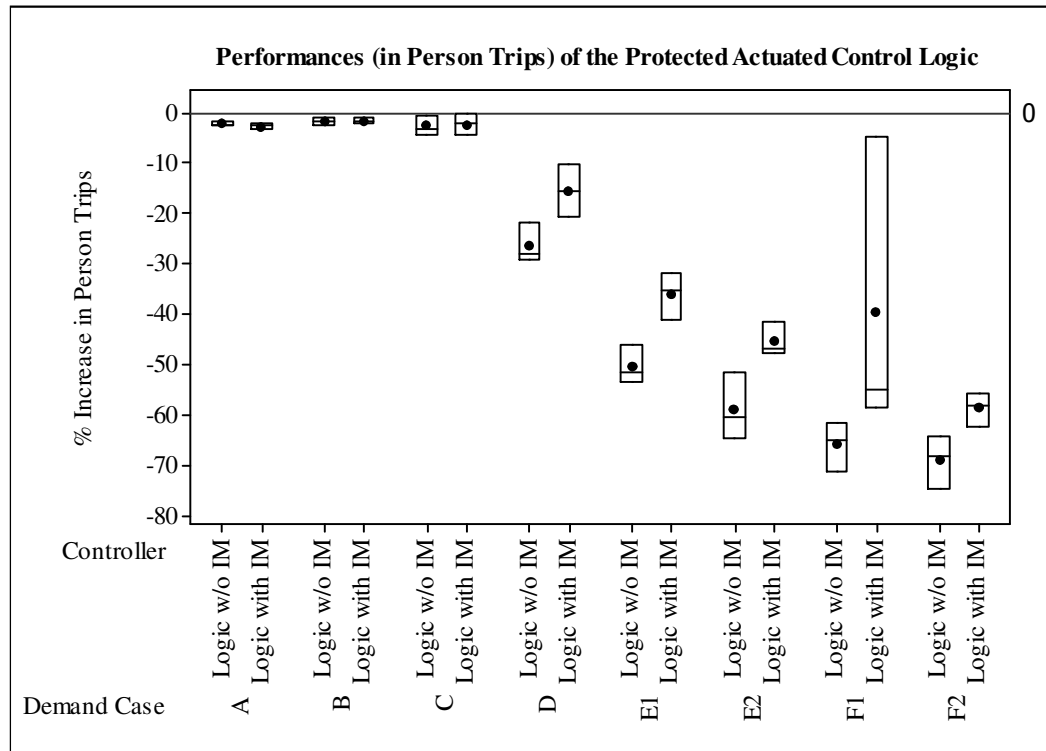
Figure 6.3: Relative productivity performance (in *% Person Trips*) of the Protected Actuated Logic

Figure 6.4 shows that the Protected Actuated logic underperforms in efficiency measures (in terms of *Average Trip Time/Person*) compared to the CORSIM-based control for demand cases A through E2. The performance of this logic without IM is slightly better for demand cases F1 and F2.
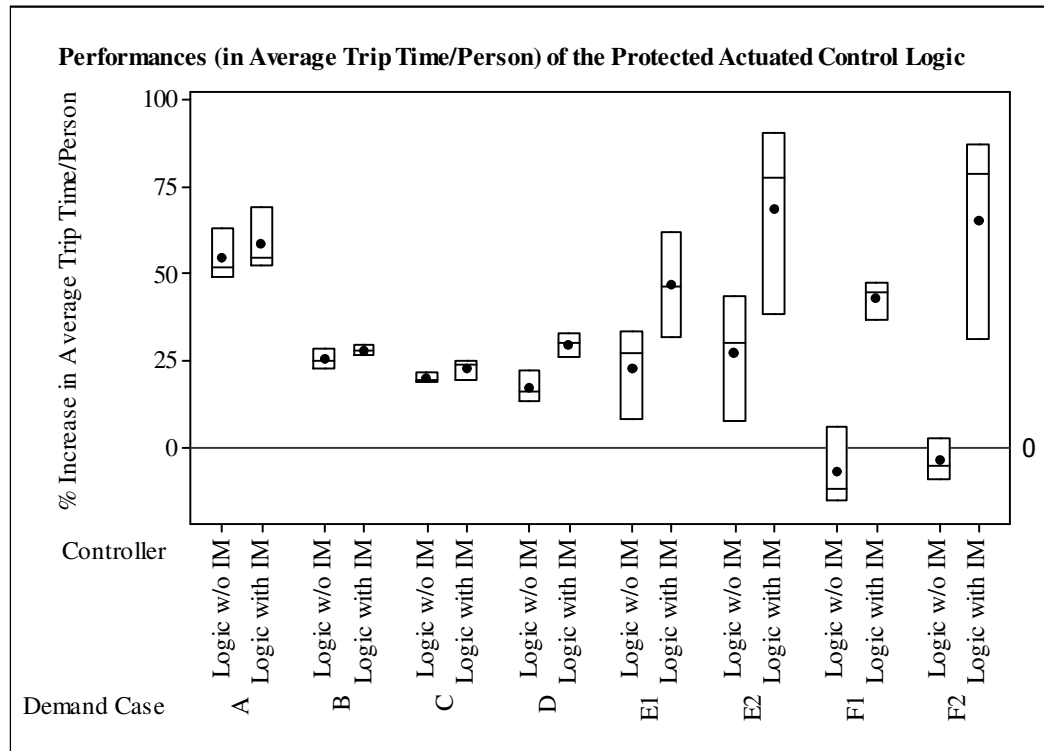
Figure 6.4: Relative efficiency performance (in *% Average Trip Time/Person*) of the Protected Actuated Logic

The Protected Pre-timed Control

The Protected Pre-timed control shows comparable productivity output in terms of *Person Trips* for demand cases A through D. Afterwards; a decline in productivity is noticed for demand cases E and F (See Figure 6.5). At such high demand levels (E and F), the productivity performance of the logic with IM is better than the one without IM.
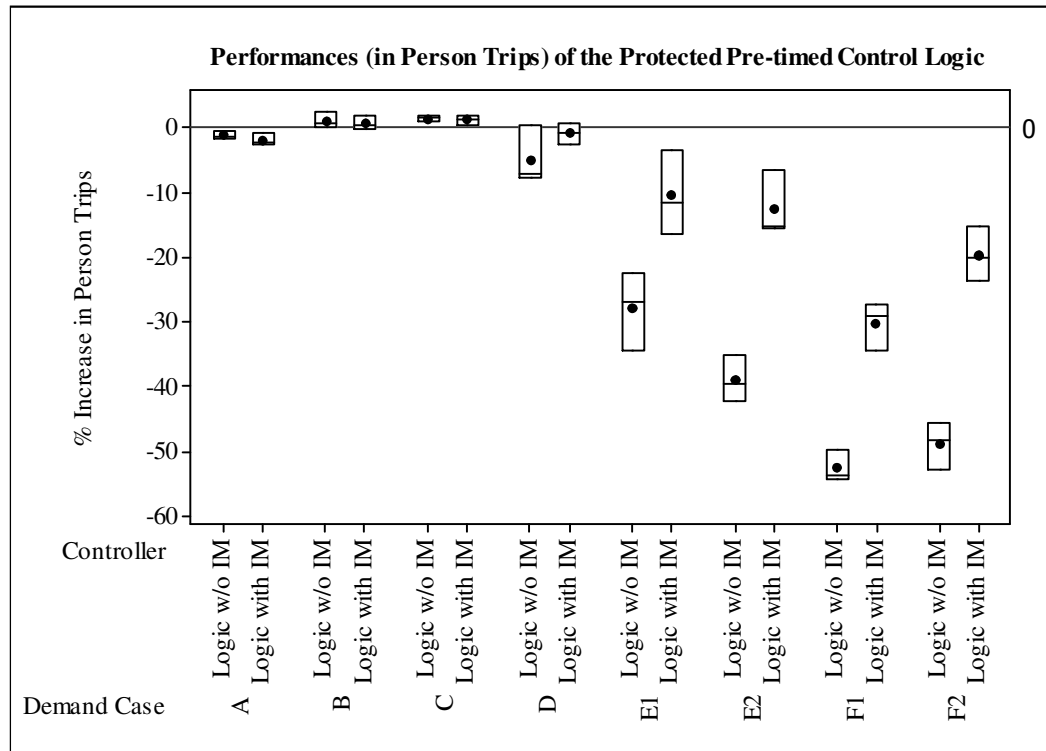
Figure 6.5: Relative productivity performance (in *% Person Trips*) of the Protected Pre-timed Logic

Figure 6.6 shows that the Protected Pre-timed logic has better efficiency performance in terms of *Average Trip Time/Person* for most of the demand cases, especially low to medium demand levels. At high demand levels (D through F), the performance of the logic without IM is significantly better than of that with the IM.

Performances (in Average Trip Time/Person) of the Protected Pre-timed Control Logic
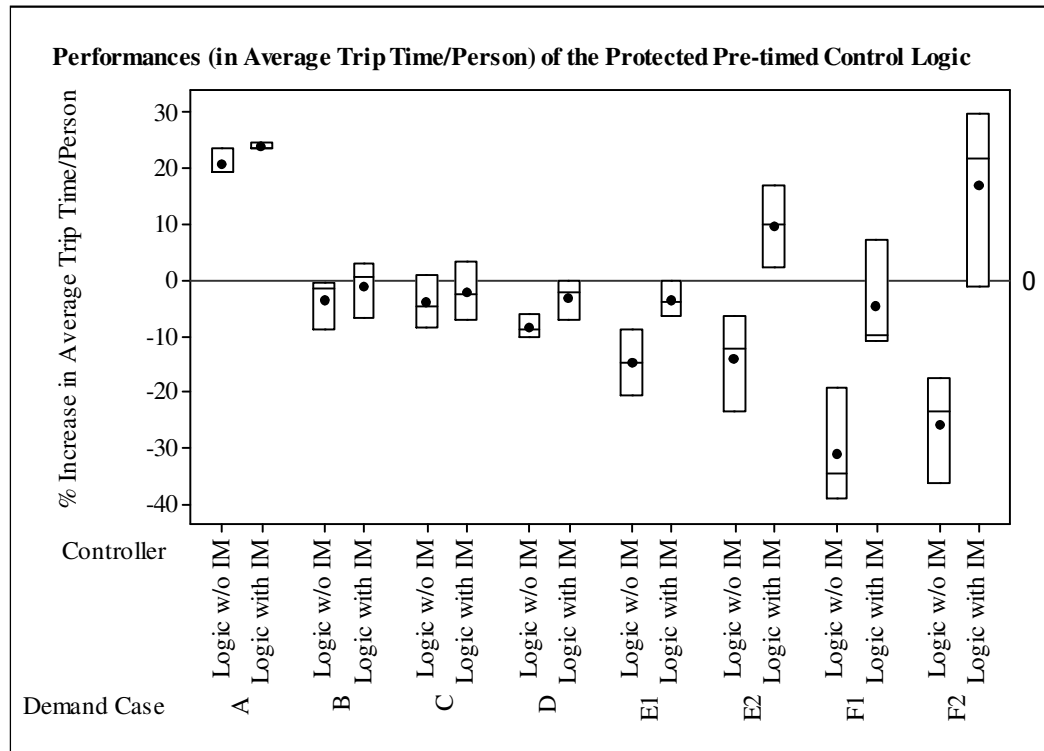
Figure 6.6: Relative efficiency performance (in *% Average Trip Time/Person*) of the Protected Pre-timed Logic

The Split Actuated Control

The Split Actuated control type of the proposed integrated control logic shows comparable productivity for demand cases A through D, (See Figure 6.7). Enhancement is noticed for cases E1 and E2, and a decline for cases F1 and F2. The control logic without IM performs better.

Figures A3.4 and A3.5 (in Appendix 3) show that for demand cases F1 and F2, the Split Actuated logic exhibits slightly better productivity measures in the big grid network.

157
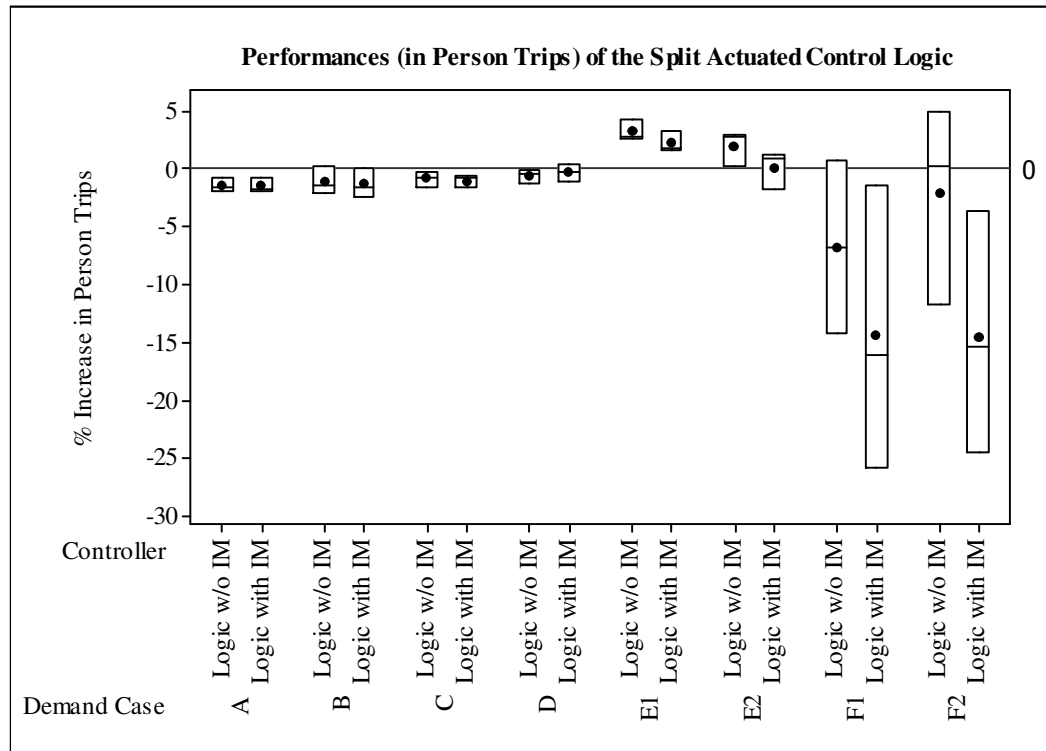
Figure 6.7: Relative productivity performance (in *% Person Trips*) of the Split Actuated Logic

As for efficiency, Figure 6.8 shows that the Split Actuated logic is generally performing worse than the CORSIM-based logic, except for demand cases E1 and E2.
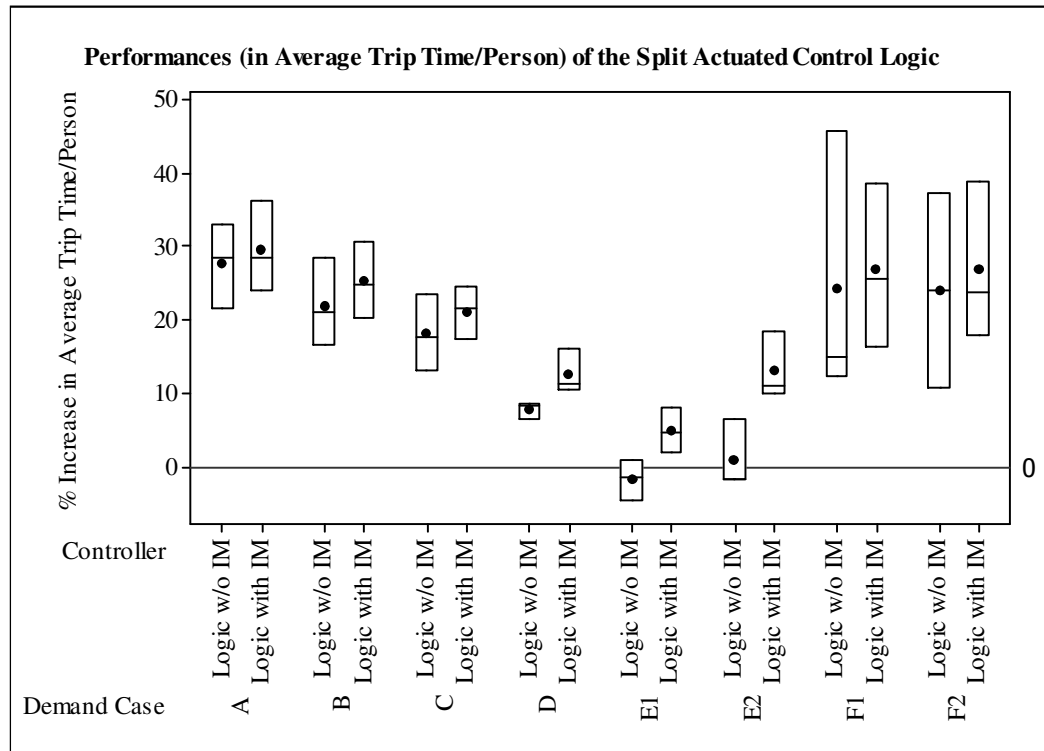
Figure 6.8: Relative efficiency performance (in *% Average Trip Time/Person*) of the Split Actuated Logic

The Split Pre-timed Control

The Split Pre-timed logic is the only control type which outperforms the productivity measures (*Person Trips*) of the CORSIM-based controller in almost all of the demand cases shown in Figure 6.9. An increase in productivity is evident at very high traffic congestion levels (F1 and F2), especially without the IM. It is interesting to note that the relative gain in productivity is higher with a relative increase in traffic demand levels.

Figures A3.6 and A3.7 (in Appendix 3) indicate that for both cases F1 and F2, the Split Pre-timed logic outperforms the CORSIM-based control for all of grid

159

network types. The logic with IM shows a slight loss of productivity in the case of F2.

Performances (in Person Trips) of the Split Pre-timed Control Logic
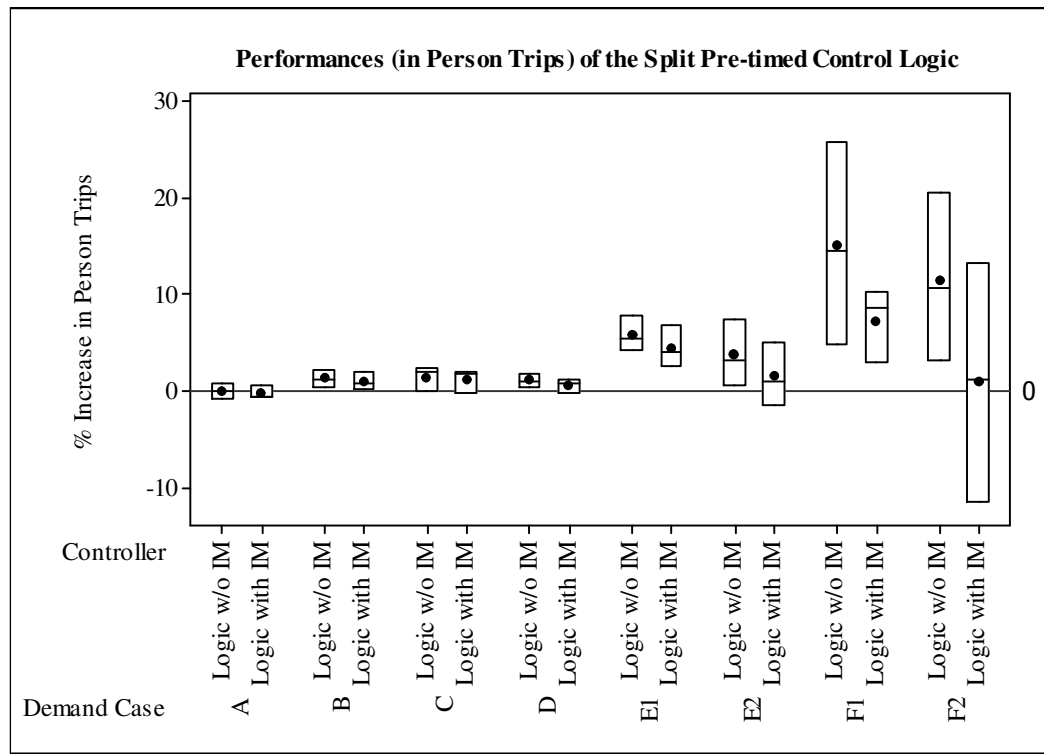
Figure 6.9: Relative productivity performance (in *% Person Trips*) of the Split Pre-timed Logic

On the other hand, Figure 6.10 shows that this control logic has emerged with improved efficiency levels for demand cases A to through E1. This result is quite promising. Degradation in efficiency measures is noticed at high demand levels (F1 and F2). This reduction in efficiency is likely caused by a significant increase in productivity at these high demand levels.
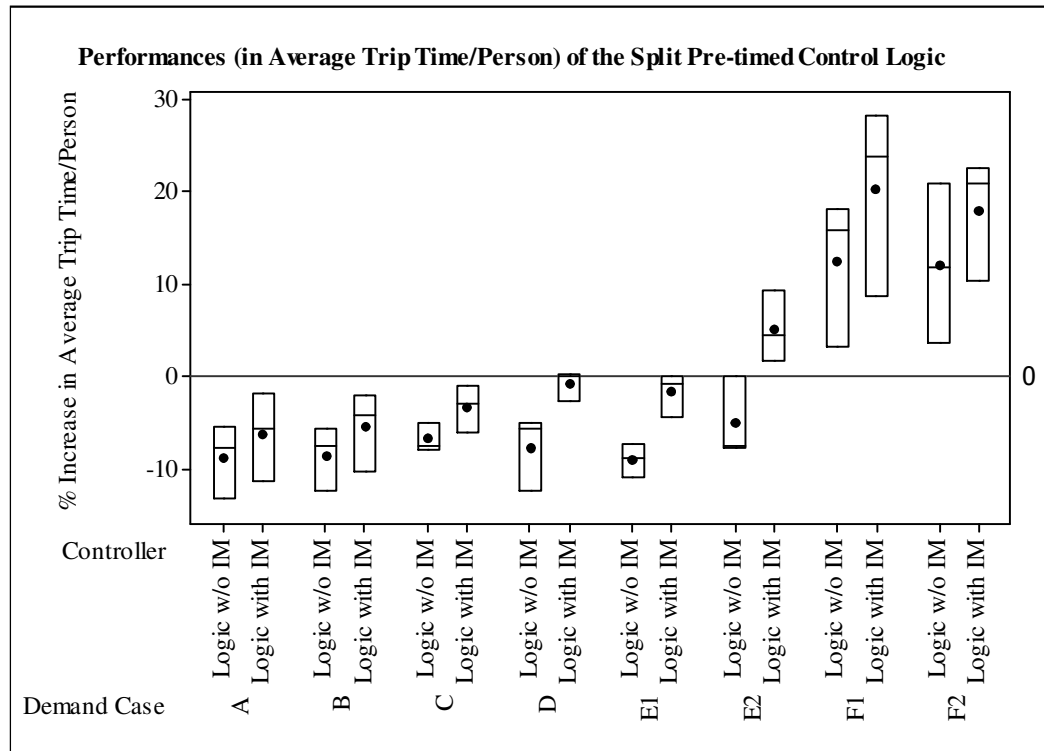
Figure 6.10: Relative efficiency performance (in *% Average Trip Time/Person*) of the Split Pre-timed Logic

6.3.2 Performances of the Control Logic in Different Grid Networks

From the findings of the previous section, it is clear that the proposed signal control logic performs better at low traffic demand levels (A and B) with the Protected Pre-timed and the Split Pre-timed logics. Even with higher demand levels, these two logics perform well. Further analysis will be carried out to assess the impact of network size or topology on the performance of the various control types. Control performance is assessed with and without activation of the IM. Medium to high demand levels (C through F2) are used in carrying out this analysis.

Figures 6.11 and 6.12 illustrate the relative productivity measures (*Bus Trips*) for the proposed integrated control logics with and without IM, respectively. Figures

6.13 and 6.14 illustrate the relative productivity measures (*Person Trips*) for the proposed integrated control logics with and without IM, respectively. Figures 6.15 and 6.16 illustrate the relative efficiency measures (*Average Delay/Person*) for the proposed integrated control logics with and without IM, respectively. Figures 6.17 and 6.18 illustrate the relative efficiency measures (*Average Trip Time/Person*) for the proposed integrated control logics with and without IM, respectively.

As for the *Bus Trips* measure (Figure 6.11), the integrated control logic with IM works better in the mix and big grid networks. The Protected Actuated logic with IM control type performs worst in every grid network type under medium to heavy traffic demand cases. The performance of the Dual Actuated logic with IM is comparable in each network type. The Protected Pre-timed with IM also shows slight variations from the CORSIM-based system in the large and mix grid networks, and it seems worse in the smaller grid network. Split Actuated with IM works best for the big grid network, its performance is comparable. The Split Pre-timed with IM seems to perform similarly in every grid network. The Dual Actuated with IM and the Split Pre-timed with IM logics work better than the other control logics in the small grid network. This small grid network when loaded with heavy demand traffic levels is probably the most congested network.

Performances (in % Increase in Bus Trips) of Control Logic with IM [Demand Cases: C to F2]
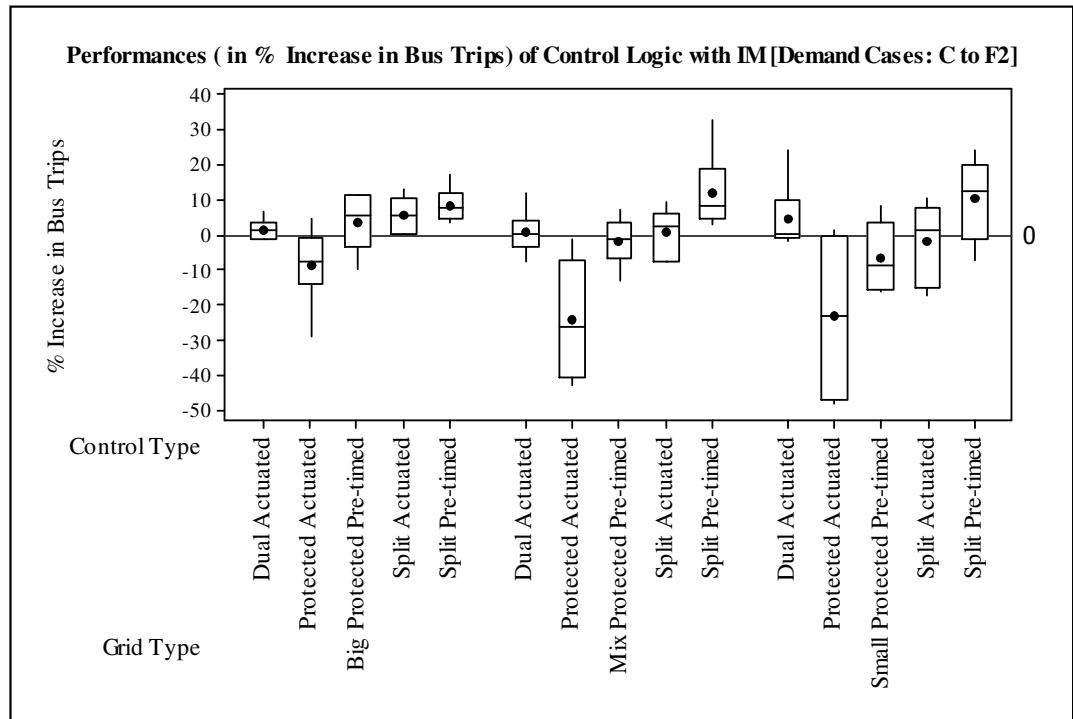
Figure 6.11: Relative productivity performance (in *% Bus Trips*) of various control (with IM) and grid types

A similar pattern of *Bus Trips* performance is observed (See Figure 6.12) for each control logics without IM. Only in the large network, does the Protected Pre-timed control logic without IM perform worse than that of the control logic with IM.
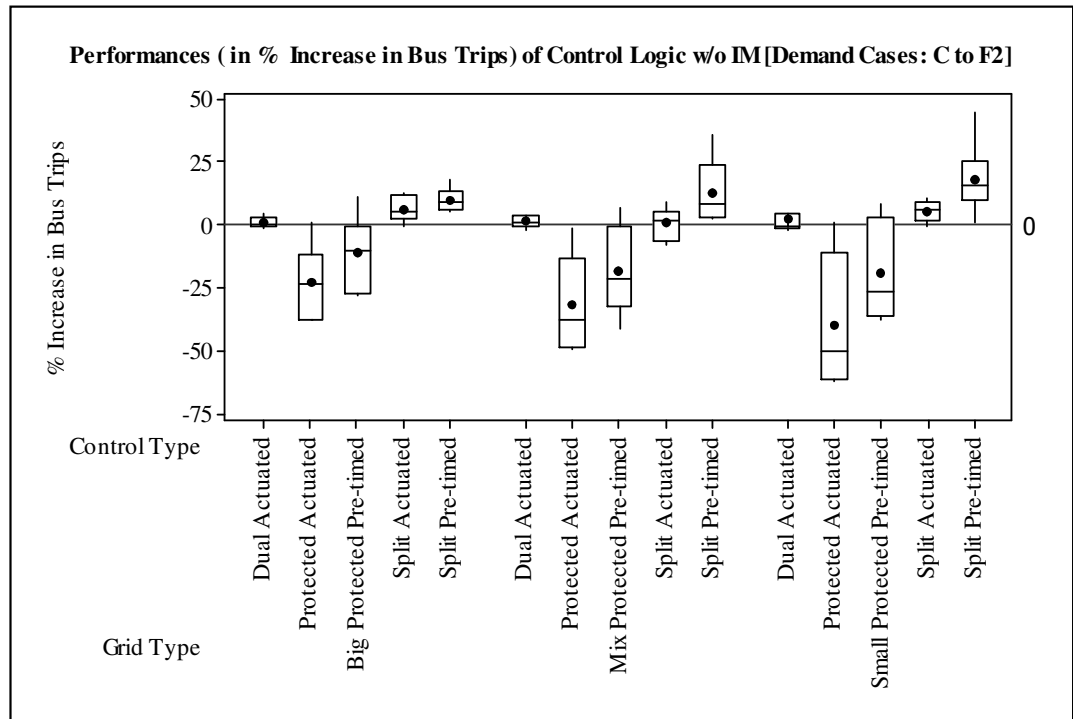
Figure 6.12: Relative productivity performance (in *% Bus Trips*) of various control (without IM) and grid types

For the overall network *Person Trips* measure (Figure 6.13), the integrated control system logic with IM follows a similar pattern as for the *Bus Trips*, but with different variations. Both Protected Actuated and Protected Pre-timed logics with IM underperform (with significant losses of productivity) in the three grid networks. Dual Actuated with IM shows a stable performance in every grid network. Split Actuated with IM shows a slight than a significant loss of productivity with mix and small grid, respectively. The Split Pre-timed with IM shows a stable performances with slightly improved productivity in every grid network irrespective of demand cases.

164

Performances (in % Increase in Person Trips) of Control Logic with IM [Demand Cases: C to F2]
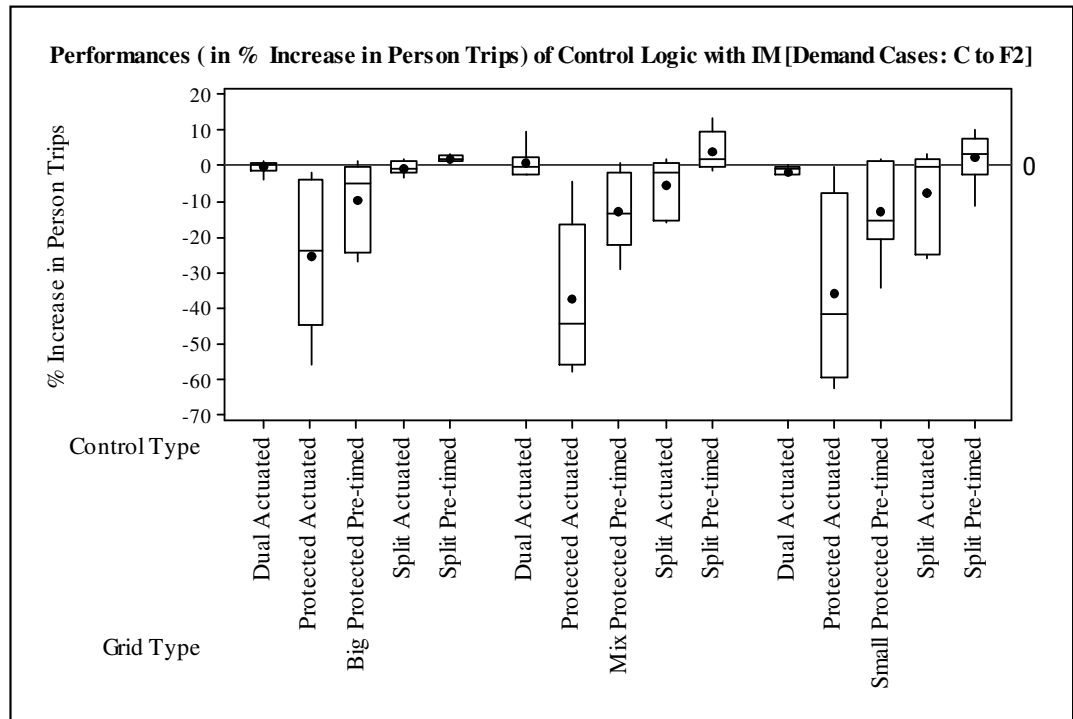
Figure 6.13: Relative productivity performance (in *% Person Trips*) of various control (with IM) and grid Types

On the other hand, Figure 6.14 shows a similar performance from the control logic without IM to that of with IM logic. The Split Actuated without IM shows better productivity compared to the logic with IM. The Split Pre-timed without IM outperforms the CORSIM-based control logic with a slight to more significant increase in productivity (in *Person Trips*) for both mix and small grid networks.
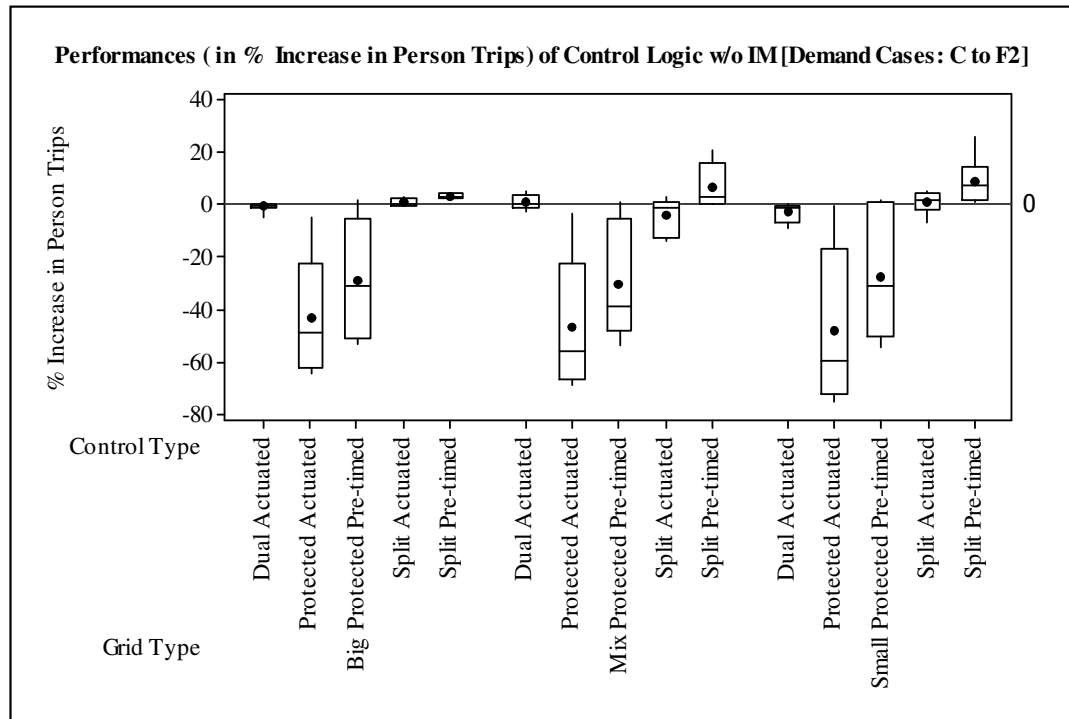
Figure 6.14: Relative productivity performance (in *% Person Trips*) of various control (without IM) and grid types

As for the efficiency measure represented by the *Average Delay/Person* measure (See Figure 6.15), the integrated control system logic with IM shows poorer values than that of the corresponding CORSIM-based control system in every grid network. The Protected Actuated shows the worst delays per person for the small, mix and big grid networks. On the other hand, the control logic without IM incurs relatively less *Average Delay/Person* than that of the control logic with IM. Figure 6.16 shows that the control logic without IM has better efficiency values than the CORSIM-based ones with both the Protected and Split Pre-timed control systems.
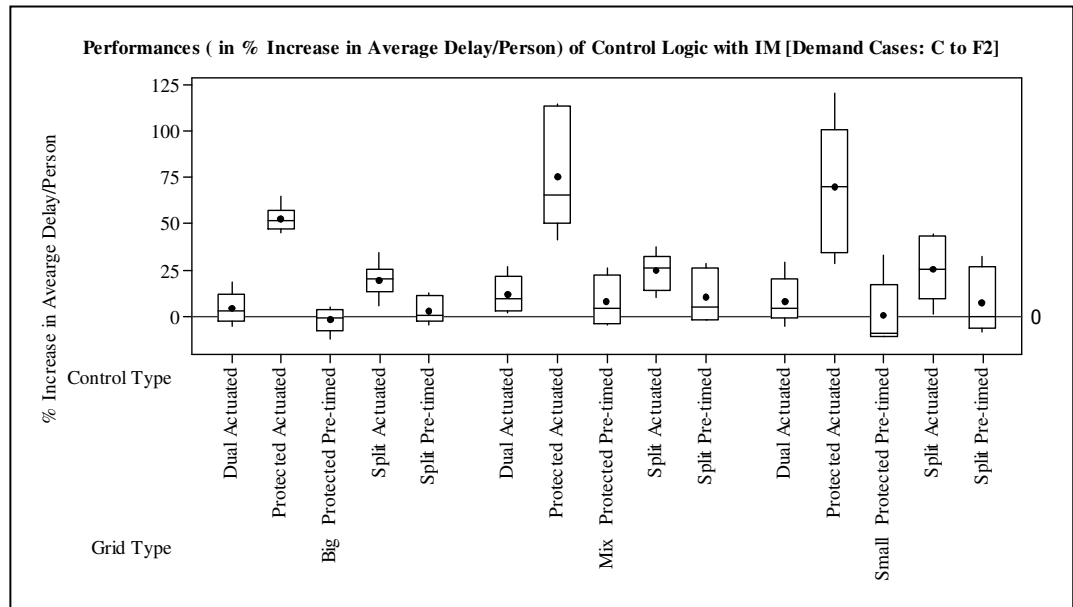
Figure 6.15: Relative efficiency performance (in *% Average Delay/Person*) of various control (with IM) and grid types
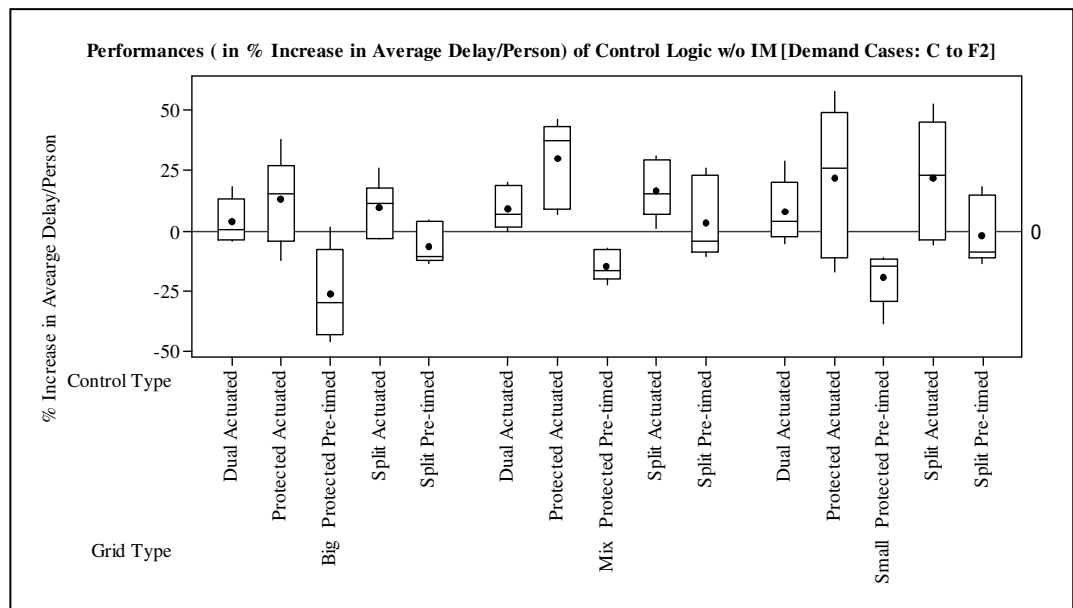
Figure 6.16: Relative efficiency performance (in *% Average Delay/Person*) of various control (without IM) and grid types

167

The pattern of efficiency measure for the *Average Trip Time/Person* (See Figure 6.17) in the case of the control with IM, is identical to that of the efficiency measure for *Average Delay/Person* (See Figure 6.15). The pattern is almost the same but with different relative performance measures.
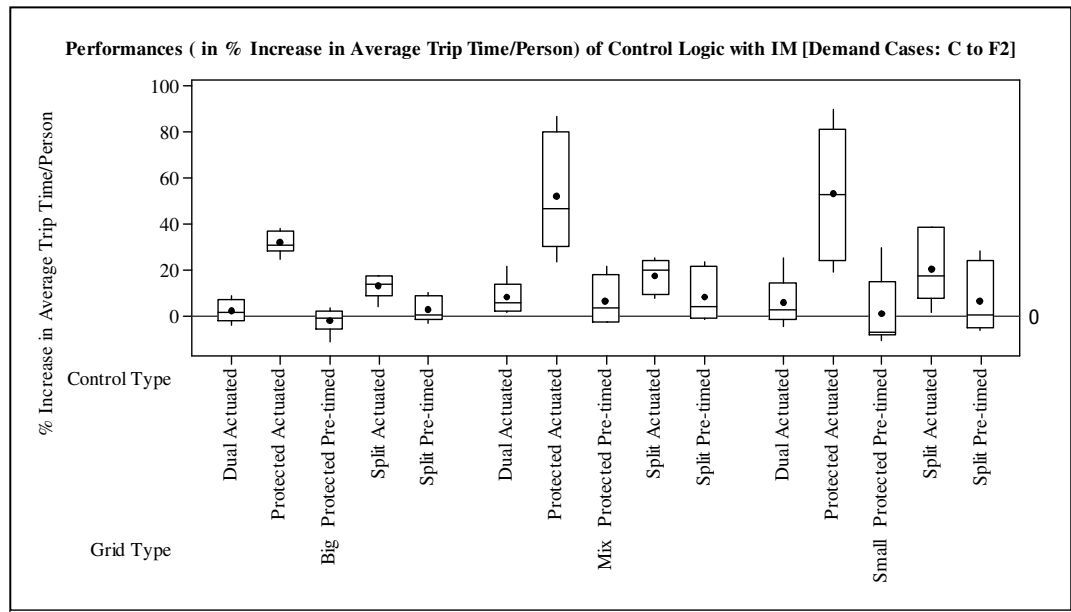
Figure 6.17: Relative efficiency performance (in *% Average Trip Time/Person*) of various control (with IM) and grid types

On the other hand, the pattern of efficiency measure for the *Average Trip Time/Person* measure (See Figure 6.18) in the case of the control without IM, is identical to that of the efficiency measure of *Average Delay/Person* (See Figure 6.16). The pattern is almost the same but with different relative performance measures.

The similar performance of these two efficiency measures could be attributed to the fact that average travel time is primarily affected by delay time, since moving time is approximately equal for a specific network topology and demand case. That

is, the control types primarily affect the delay time (not the moving time), and as such the travel time (comprising moving and delay times) pattern is the same as the delay.
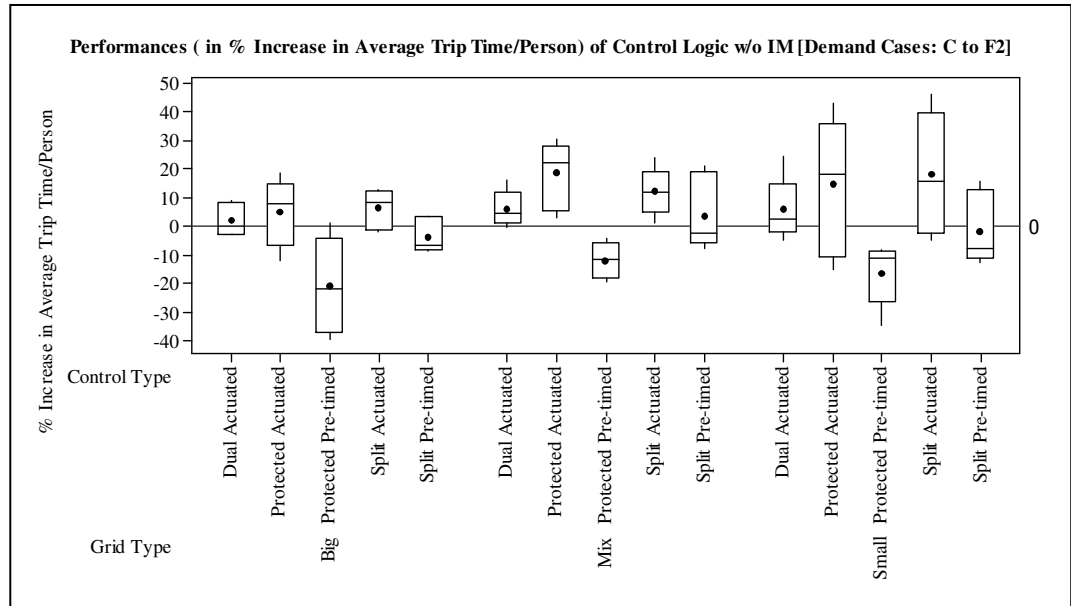
Figure 6.18: Relative efficiency performance (in *% Average Trip Time/Person*) of various control (without IM) and grid types

Based on the discussion above, this study summarizes the findings of the productivity and efficiency performance of the proposed integrated signal control system logic for different phase control type (See Table 6.2). The table shows the cases at which the proposed control types outperform the performance of the corresponding CORSIM built-in signal control system, under the same prevailing network topology and demand cases. The cells with a "Yes" entry indicate that the "column" control system (with or without IM) outperform the CORSIM-based logic in the case of a "row" demand case. It is evident that the Split pre-timed proposed logic is the best.

169

Table 6.2: The proposed control types outperforming the corresponding CORSIM-based control

Dem-and Case	Type of measure	Dual Actuated		Protected Actuated		Protected Pre-timed		Split Actuated		Split Pre-timed	
		With IM	W/O IM	With IM	W/O IM	With IM	W/O IM	With IM	W/O IM	With IM	W/O IM
A	Productivity	-	-	-	-	-	-	-	-	-	Yes
	Efficiency	-	-	-	-	-	-	-	-	Yes	Yes
B	Productivity	-	-	-	-	Yes	Yes	-	-	Yes	Yes
	Efficiency	-	-	-	-	Yes	Yes	-	-	Yes	Yes
C	Productivity	-	-	-	-	Yes	Yes	-	-	Yes	Yes
	Efficiency	-	-	-	-	Yes	Yes	-	-	Yes	Yes
D	Productivity	-	-	-	-	-	-	Yes	Yes	Yes	Yes
	Efficiency	-	-	-	-	Yes	Yes	-	-	Yes	Yes
E1	Productivity	Yes	Yes	-	-	-	-	Yes	Yes	Yes	Yes
	Efficiency	-	-	-	-	Yes	Yes	Yes	-	Yes	Yes
E2	Productivity	-	-	-	-	-	-	Yes	Yes	Yes	Yes
	Efficiency	-	-	-	-	-	-	Yes	-	-	Yes
F1	Productivity	Yes	Yes	-	-	-	-	-	-	Yes	Yes
	Efficiency	Yes	Yes	-	-	-	-	-	-	-	-
F2	Productivity	-	-	-	-	-	-	-	-	Yes	Yes
	Efficiency	-	-	-	-	-	-	-	-	-	-

It should be noted that the analysis above was carried out using a fixed incident location (for each network type, an incident was introduced on Lane 1 of one incoming approach link to one of the network intersections). To assess the stability of the proposed control logic, and its ability to handle incidents at different locations, incidents at various locations were introduced. The following section will address the effect of incident location on the control performance.

6.3.3 Stability of the Proposed Control Logic under Various Incident Scenarios

In order to test the stability of the integrated control logic and it's apparently better performing phase settings in medium and heavy traffic demand scenarios, some additional incident models were developed with incidents generated on Lane 2 or Lane 3.

170

In carrying at this analysis, only the best performing three control types (under demand cases D, E1, and F1) were considered, namely the Dual Actuated, Split Actuated and Split Protected. For these demand cases, incidents were generated on Lane 2 on the link between intersection 24 and 25 (Figure 5.2). The duration of this incident is 15 minutes, with a starting time at the 1800th simulation second. Similarly, Lane 3 incidents were generated on the link between intersection 9 and 10 (Figure 5.2). These incidents also start at the 1800th simulation second, with a 20-minute duration.

Table A3.5 through A3.8 (in Appendix 3) summarize the comparative performance of the three control systems in the case of the Lane 2 or Lane 3 incidents, in terms of *Bus Trips* and *Person Trips, Average Delay/Person* and *Average Trip Time/Person*, respectively.

Figures 6.19 and 6.20 illustrate the productivity measures (*Person Trips*) for the proposed integrated control logic with IM and without IM, respectively, against the CORSIM-based control system, when incidents were generated on other lanes (Lane 2 or Lane 3). Similarly, Figure 6.21 and 6.22 illustrate the efficiency performance measures (*Average Trip Time/Person*) for the proposed integrated control logic with IM and without IM, respectively, against the CORSIM-based control system, where incidents have been generated on the other lanes (Lane 2 or Lane 3).

171

The Dual Actuated Control

The proposed Dual Actuated type (both with and without IM) generally outperforms the CORSIM-based control system in *Person Trips* as indicated in Figure 6.19 and 6.20. However, Dual Actuated with IM shows some slight loss of productivity in the small grid case. On the other hand, Figures 6.21 and 6.22 indicate that the Dual Actuated control with IM produces a relatively higher trip time per person than that of the same control logic without IM every the grid network.
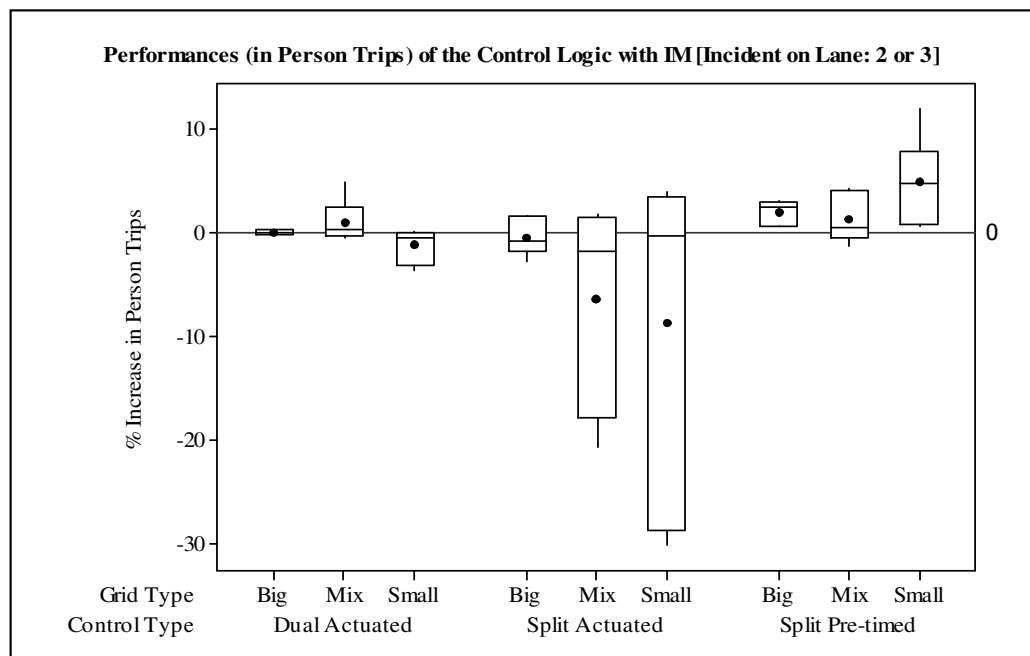
Figure 6.19: Relative productivity performance (in *% Person Trips*) for various control (with IM), grids and incident conditions
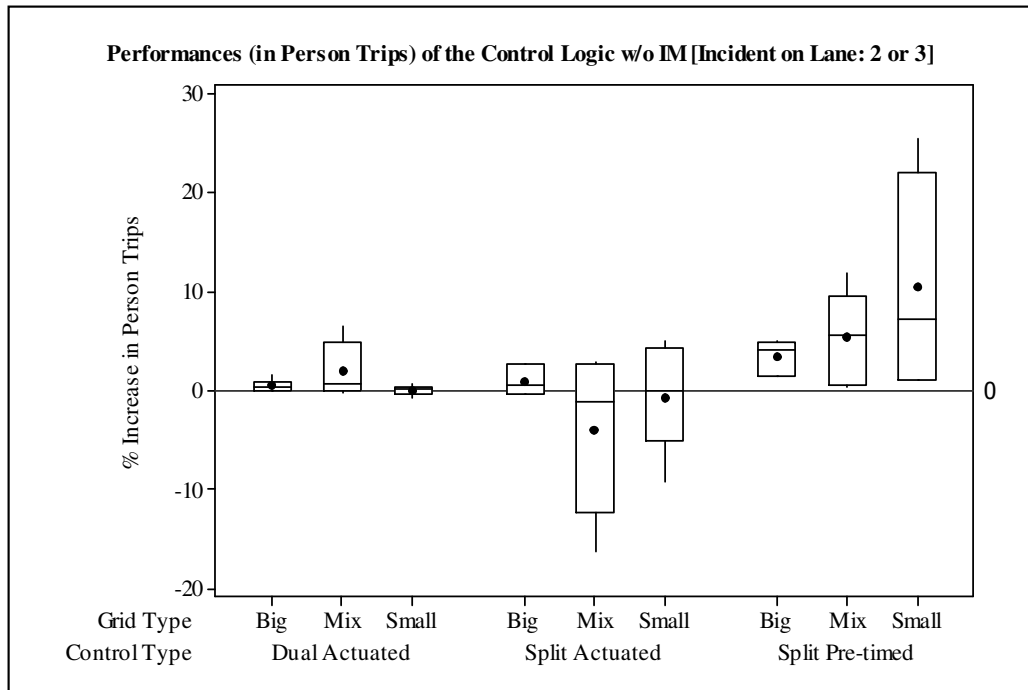
Figure 6.20: Relative productivity performance (in *% Person Trips*) for various control (without IM), grids and incident conditions
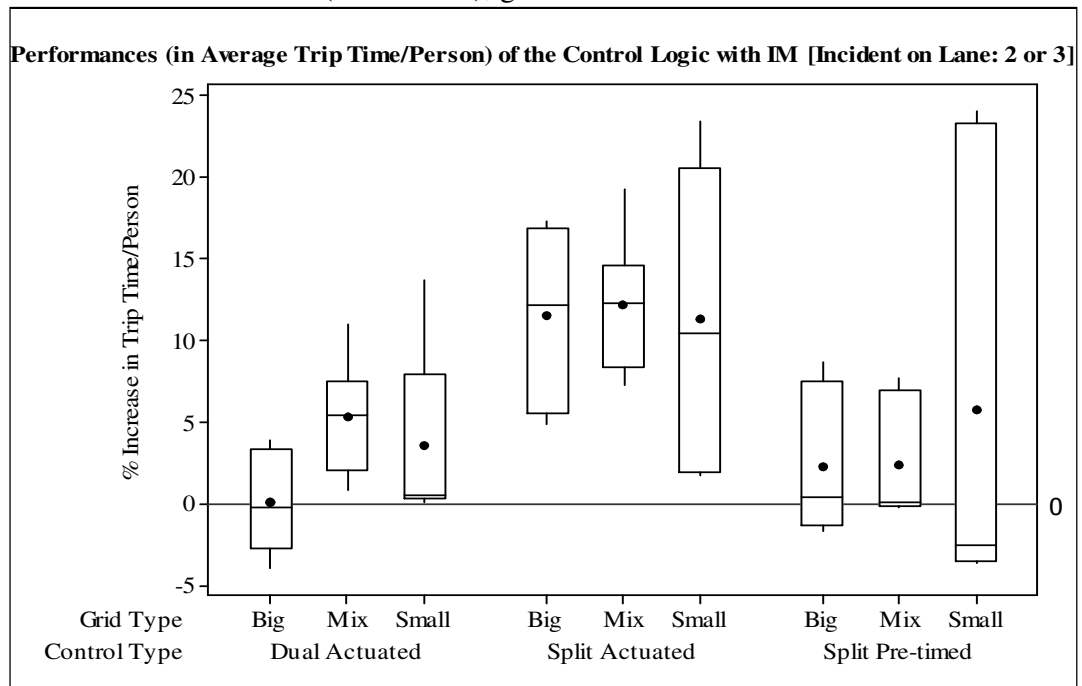
Figure 6.21: Relative efficiency performance (in *% Average Trip Time/Person*) for various control (with IM), grids and incident conditions
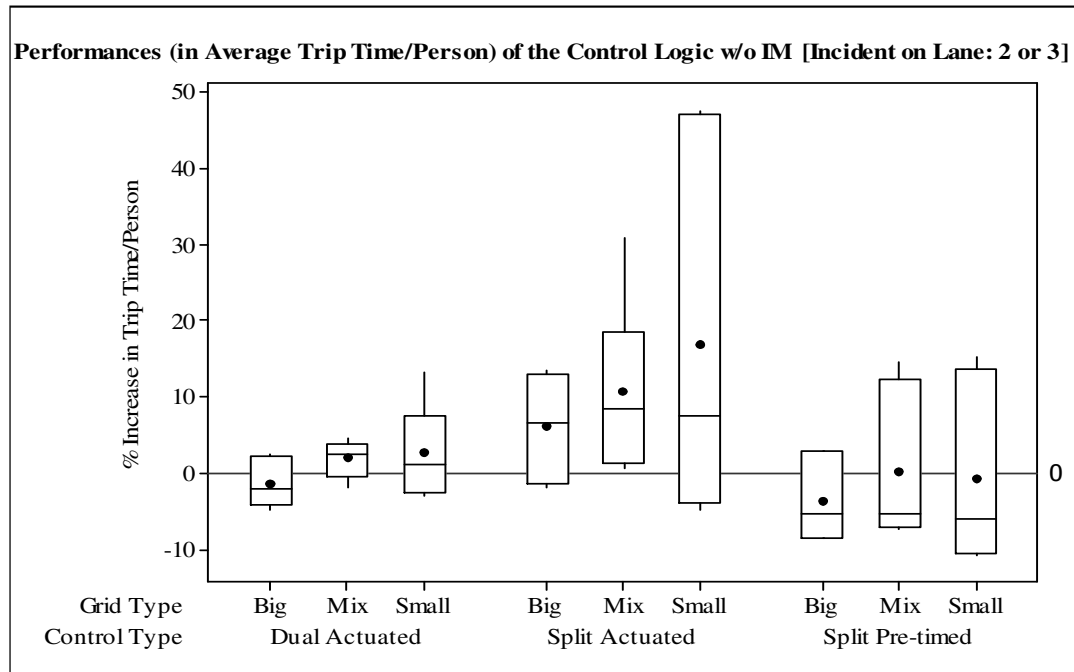
Figure 6.22: Relative efficiency performance (in *% Average Trip Time/Person*) for various control (without IM), grids and incident conditions
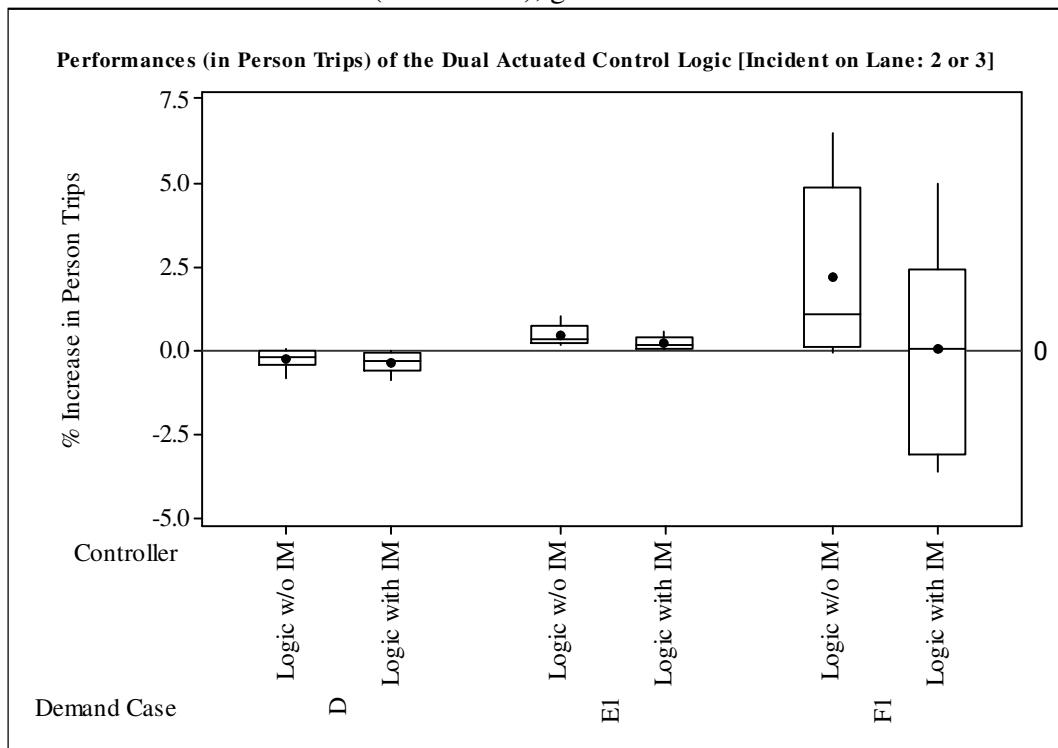
Figure 6.23: Relative productivity performance of Dual Actuated control (in *% Person Trips*) for various incidents and demand cases

174

Figure 6.23 exhibits the stable and comparable performance of the Dual Actuated logic under various demand cases, with only slight variation in the case of F1.

The Split Actuated Control

The integrated control logic of Split Actuated type (both with and without IM) shows a comparable productivity performance (in *Person Trips*) against the existing control system on the big grid network (See Figures 6.19 and 6.20). However, the level of productivity of this control logic deteriorates with the mix grid and small grid networks. Also, this control logic with IM performs worse than that of the logic without IM for different grid types.
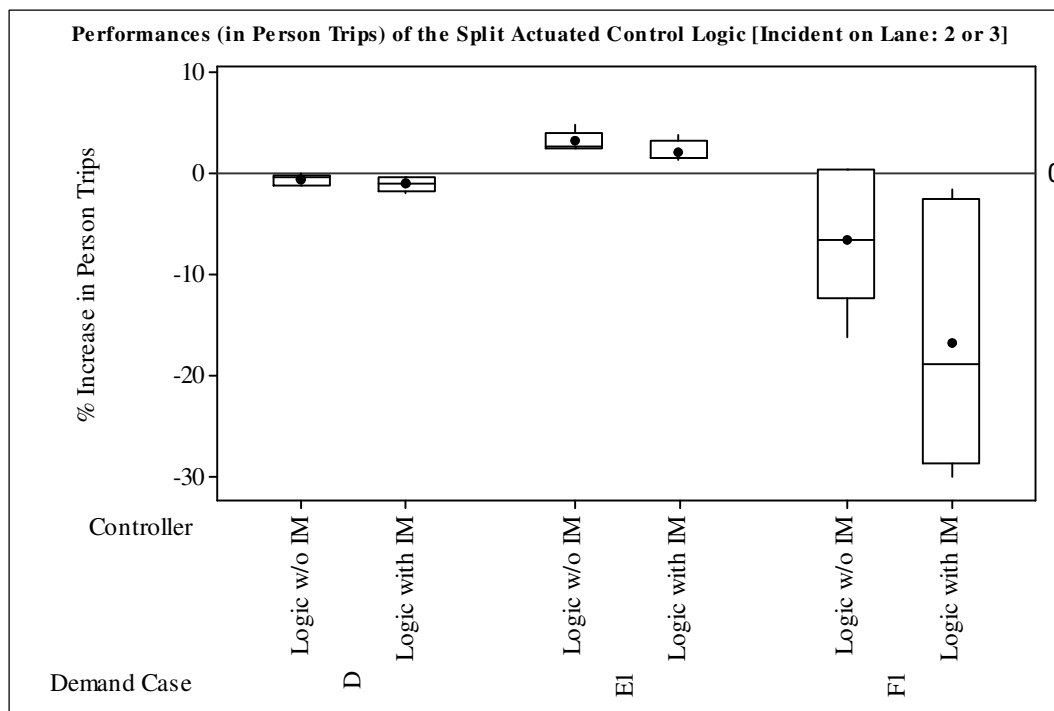
Figure 6.24: Relative productivity performance of Split Actuated control (in *% Person Trips*) for various incidents and demand cases

On the other hand, this control logic without IM shows the worst efficiency performance with significant increases in delays (See Figures 6.21 and 6.22) for the small grid network while loaded with heavy traffic demands. Figures 6.24 and 6.25 also show that this control logic performs worst in both productivity and efficiency for the demand case F1. The comparable productivity performance is observed in demand case D. It has a more productive output in demand case E1. Also, this control logic (without IM) incurs less *Average Trip Time* for demand case E1 (Figure 6.25).
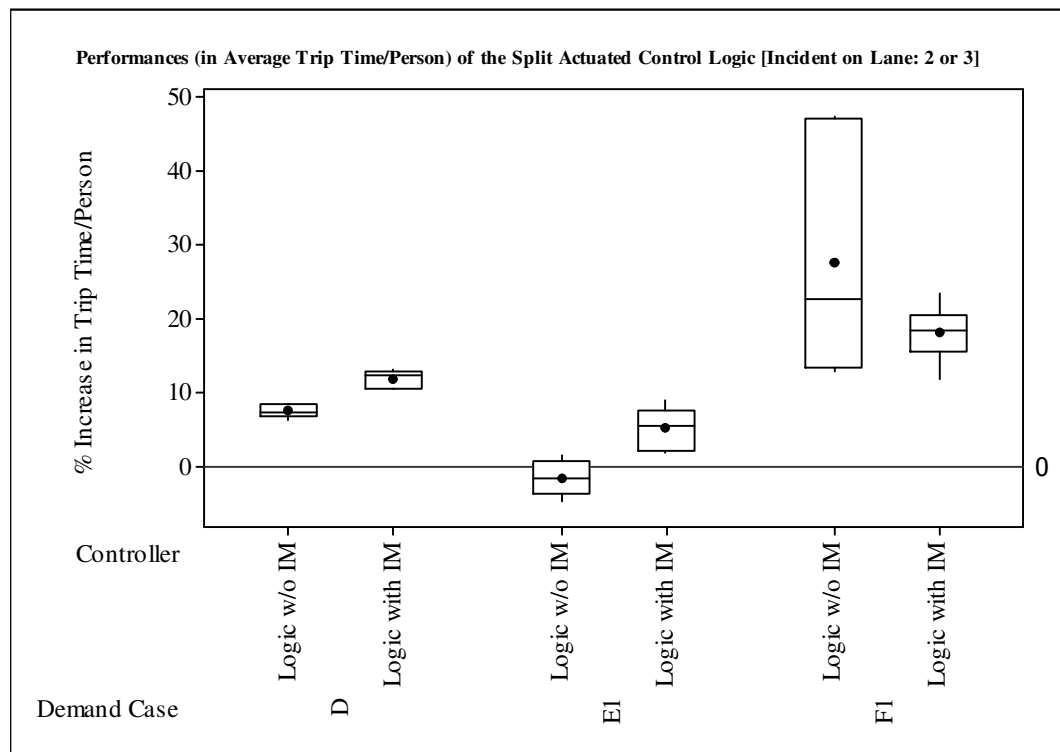
Figure 6.25: Relative efficiency performance of Split Actuated Control (in *% Average Trip Time/Person*) for various incidents and demand cases

The Split Pre-timed Control

The Split Pre-timed control type (with and without IM) outperforms the existing control logic in productivity every grid network type. More interestingly, it performs even better in cases of small grid networks, with significant increases in productivity (Figures 6.19 and 6.20). The control logic without IM performs better than the control logic with IM. On the other hand, the logic without IM shows comparable efficiency (in terms of *Average Trip Time/Person*) every grid network types (Figures 6.21 and 6.22).
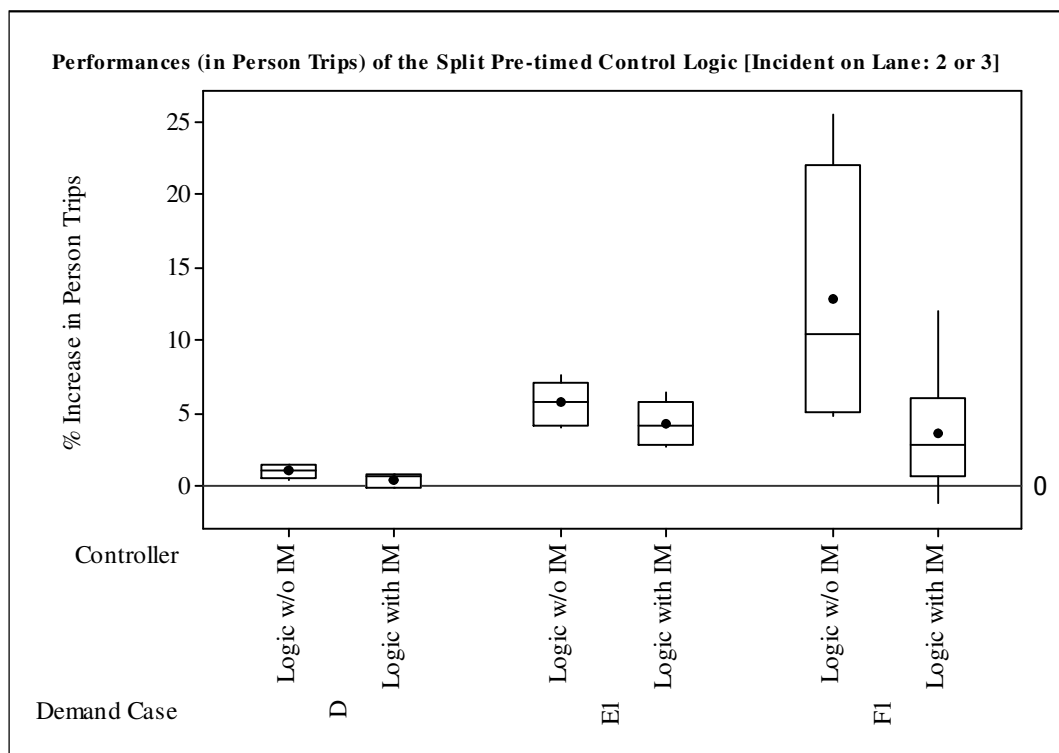
Figure 6.26: Relative productivity performance of Split Pre-Timed Control (in *% Person Trips*) for various incidents and demand cases

This control logic outperforms the CORSIM-based control in *Person Trips* in demand cases D, E1 and F1 (Figure 6.26). Furthermore, Figure 6.27 shows that for demand cases D and E1, this control logic produces even shorter trip times per person.
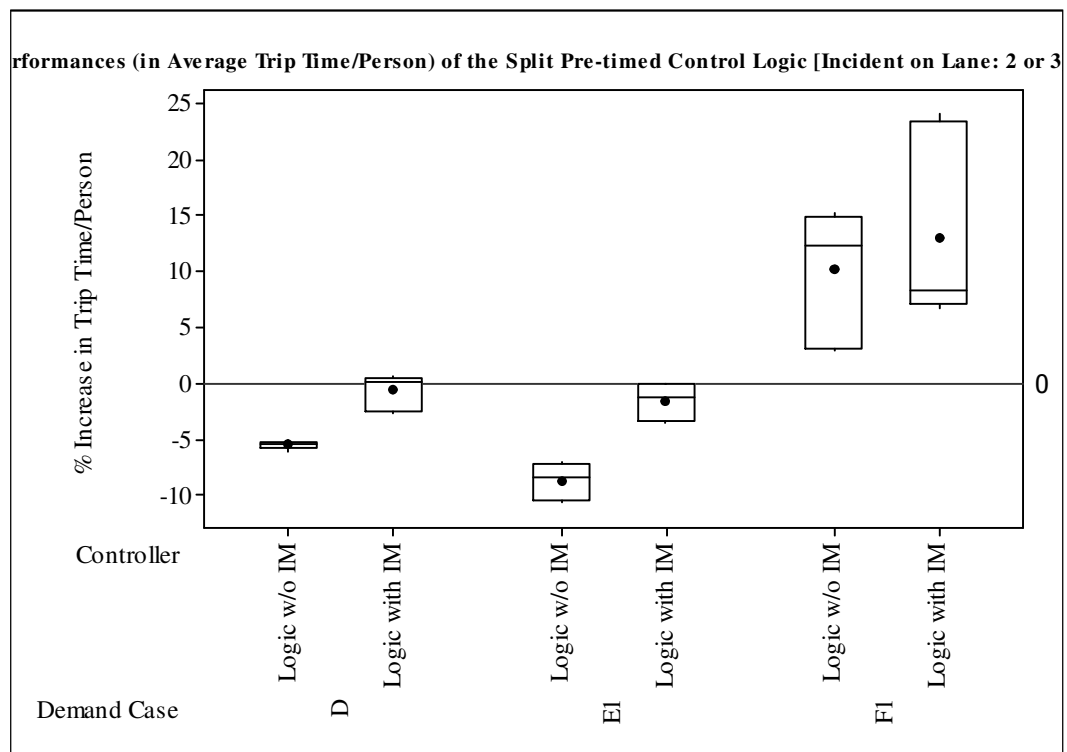
Figure 6.27: Relative efficiency performance of Split Pre-Timed Control (in *% Average Trip Time/Person*) for various incidents and demand cases

A wide variety of traffic demand levels, different grid network types, and different incident scenarios, reflecting different durations and incident locations were tested. It can be concluded that the Dual Actuated control logic performs in a relatively stable manner with comparable levels of output against the existing CORSIM-based control system. The Split Pre-timed logic mostly shows outstanding

productivity performance in every scenarios. The Protected Pre-timed logic performs better for cases of low demand to relatively heavy demand cases. The Split Actuated logic performs better in the case of relatively medium to slightly heavy traffic demand levels. It can be also concluded that generally the control logic without IM performs better than the same control logic with IM.

6.4   Analyses of Performance Results

The proposed control logic results in a better productivity performance in medium and high demand cases. As per the formulation of the *congestion indicator of an individual phase*, ϕ_j (J_{i,ϕ_j}^t), the logic gives higher penalty values to the phase set with an indication of incident condition, higher car queue lengths and a greater number of buses. On the other hand, for low traffic demand conditions, both the on-line Incident Detection Rate (IDR_{on}) and on-line False Alarm Rate (FAR_{on}) are lower, leading to low incident alarms (See Chapter 4). Moreover, the number of buses and the number of car queue lengths are relatively low, and as such, the proposed logic is not expected to achieve a better performances then CORSIM-based control systems.

The proposed control logic results in better productivity (higher bus trip throughput) for almost all medium to heavy demand levels. The exact figure for each of the demand models is listed in Table A3.1 (in Appendix 3). The reason could be that the coefficient for bus priority ($\beta_{i,\phi_j,u^\prime}^p$) was assigned a relatively high value compared to other coefficients in estimating the *congestion indicator of an individual*

phase (J_{i,ϕ_j}^t). The higher penalty values assigned to bus priority, the more frequent switching to the phase set(s) for a higher number of buses.

The proposed control logic exhibits better efficiency without the *Incident status module* (IM) option. This might be attributed to the following facts:

- The online IM module can result in some false alarms represented by the on-line FAR_{on} (%). As such, it may falsely label some-non incident conditions as incidents, resulting in higher penalty value to the associated incident phase(s) by the coefficient of incident ($\beta_{i,\phi_j,u\prime}^N$). This could result in unnecessary phase switching(s) and more delays.

- Given that the implemented base Logit model in the proposed control was derived from the calibration data of a split pre-timed signalized network (See Chapter 4), the logic performs relatively better with such control setting as compared to the other signal settings.

- The base Logit model was developed using calibration data representing an isolated pre-timed traffic intersection with different link length condition than that of the adopted network to test the control logic itself. Therefore, this condition might have affected in the predicted outcome of the Logit model.

With the Split Pre-timed phase settings, the integrated control logic shows better productivity performance(s) even for the relatively short link length grid networks (small and mix grid types). The reason could be that vehicle queue length accumulates faster on short links than on relatively longer links. This leads to higher

$r_{i,\phi_j,u/}^{V,t}$ (*ratio of the vehicle queue length* over the physical capacity of the corresponding link length). As such, higher penalties are given to the approaches with higher values of $r_{i,\phi_j,u/}^{V,t}$ through the application of the penalty coefficient of $\beta_{i,\phi_j,u/}^{V}$ (coefficient for *virtual queue of vehicles* on the *upstream* approach link). This results in favoring the phase set (s) associated with upstream shorter link length.

At low traffic volume levels, for the CORSIM-based actuated signals, the actuation call of the opposite phase can be served green at the *same instant* if any of the max-out or gap-out conditions prevails. This helps in minimizing the delay in a low traffic volume scenario. On the other hand, the proposed control logic makes the decision, either to extend green (for the current phase set) or allocate green to another deserving candidate phase set, after a *decision time interval* of $\Delta g_{i,\Phi_k}$ (i.e. the green extension time). Given that the counts such as $C_{i,\phi_j,u/}^{c,t}$ are updated at each detector data aggregation time interval (Δt), which may come after the next decision time interval, there is a chance of delay in making the appropriate decision by the actuated controller in cases of low demand levels.

For high demand levels, the protected control logic (with and without IM) results in worse performance (both productivity and efficiency) compared to the CORSIM-based one. The protected logic (See Chapter 3) assigns separate phases to left and through movements. The left most lane of the approach is used by both movements, then the left turning vehicles use the left turning pocket(s). At such high demands, with high left turns likely, it is expected to encounter frequent spill backs on left turning pockets (when the left turn volumes exceed the capacity of the left turn

181

pockets). This will lead to underestimating the car counts by the upstream detectors of the odd (left turning) phases, and overestimating the car counts on the even (through) phases. This subsequently leads to higher *congestion indicator* (J^t_{i,ϕ_j}) for the even (through) phases traffic, and lesser values for the odd (left) phases, which in turn leads to the more frequent switching (or preference) to serve the even (through) phase(s). This makes the situation worse and leads to more excessive delays on the left turning phases coupled with more queue spill back (on the left most lane of the approach adjacent to the turning pockets). This spill back may even extend to obstruct the upstream intersection by blocking vehicles from passing the upstream intersection of the spill back approach. This leads to considerable productivity and efficiency degradation.

In the case of split control settings and high demand levels, where both left and through movements on a link are served concurrently, the estimates for actuation index of the various phases are more accurate (than that of the protected settings). This, in turn, helps the split logic to properly switch to the most deserving candidate phase(s). This is the reason why the split logic performs relatively better than the protected logic at such high demand levels.

6.5   Model Coefficients Sensitivity Analyses

To assess the impact of the various parameters (of the actuation index formula presented in Chapter 3), on the productivity and efficiency measures of the proposed control logic, a set of simulation experiments were conducted (See Chapter 5: Section 5.4). The presented analyses and results are limited to one actuated and one pre-timed controller (Dual Actuated and Split Pre-timed), and to the two demand cases of

medium (C) and heavy (F2). The demand case C was trialed on the small grid network, and the F2 case was piloted on the mix grid network. The base values of the coefficients of the control logic are shown in Table 6.3.

Table 6.3: The base coefficients of the Dual Actuated and Split Pre-Timed control types

Coefficient	Dual Actuated	Split Pre-timed
$\beta^V_{i,\phi_j,u\prime}$ (Coeff. of Virtual Queue)	1000	1000
$\beta^N_{i,\phi_j,u\prime}$ (Coeff. of Incident Penalty)	10	10
$\beta^p_{i,\phi_j,u\prime}$ (Coeff. of Transit Priority)	100	500
$\beta^B_{i,\phi_j,d\prime}$ (Coeff. of Downstream Blockage)	3	3

For each demand case and control logic the value of a specific coefficient varied while keeping the base values of the remaining coefficients fixed. Then, all the models with individually varied coefficients are combined together. This helps in analyzing the pair-wise performance behaviour of each pair of coefficients for each demand case and control logic type. Tables 6.4 and 6.5 summarize the resulting performance associated with the various parameters (for the two control types and the demand cases C and F2). The shaded cells of the tables show the performance measures associated with the base values of the four coefficients.

Table 6.4: Sensitivity analyses of the coefficients of Dual Actuated logic

	$\beta^V_{i,\phi_j,u\prime}$	$\beta^N_{i,\phi_j,u\prime}$	$\beta^p_{i,\phi_j,u\prime}$	$\beta^B_{i,\phi_j,d\prime}$	Bus Trips	Person Trips	Average Trip Time/Person
Demand Case C							
Variations in $\beta^V_{i,\phi_j,u\prime}$	10	10	100	3	89	27999	297
	100	10	100	3	90	27996	301.8
	500	10	100	3	90	27963	301.3
	1000	10	100	3	89	27933	302.6
	5000	10	100	3	89	27999	302.6
Variations in $\beta^N_{i,\phi_j,u\prime}$	1000	10	100	3	89	27933	302.6
	1000	100	100	3	88	27802	311.6
	1000	500	100	3	88	27892	308.6
	1000	1000	100	3	89	27945	309.8
	1000	5000	100	3	88	27886	310.7
Variations in $\beta^p_{i,\phi_j,u\prime}$	1000	10	10	3	88	27901	302.5
	1000	10	100	3	89	27933	302.6
	1000	10	500	3	88	27901	302.5
	1000	10	1000	3	89	27990	308.4
	1000	10	5000	3	89	27990	308.4
Variations in $\beta^B_{i,\phi_j,d\prime}$	1000	10	100	2	89	27933	302.6
	1000	10	100	3	89	27933	302.6
	1000	10	100	4	89	27933	302.6
	1000	10	100	10	89	27933	302.6
Demand Case F2							
Variations in $\beta^V_{i,\phi_j,u\prime}$	10	10	100	3	210	55929	864.1
	100	10	100	3	196	52298	810.9
	500	10	100	3	210	55816	846.3
	1000	10	100	3	210	57614	886.6
	5000	10	100	3	210	55929	864.1
Variations in $\beta^N_{i,\phi_j,u\prime}$	1000	10	100	3	210	57614	886.6
	1000	100	100	3	216	56340	876.4
	1000	500	100	3	198	53208	908.2
	1000	1000	100	3	206	55306	943.2
	1000	5000	100	3	206	54558	948.4
Variations in $\beta^p_{i,\phi_j,u\prime}$	1000	10	10	3	213	56789	857.6
	1000	10	100	3	210	57614	886.6
	1000	10	500	3	205	55096	846
	1000	10	1000	3	199	54376	861.6
	1000	10	5000	3	218	56902	844.9
Variations in $\beta^B_{i,\phi_j,d\prime}$	1000	10	100	2	211	57078	840.6
	1000	10	100	3	210	57614	886.6
	1000	10	100	4	204	55896	841.7
	1000	10	100	10	204	56246	846.5

Table 6.5: Sensitivity analyses of the coefficients of Split Pre-timed logic

	$\beta^V_{i,\phi_j,u/}$	$\beta^N_{i,\phi_j,u/}$	$\beta^p_{i,\phi_j,u/}$	$\beta^B_{i,\phi_j,d/}$	Bus Trips	Person Trips	Average Trip Time/Person
Demand Case C							
Variations in $\beta^V_{i,\phi_j,u/}$	10	10	500	3	90	27506	387.7
	100	10	500	3	90	27496	380.1
	500	10	500	3	90	27517	382
	1000	10	500	3	90	27477	378
	5000	10	500	3	90	27531	378.1
Variations in $\beta^N_{i,\phi_j,u/}$	1000	10	500	3	90	27477	378
	1000	100	500	3	90	27360	405.1
	1000	500	500	3	88	27160	429.4
	1000	1000	500	3	89	27154	438.7
	1000	5000	500	3	84	26467	512.4
Variations in $\beta^p_{i,\phi_j,u/}$	1000	10	10	3	90	27517	377.7
	1000	10	100	3	90	27504	379.1
	1000	10	500	3	90	27477	378
	1000	10	1000	3	90	27500	380.2
	1000	10	5000	3	90	27482	381.7
Variations in $\beta^B_{i,\phi_j,d/}$	1000	10	500	2	90	27477	378
	1000	10	500	3	90	27477	378
	1000	10	500	4	90	27477	378
	1000	10	500	10	90	27477	378
Demand Case F2							
Variations in $\beta^V_{i,\phi_j,u/}$	10	10	500	3	192	44982	1052.1
	100	10	500	3	204	50352	1080.9
	500	10	500	3	204	51511	1030.6
	1000	10	500	3	204	51511	1030.6
	5000	10	500	3	187	50403	1060.5
Variations in $\beta^N_{i,\phi_j,u/}$	1000	10	500	3	204	51511	1030.6
	1000	100	500	3	150	41507	1205
	1000	500	500	3	127	37415	1432.1
	1000	1000	500	3	124	35538	1449.8
	1000	5000	500	3	130	34810	1444.9
Variations in $\beta^p_{i,\phi_j,u/}$	1000	10	10	3	143	42873	1010.2
	1000	10	100	3	164	45476	1048.7
	1000	10	500	3	204	51511	1030.6
	1000	10	1000	3	166	44547	958.8
	1000	10	5000	3	174	43342	985.3
Variations in $\beta^B_{i,\phi_j,d/}$	1000	10	500	2	182	49903	1109.2
	1000	10	500	3	204	51511	1030.6
	1000	10	500	4	211	52893	1050.5
	1000	10	500	10	176	46660	1108.9

Figures 6.28 and 6.29 (as well as Figures A4.1 through A4.8 in Appendix 4) illustrate the detailed pair-wise performance of the variations in the coefficients for the two control types and demand cases. The variations are explained by the mean

percent of changes from the measure of the base case(s). In these figures, each cell presents the performance measure of the specific coefficient (named at the bottom the column) while coupled with variations of other coefficients (named on the right-side or left-side).

6.5.1 Model Coefficients Sensitivity Analyses (Dual Actuated Control)

Individual Coefficient Variations (Demand Case C)

Variations of the *virtual queue of vehicles* coefficient (from its base value) results in slightly higher (0.2%) *Person Trips* and slightly lower (-1.9%) *Average Trip Time/Person* than those of the base case (as shown in Table 6.4). Almost no change in *Bus Trips* is observed with variation of this coefficient. The decrease in travel time was observed with slightly lower values to the base coefficient.

Variations in *incident penalty* coefficient results in a slight decrease of *Person Trips* (-0.5%) and a slight increase in *Average Trip Time/Person* (2.7%). An insignificant change in *Bus Trips* is observed with this coefficient.

Variations in *transit priority* coefficient results in slight fluctuations of *Person Trips* (within 0.2%). In contrast, *Average Trip Time/Person* remains the same except for some slight increase (1.9%) with a higher *transit priority* coefficient.

Finally, no change is observed for individual variations of the *downstream blockage penalty* coefficient.

Individual Coefficient Variations (Demand Case F2)

In heavy traffic demand, the variations of the *virtual queue coefficient* results in significantly lower *Person Trips* (- 9.2%) and significantly lower *Average Trip*

Time/Person (- 8.5%), compared to the values of the base case (as shown in Table 6.4). No significant fluctuations in *Bus Trips* are observed, except for $\beta^V_{i,\phi_j,u/} = 100$.

Similar *Person Trips* patterns are observed for individual variations of the *incident penalty*, *transit priority* and the *downstream blockage penalty* coefficients. A slight increase in *Bus Trips* (3.8%) is observed at very high value *transit priority*. An increase in *Average Trip Time/Person* (up to 7%) is observed with the increase of the *incident penalty* coefficient. The variation of the coefficients of *transit priority* and *downstream blockage* result in a reduction in the *Average Trip Time/Person* (5.2%).

Pair-Wise Coefficients Interactions (Demand Case C)

As shown in Figure 6.28, the fluctuations of the mean percent change in *Person Trips* are limited to a very narrow band with the variation of all of the pairs among the coefficients. Also, there is almost no variation of *Person Trips* for the different values of the *downstream blockage* coefficient. Similar patterns of very slight variations are observed in *Average Trip Time/Person* by the pair-wise coefficient interactions (See Figure 6.29).

Pair-Wise Coefficients Interactions (Demand Case F2)

Figure A4.1 shows significant reductions in *Person Trips* with the base value of *virtual queue of vehicles* and the relatively higher *incident penalty* coefficients. Also, interactions of other coefficient pairs show slightly significant to significant reductions in *Person Trips*. The percentage of change in *Person Trips* is limited to within 10% of the base cases.

The percentage of change in *Average Trip Time/Person* is around -5% (See Figure A4.2) from the base case, for interactions with the coefficient of *transit priority* and interactions with the coefficient for *downstream blockage*. For the interaction of the *virtual queue of vehicles* and *incident penalty* coefficients, the deviation of the *Average Trip Time/Person* generally increases with the increase of the *incident penalty* coefficient (limited to within 10%).

In conclusion, the Dual Actuated control logic shows very mild changes in performance measures with the variation of the coefficients (from base values) in medium traffic demand scenarios (C). For the heavy traffic demand cases (F2), slightly significant changes in the measures are noticed, indicating that the adopted base values of the coefficients yield better productivity results.
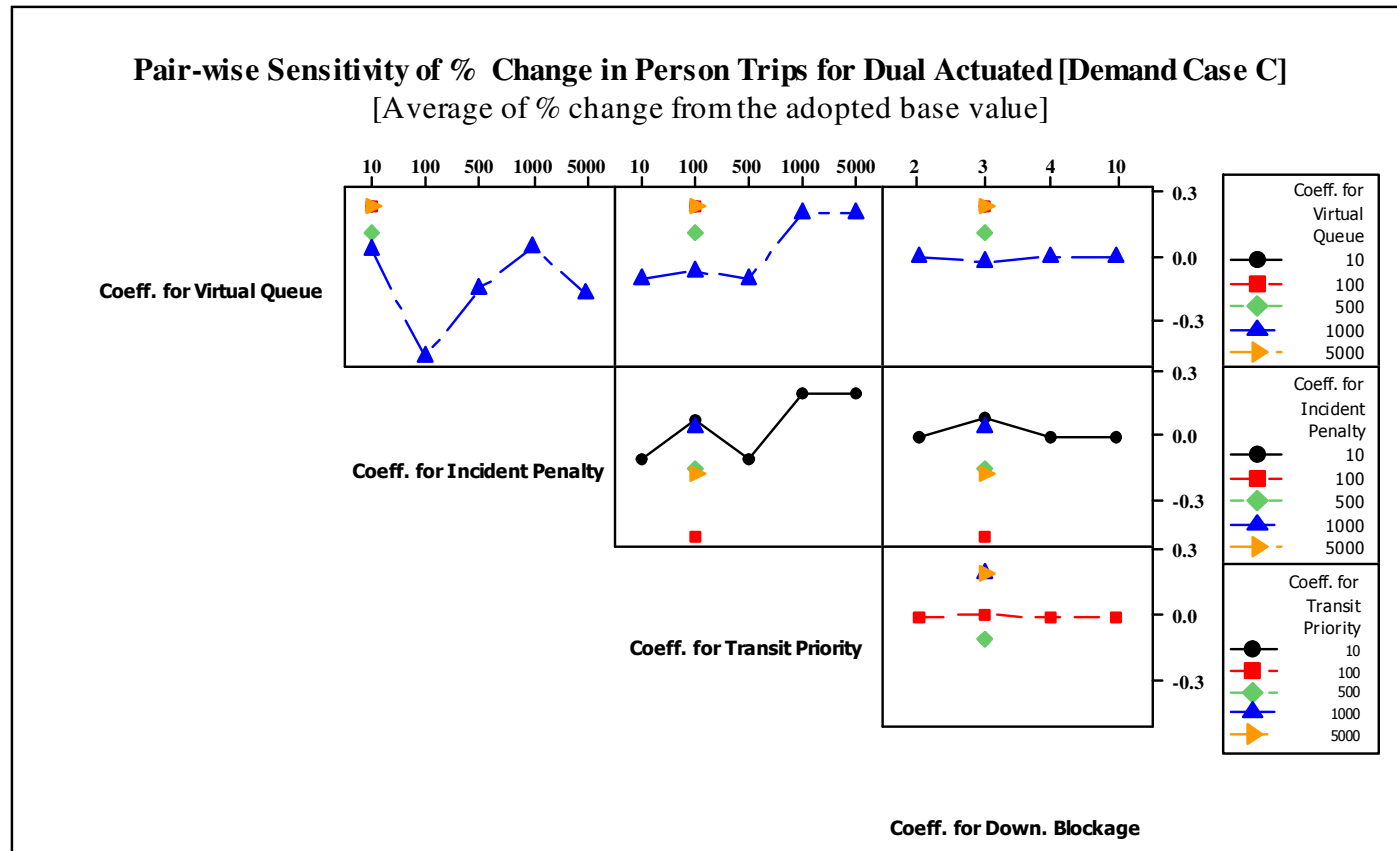
Figure 6.28: Coefficients' sensitivity patterns (*% change of Person Trips*) for Dual Actuated control (Demand Case C)
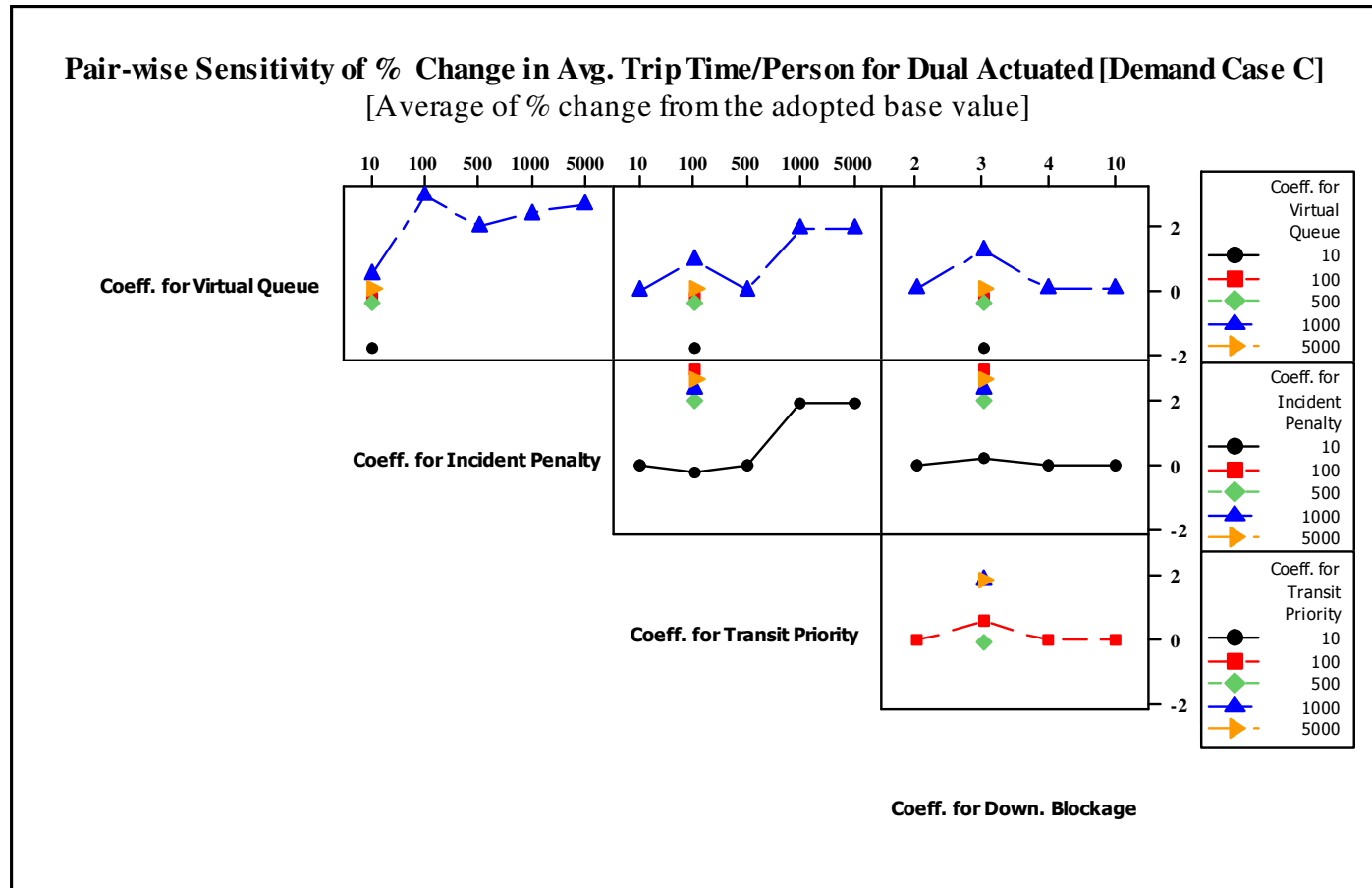
Figure 6.29: Coefficients' sensitivity patterns (% change of *Average Trip Time/Person*) for Dual Actuated control (Demand Case C)

6.5.2 Model Coefficients Sensitivity Analyses (Split Pre-timed Control)

Individual Coefficient Variations (Demand Case C)

The variations of the *virtual queue of vehicles* coefficient (from its base value) result in slightly more (up to 0.2%) *Person Trips* and slightly higher (up to 2.6%) *Average Trip Time/Person* (See Table 6.5). No change in *Bus Trips* is observed with variation of this coefficient. An increase in *Average Trip Time/Person* was observed for the slightly lower values of this coefficient.

The variations in the *incident penalty* coefficient resulted in a slight decrease in *Person Trips* (-3.7%) and *Bus Trips* (up to -6.7%). In contrast, a very significant increase (up to 35.6%) in *Average Trip Time/Person* was observed.

The variations in the *transit priority* coefficient show almost no fluctuations in *Person Trips* (within 0.1%). In contrast, the *Average Trip Time/Person* fluctuates slightly (up to 0.6%). No change in *Bus Trips was* observed.

Variations in the *downstream blockage penalty* coefficient resulted in no change to any of the productivity or efficiency measures for this demand case.

Individual Coefficient Variations (Demand Case F2)

Variations in the *virtual queue of vehicles* coefficient show significantly lower (up to -12.7%) *Person Trips* and significantly higher (4.9%) *Average Trip Time/Person* than those of the base case (See Table 6.4). Also, significantly lower *Bus Trips* (- 8.3%) were observed for $\beta^V_{i,\phi_j,u/} = 5000$.

With the increase in the *incident penalty* coefficient, a considerable reduction in *Bus Trips* (-39.2%) was observed. Also, a considerable reduction in *Person Trips* (-32.4%) and an increase in *Average Trip Time/Person* (40.7%) were observed with variations of this coefficient.

Similarly, a variation in the *transit priority* coefficient resulted in significant reduction in *Bus Trips* (-29.9%) and significant reduction in *Person Trips* (-16.8%). A fluctuation in the *Average Trip Time/Person* (-4.4%) was also observed.

The variation in the *downstream blockage* coefficient resulted in a significant reduction in *Bus Trips* (- 13.7%) and *Person Trips* (- 9.4%). In contrast, an increase in *Average Trip Time/Person* (7.6%) was observed with the variations of this coefficient.

Pair-Wise Coefficients Interactions (Demand Case C)

For pair-wise interactions (Figure A4.3), fluctuations in the mean percent change in *Person Trips* were limited to a very narrow band (up to -4%) with variations of in each coefficient pair. Only, a relatively higher sensitivity in *Person Trips* is found for the variation interactions between the *virtual queue of vehicles* and the *incident penalty* coefficients.

Similar sensitivity patterns were observed in the case of *Average Trip Time/Person*, but in the opposite direction (i.e. higher trip times) (Figure A4.4). Higher sensitivity in the *Average Trip Time/Person* (up to 40%) is found for variation interactions between the *virtual queue of vehicles* and *incident penalty* coefficients.

Pair-Wise Coefficients Interactions (Demand Case F2)

Figure A4.5 shows significant reductions (up to -30%) in *Person Trips* for the variation interactions between the base value of the *virtual queue of vehicles* and the relatively higher *incident penalty* coefficients. Interactions between the other coefficient pairs also show significant reductions in *Person Trips* (-15%).

The change in *Average Trip Time/Person* is about 25% (Figure A4.6) for the interactions of the *transit priority* coefficient and also for interactions involving the *downstream blockage* coefficient. Interactions between the *virtual queue of vehicles* and *incident penalty* coefficients result in significant deviations in *Average Trip Time/Person* (40%), with the deviation typically increasing as the *incident penalty* coefficient increases.

In conclusion, the Split Pre-timed control shows mild changes in the performances measures with the variations of associated coefficients (from the base) in the case of medium traffic demand (C). In contrast, it shows significant fluctuations in performance in a heavy traffic demand case (Case F2).

It was expected that both control types (Split Pre-timed and Dual Actuated) would exhibit stable performances in low to medium traffic demand scenarios. At medium traffic demand, the downstream exit links are mostly uncongested with no spill back, and as such, the controllers become insensitive to variations in the *downstream blockage penalty* coefficient. Slight performance deviations were observed for the Split Pre-timed signal, when the *incident penalty* coefficients interact with the coefficient for the *virtual queue of vehicles*. However, it can be concluded that the level of individual coefficients show stable performances at medium traffic demand level for both control types.

On the other hand, significant deviations are encountered with Split Pre-timed control in heavy traffic demand cases. In such a case, a higher value for the *transit priority* coefficient does not guarantee more *Bus Trips*. *Person Trips* deteriorates with interaction between the *virtual queue of vehicles* and *incident penalty* coefficients. In contrast, the Dual Actuated control shows only slight deviations.

In conclusion, it is evident that both control types perform comparably (both in productivity and efficiency) against the existing CORSIM-based models. The base levels of the individual coefficients for both control types perform better against other variations of these coefficients.

6.6   Conventional Performance Analyses

This chapter has primarily utilized person-based traffic measures in assessing the productivity and efficiency of the proposed control types in various operational scenarios.

Typically, the performance of most other control systems, reported in literature, have been evaluated primarily in terms of *throughput (*in terms of *vehicle trips)* and the *average delay of the vehicle* (in *seconds/vehicle*). Mirchandani and Head (2001) suggested that the offered load, throughput and delay should be measured in assessing the performance of a new signal control strategy. Thus, it is also important to assess the performance of the proposed control system using the same evaluation criteria and measures.

Figures 6.30 to 6.33 present samples of network offered loads (demand) versus the vehicular throughput and delay, for the Split Pre-timed control (in a small grid network) and Dual Actuated control (in a big grid network). Figures A4.7 through A4.26 (Appendix 4) show the throughput and delay values for other grid networks. Furthermore, it shows the conventional measures for two other controllers; Split Actuated and Protected Pre-timed control types.

The offered load is considered to be the number of car trips entering the network for a specific demand case over a period of 1.5 hours of simulation. The throughput is the number of vehicle trips (including car and *Bus Trips*) exiting the

network (obtained from the post-processed output of the simulation run for each demand case).

Figures 6.30 and 6.31 show the throughput and delay for the various load levels (by various demand cases) for Split Actuated control in the case of the small grid network. This small grid network represents the worst case conditions under any level of traffic demand. Figures 6.32 and 6.33 also show the throughput and delay for the Dual Actuated control type in the big grid network.
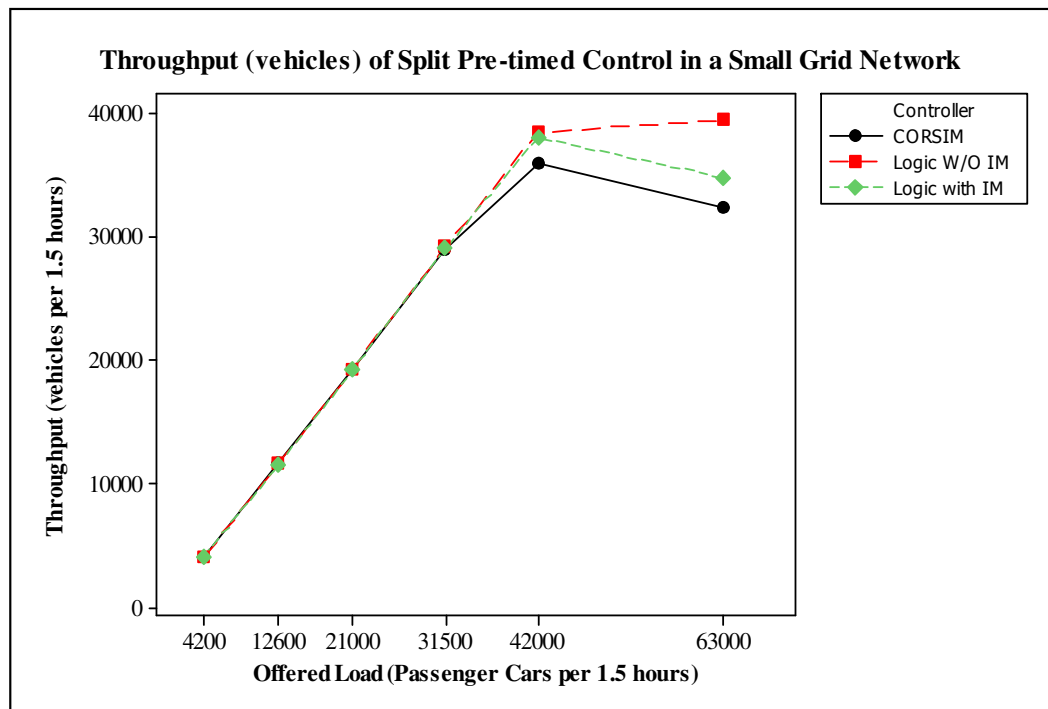
Figure 6.30: Offered load versus throughput for Split Pre-timed in small grid network
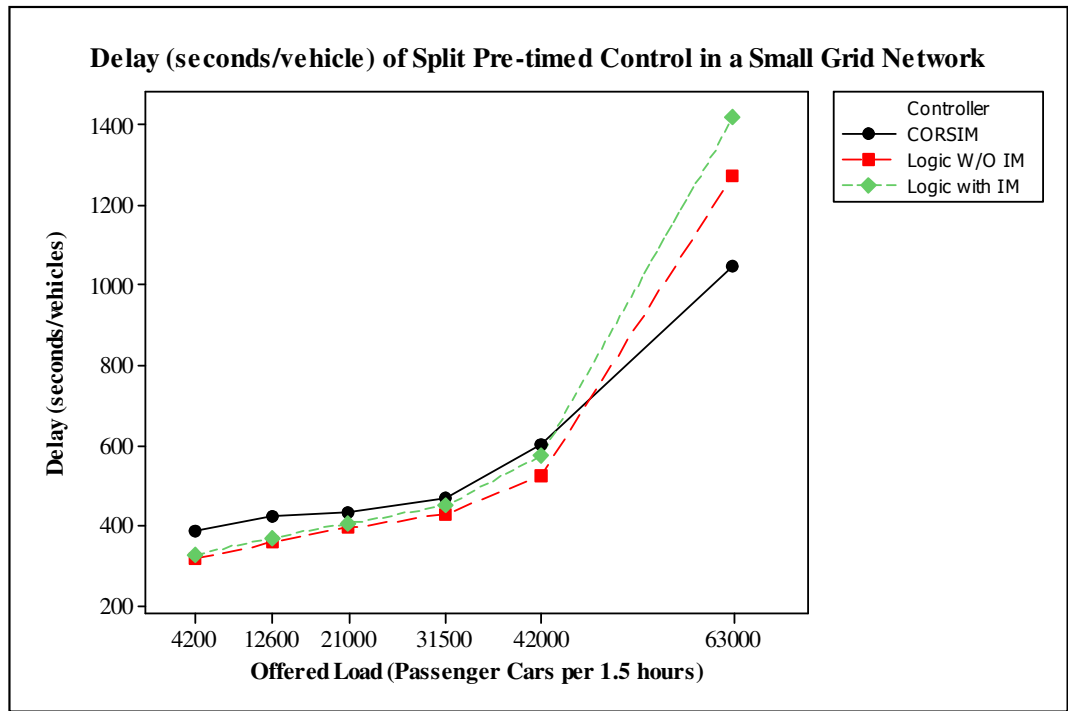
Figure 6.31: Offered load versus delay for Split Pre-timed in small grid network
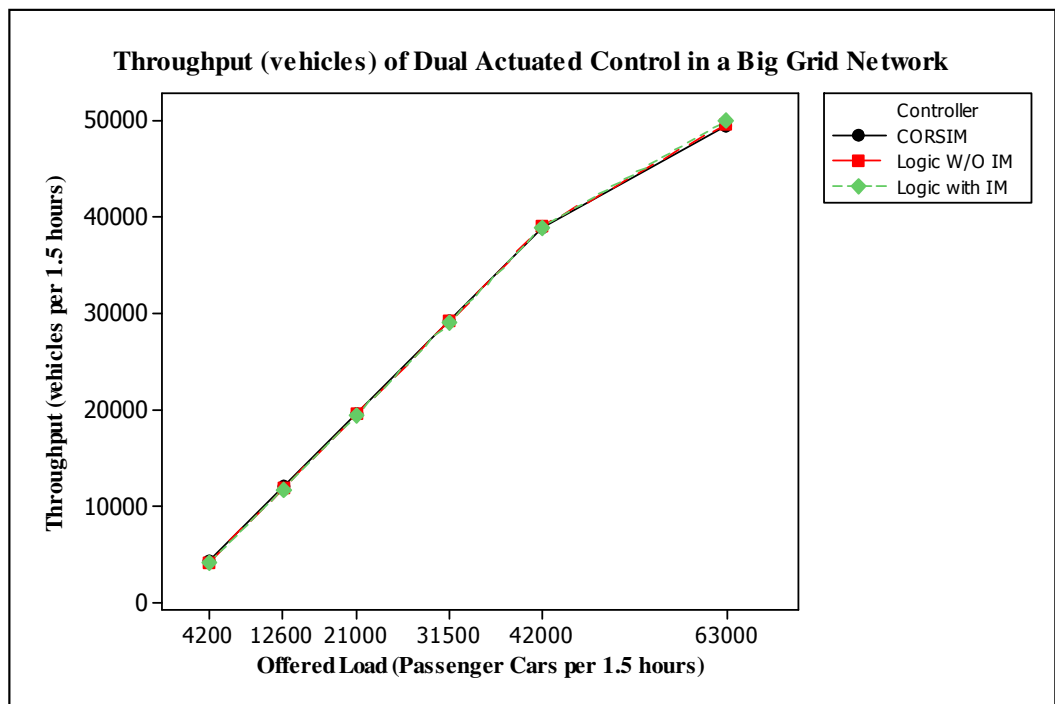
Figure 6.32: Offered load versus throughput for Dual Actuated in big grid network

196

As shown in Figure 6.30, for the small grid network, the Split Pre-timed control logic shows similar vehicular throughput up to demand level (D), and more throughput up to demand level (E1) (Figure 6.31). The small grid network generates the worst case for traffic conditions when loaded with heavy traffic. The Split Pre-timed control logic outperforms the CORSIM-based in producing significant throughput in this small grid network with relatively heavy to extreme congestion levels. Over 1.5 hours of simulation, the Split Pre-timed control logic without IM results in 7,180 more throughput vehicles than that of the CORSIM-based logic, and for the case of Split Pre-timed control logic with IM, the difference in throughput is at least 2,490 vehicles. This huge gain in productivity comes at the expense of sacrificing efficiency levels in terms of delay as shown in Figure 6.31. The productivity and efficiency performances of the Split Pre-timed logic in the mix grid network are shown in Figures A4.7 and A4.8. Also, Figures A4.9 and A4.10 show the performances of the big grid network.

Delay (seconds/vehicle) of Dual Actuated Control in a Big Grid Network
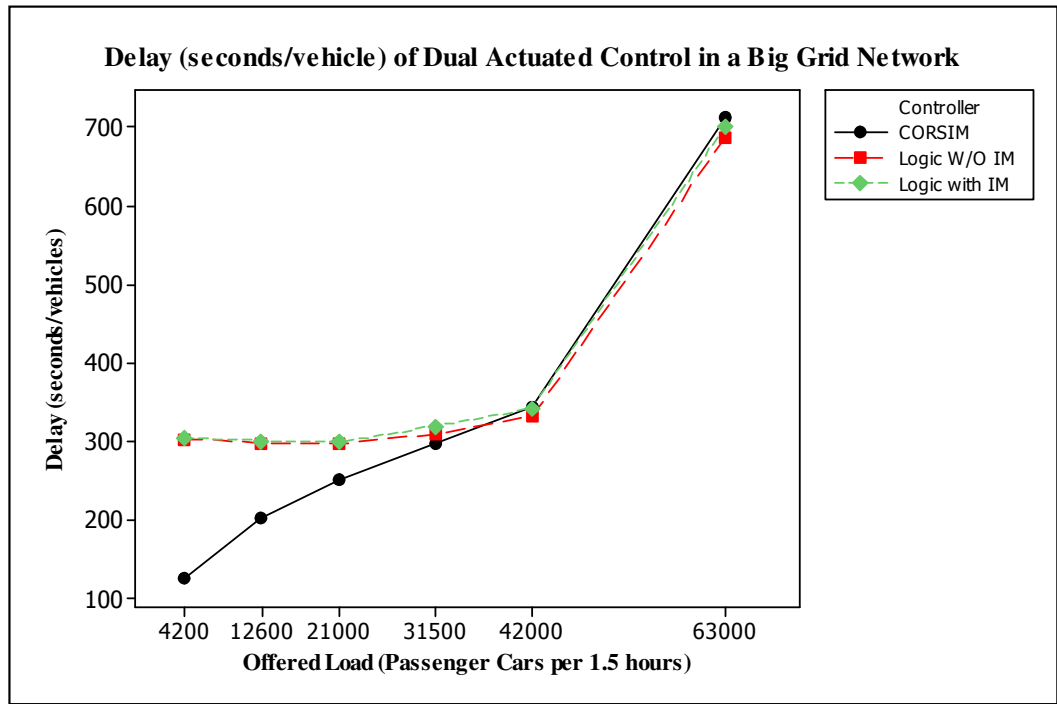
Figure 6.33: Offered load versus delay for Dual Actuated in big grid network

The Dual Actuated control without IM also produces similar throughput in the big grid network for every demand case (Figure 6.32). This control logic seems more efficient in very congested traffic demand cases as shown in Figure 6.33. The similar (or better) throughput in every demand case and better efficiency in very congested cases are also evident for the Dual Actuated logic in the small and mix grid networks as shown in Figures A4.11 through A4.14.

Figures 6.34, 6.35, 6.36 and 6.37 summarize the performance of the Split Pre-timed logic, the Dual Actuated logic, the Split Actuated logic and the Protected Pre-timed logic, respectively, against the existing CORSIM-based one in terms of gains in throughput.

Figures A4.15 and A4.16 indicate similar (and better) throughput and less efficiency for the Split Actuated control logic in the small grid network. It seems

that this control logic performs worse in the most congested demand case (F). Figures A4.17 through A4.20 indicate similar performances for this logic in mix and big grid networks.

Figures A4.21 through A4.26 show the performance of the Protected Pre-timed control logic for small, mix and big grid networks. The logic shows similar (or better) throughput for demand cases (A) through (C). The Protected Pre-timed logic with IM shows better throughput and better efficiency for demand case (D) on the small grid network. The control logic without IM performs worse with increasing traffic demand levels (D, E1, and F1).

In conclusion, the above four types of proposed control logic resulted in enhanced productivity (more throughput) for some specific levels of traffic demand and road network geometry. They also proved more efficient (less delay) in many situations. The Split Pre-timed logic in particular shows much enhanced throughput for cases with extreme levels of congestions.
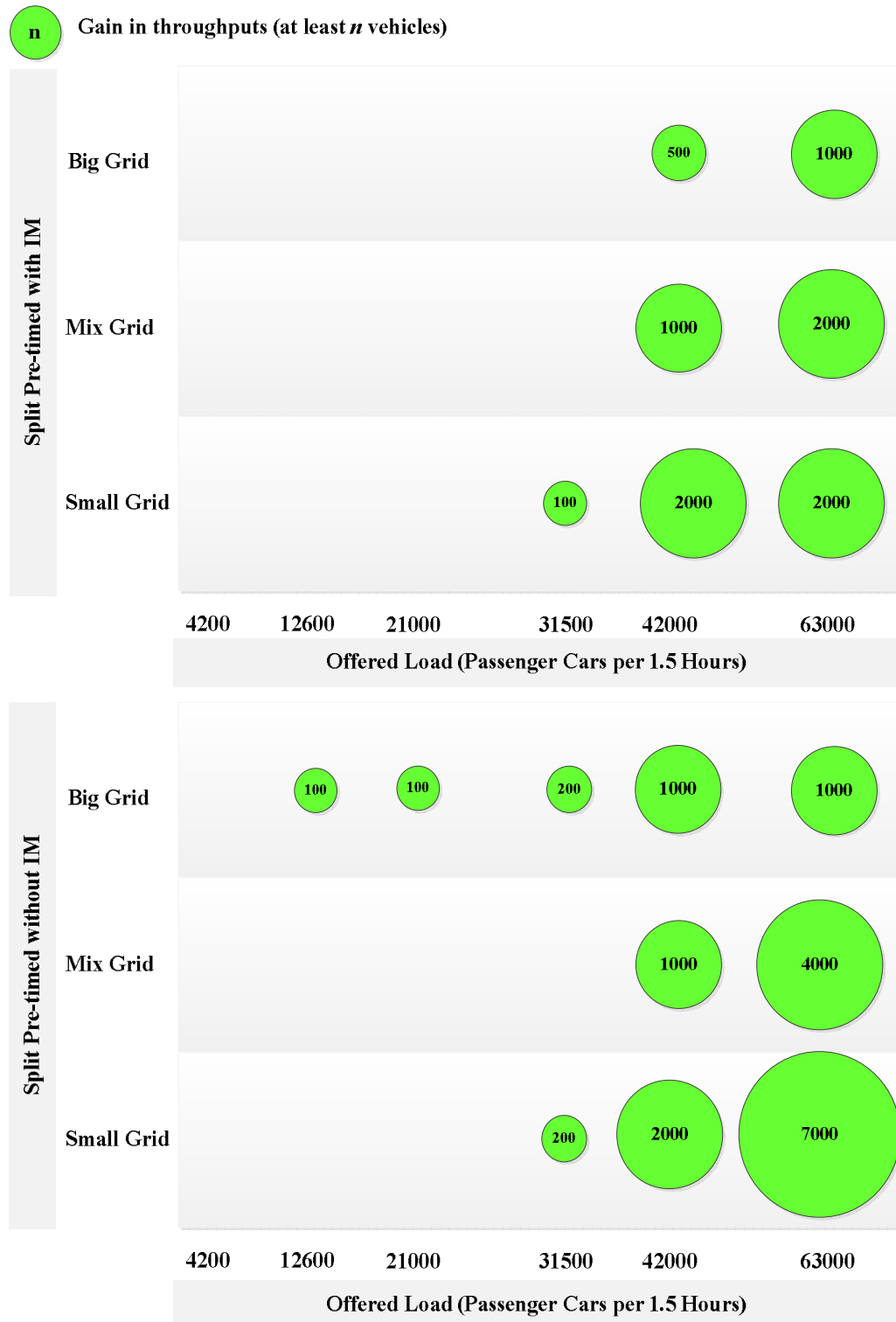
Figure 6.34: Gains in throughputs by the Split Pre-timed control logic

Performances of Dual Actuated Control Logic :

(Against Embedded Existing Control System in CORSIM)
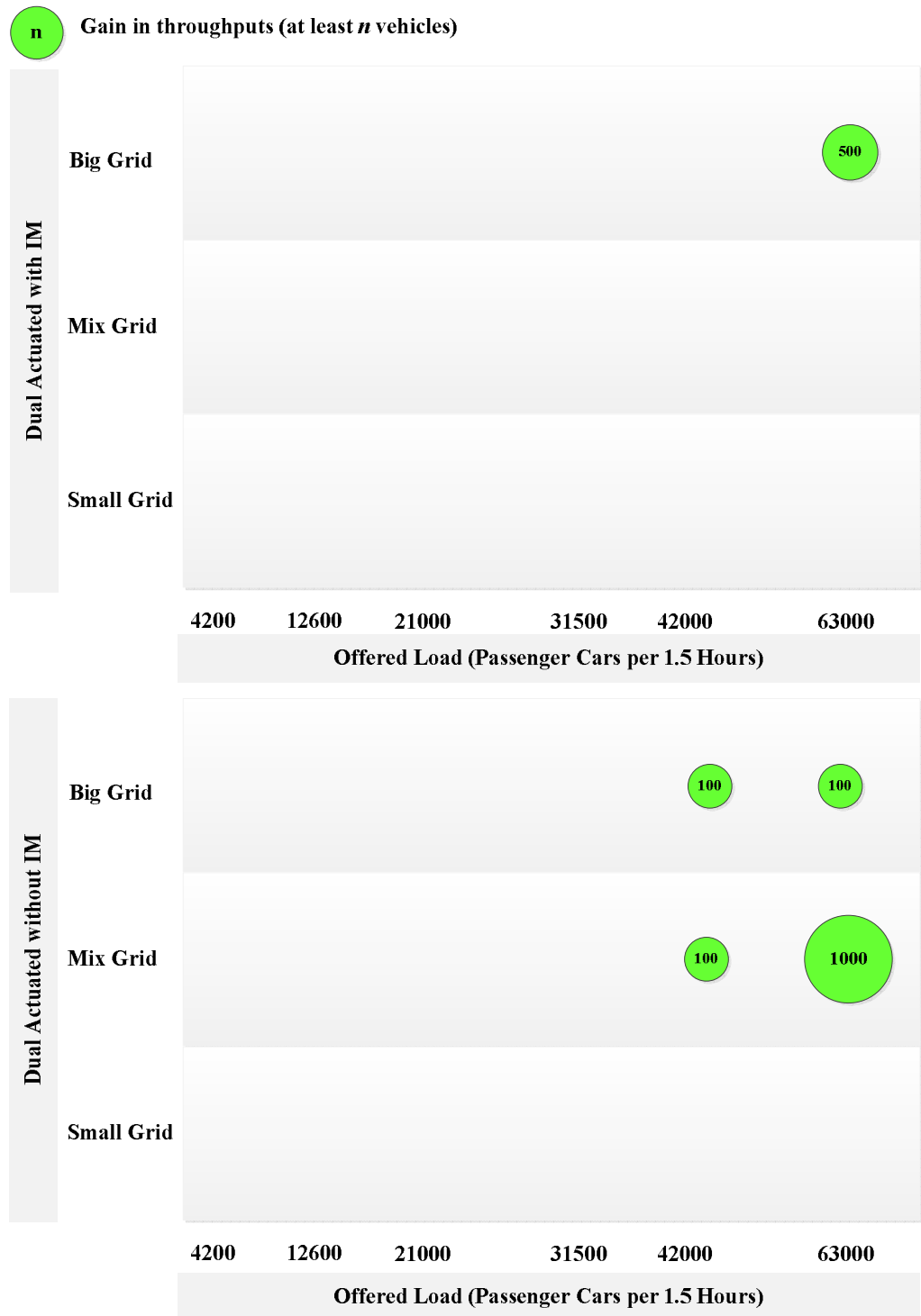
Figure 6.35: Gains in throughputs by the Dual Actuated control logic

201

Performances of Split Actuated Control Logic :
(Against Embedded Existing Control System in CORSIM)
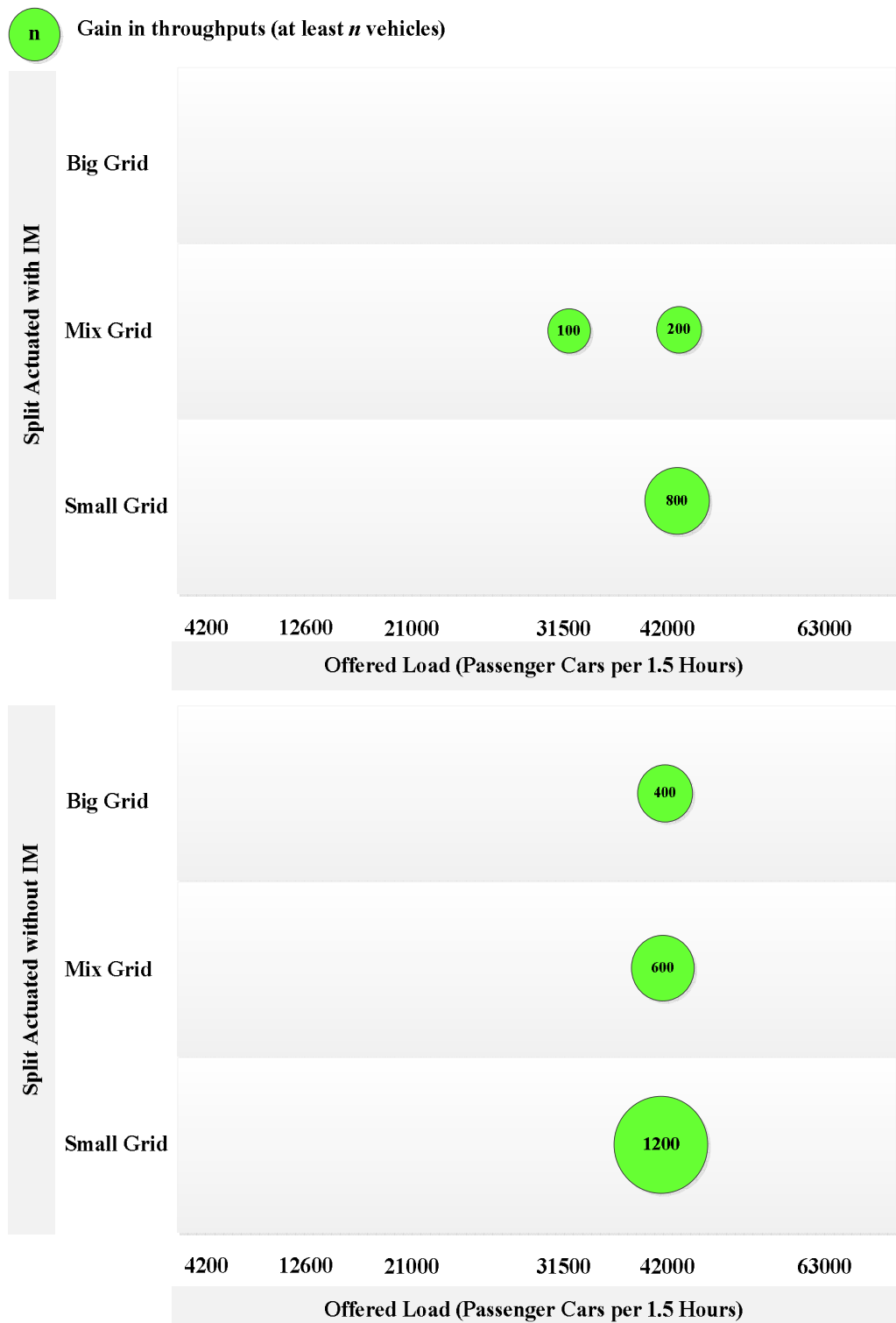
Figure 6.36: Gains in throughputs by the Split Actuated control logic

Performances of Protected Pre-timed Control Logic :

(Against Embedded Existing Control System in CORSIM)

(**n**) **Gain in throughputs (at least _n_ vehicles)**
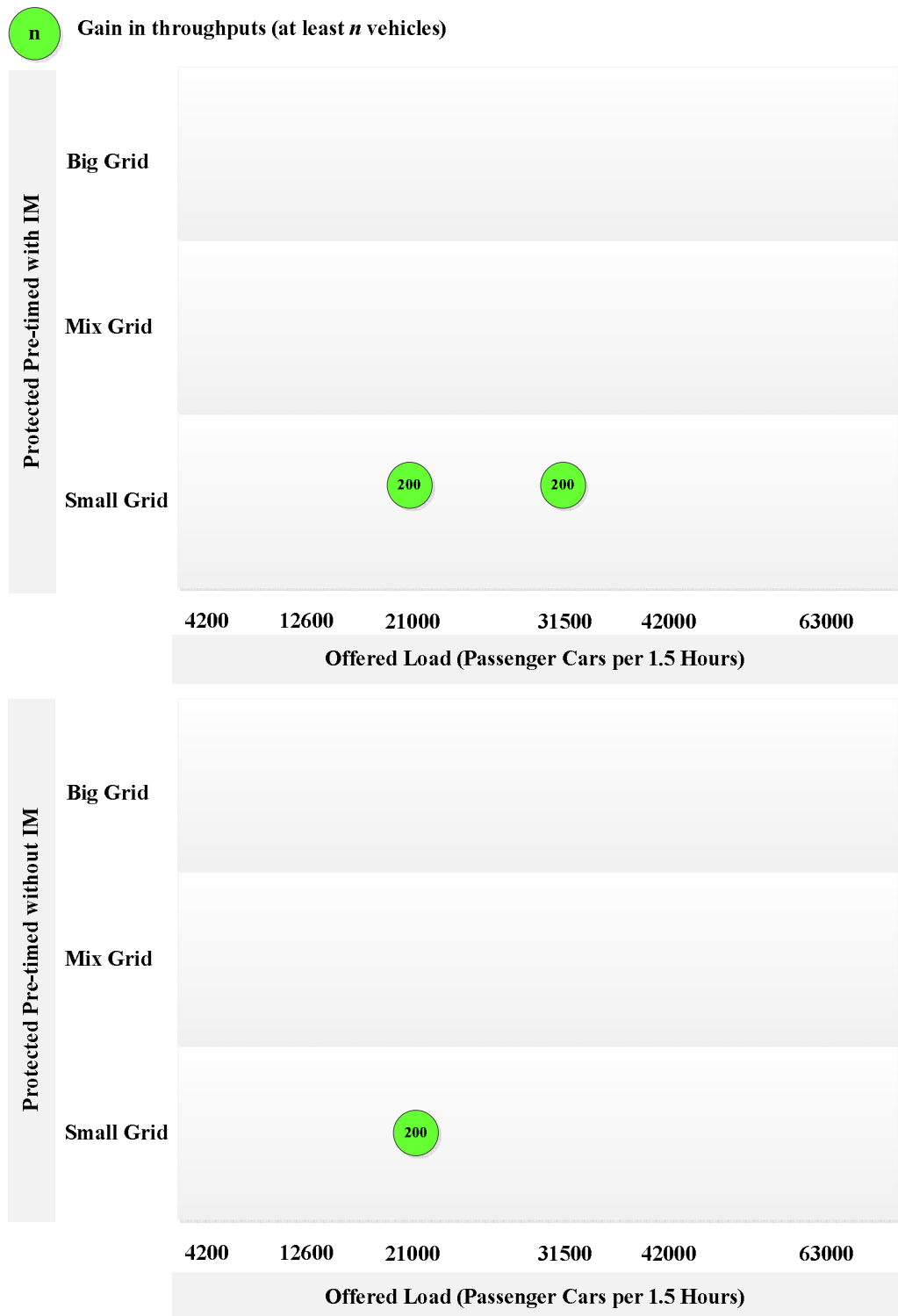
Figure 6.37: Gains in throughputs by the Protected Pre-timed control logic

6.7 Summary

From the discussion above on the performance of the proposed integrated signal control logic as seen from the perspectives of both passenger-based and conventional evaluation criteria, the following conclusions can be made:

- The Split Pre-timed signal control logic (both with and without IM) is productive and results in significant throughput gains (in both *Person Trips* and *Vehicle Trips*) especially for medium to heavily congested traffic demand conditions on all types of network configurations.

- The Split Pre-timed control logic demonstrates better efficiency (in terms of *Average Trip Time/Person* and delay in *seconds/vehicle*) for relatively low to heavy traffic demand conditions. At a very high level of traffic demand, it is capable of producing significantly enhanced throughput, but incurs significant network delay times.

- The Split Pre-timed control logic without IM performs better than the logic with IM.

- The Dual Actuated signal control logic (both with and without IM) displays comparable throughput (in both *Person Trips* and *Vehicle Trips*) especially for low to medium congested traffic demand conditions on all network configurations. It also shows greater productivity and efficiency for heavy congestion levels.

- The Dual Actuated control logic without IM performs better than the logic with IM.

- The Split Actuated signal control logic (both with and without IM) displays comparable throughput (*Person Trips* and *Vehicle Trips*) especially for low to relatively medium congested traffic demand

conditions on all network configurations. It also shows some better productivity for heavy congestion levels on all types of network configurations. Also better efficiency is achieved at this demand level without the IM option.

- The Split Actuated control logic without IM performs better than the logic with IM.

- The Protected Pre-timed signal control logic (both with and without IM) also shows comparable throughput (*Person Trips* and *Vehicle Trips*) especially for low to relatively medium congested traffic demand conditions on all network configurations. This logic outperforms the productivity and efficiency measures of CORSIM-based ones in the small and mix grid networks at relatively low to medium traffic demand levels.

- The Protected Pre-timed control logic with IM performs better than the logic without IM.

- The Protected Actuated control logic (both with and without IM) shows the worst performance in every demand case.

CHAPTER 7:   CONCLUSIONS

7.1   Introduction

This chapter concludes the dissertation. Section 7.2 summarizes the major findings of this research. Section 7.3 draws some general conclusions. Section 7.4 highlights the research contribution. Finally Section 7.5 suggests some future research directions.

7.2   Major Findings

The developed signal control logic shows enhanced performance in productivity (in *Person Trips* and *Vehicle Trips*) compared to the existing control system in medium to heavily congested conditions with the Split Pre-timed phase settings on all types of network configurations. Also, greater efficiency (in terms of *Average Trip Time/Person* and delay in *seconds/vehicle*) is achieved for relatively low to heavy traffic demand conditions with this phase setting. The control logic with the Split Actuated phase settings also shows better productivity for heavy congestion levels on all types of network configurations. The control logic with Dual Actuated phase settings also comes up with better productivity and efficiency in the heavy congestion scenario.

On the other hand, the signal control logic with Protected Pre-timed shows improved performance in productivity and efficiency at relatively low to medium traffic demand levels in the small and mix grid networks. All these phase settings perform better without the IM option. In contrast, the Protected Pre-timed signal

206

control logic works better with the IM option. The Protected Actuated control displays poor performances in every traffic demand case.

The reasons for better performance with Split Pre-timed, Split Actuated and Dual Actuated phase settings can be attributed to the following:

- The proposed signal control logic was formulated to maximize passenger throughput during the estimation of actuation index of a phase set. The estimate of the combined demand (of passengers) on both even phases (through and right turns) and odd phases (left-turning movements) during a split phase set, without the IM module, is accurate.

- On the other hand, the protected (both Pre-timed and Actuated) phase set requires either an estimate of passenger demands for exclusive left-turns or either the shared through and right turns only. The signal control logic may underestimate the left-turning passenger demand as this is captured only from left-pocket lanes (in the case of left turning pocket spill back). Thus, the logic may overestimate the through and right turning approach demands. As a result, this control logic has a tendency to serve predominantly green for the shared through and right movements. This results in more spill-back on the left-turning pocket lane in cases of relatively medium to higher left-turning traffic demand. This spill-back grows further back to the upstream junction and may block the movement(s) of the immediate upstream junction. This subsequently leads to significant losses of productivity and efficiency.

- The Dual actuated logic contains both types of control. Half of the phase sets are split type and the remaining are protected type. The logic acts similarly to the split phase type at high traffic demand conditions. The

underestimation of the passenger demands on exclusive left-turning protected phases are compensated by the relatively accurate estimation of vehicles (and passengers) by the split type phase set (i.e. simultaneous left and through turns) which also includes left-turning movement.

Therefore, to overcome this shortcoming in the protected logic, the following measures are suggested:

- The adoption of a separate coefficient for the *virtual queue of left-turning vehicles* on the *upstream* approach link.
- A predictive turning percentage model could be employed to better estimate the left-turning traffic demand in medium to highly congested demand scenarios.

Coupling the logic with the IM option, the Split Pre-timed, Split Actuated and Dual Actuated phase settings perform worse than the logic without IM option. The reasons for this could be attributed to the following:

- Errors in predicting the real status (incident-induced or incident-free conditions) by the incident status module (i.e. Binary Logit Model) may be a contributing factor. Because of different time resolutions for actuated signal systems, the control decisions have to be taken within a very short time interval, while a wrong incident status remains for a longer incident detection time interval. This may lead to switching green to some non-deserving phase sets, which, in turn, causes unnecessary delays to the more deserving phase sets. With high traffic demand cases, the consequences of the mistaken detection of incident-status can be severe.

- The adoption of the BLM model (which was developed using the Split Pre-timed signal phase data only) for the dual phase settings, may cause errors.

On the contrary, the Protected Pre-timed shows some improvement in terms of productivity with the IM option for some heavy traffic demand scenarios. The weakness of the IM option with split and dual systems may be beneficial for the Protected Pre-timed phase settings. The erroneous detection of incident status might have favorable effects in switching green to the left-turning movements.

To overcome this weakness the following measures are suggested:

- The adoption of a relatively lower value for the coefficient of incidents within the adopted BLM of this study.
- The adoption of a separate BLM for the non-split type signal settings.

For both split or protected signal control logic, the pre-timed phase settings performs better than that of the actuated logic in medium to heavy traffic demand conditions. The control decision time interval for actuated settings is a short interval (green extension time), but for pre-timed settings the decision time interval is maximum green time (the allocated green split time). The actuated settings can extend the green time frequently to the currently green phase set based on the last updated detector data, while the actual traffic demand might be already higher for other competing phase sets. The pre-timed settings do not extend green for the same phase set after its green split time (maximum green time). In relatively congested conditions, it may give green to every competing phases almost equally, if sufficient passengers demand has emerged on the competing approach links. This pattern of demand and control decisions can be

seen on shorter link lengths on the small and mix grid networks. This is why the control logic works better with pre-timed logic for small and mix grid network configurations.

On the other hand, both split and dual phase settings without an IM option work better with the big grid network, when it is loaded with medium to heavy traffic demand. Longer link lengths of big grid network, when loaded with these traffic demands, can have sufficient passenger demands within shorter time interval. This might help the associated phase set to have a sufficient actuation index (in terms of numerical value) to become competitive with other phase sets.

7.3   General Conclusions

The objective of this thesis is to devise, manage, deliver and document research on a newly developed distributed adaptive control system logic that is able to handle boundary conditions of recurrent, non-recurrent congestion, transit signal priority and downstream blockage. The control decisions of this control logic emerged with significant enhancement to productivity (in terms of *Person Trips* and *Vehicle Trips*) against the existing signal control systems in medium to heavily congested traffic demand conditions on different types of networks. Also, greater efficiency (in terms of *Average Trip Time/Person* and delay in *seconds/vehicle*) was achieved for relatively low to heavy traffic demand conditions with this control logic (using Split Pre-timed). However, it performs worse using the Protected Actuated logic.

As expected from the objective function of the control system, the logic should be biased to the phase set(s) with more transit priority calls or with the

status of incident condition. A significant increase in productivity in heavily congested scenarios come with increases delays. It is not uncommon that provision of transit signal strategy on the main flow direction should yield greater delays on cross streets that have no transit priority calls. In a heavily congested scenario on a larger road network, the increase in delay is compensated by a significant increase of throughput.

The signal control logic yields better productivity than existing signal control systems in a typical congested urban network or closely spaced intersections, where traffic demand can be similarly high on both sides at peak periods. It is promising to see how this signal control logic performs well in a network with a high number of junctions. This performance was rarely reported in the previous literature.

The signal control logic yields better throughput (in terms of vehicles exiting the network in congested traffic demand conditions) than the actuated controller with free mode. This was reported in the literature as a reference to the actuated control system for better throughput than either actuated coordinated controller or transit priority coordinated systems.

The best performing phase settings of the signal control logic were investigated thoroughly, which is rarely reported with other adaptive signal control systems in the literature. The signal control logic has also been extended with the logic of pre-timed styled signal phase settings to create the possibility of an enhancement in productivity for heavily congested scenarios in a closely spaced urban network. The performance of this pre-timed signal control is impressive. An extension of existing pre-timed signal controls to act as an adaptive control has rarely been reported in the literature.

The activation of the incident status module with the signal control logic yields an acceptable performance in most of the experimental cases, yet the control logic itself works better without the IM with the Split Pre-timed and Dual Actuated phase settings. The Protected Pre-timed phase setting displays advantages in activating the IM in medium congested demand.

It should also be noted that only the phase IDs are similar to the NEMA system. Therefore, any phase IDs and phase combinations could be used to avoid conflicting movements. Internal formulations and control decision check point(s) are entirely different from the existing control systems which have propriety rights. Also, the logic works on the basis of phase set only. Therefore, the logic is not dependent on any individual controller characteristics.

To conclude, this research has shown the potential for further productivity (and/or efficiency) enhancements in signal control systems under different traffic demand conditions. The integrated signal control logic works primarily to enhance productivity compared to existing base control systems for medium to heavily congested urban road networks. Also, the Split Pre-timed control system can be converted to an adaptive control system for further enhancement of throughput under medium to heavy traffic demand conditions. Comparable performances in both productivity and efficiency in lower traffic demand conditions was also observed.

7.4 Research Contributions

The two primary contributions of this thesis are as follows:

- Developing formulations for the urban incident detection systems.

  - The weaknesses of the existing urban incident detection model(s) were identified. A General Regression Model (GLM), a Neuro-Fuzzy Model and finally, a Binary Logit Model were developed and validated in micro-simulation.

  - The validated Binary Logit Model was integrated with the proposed integrated signal control logic as the Incident status module.

- Developing and testing the formulation of the integrated control logic to maximize the throughput of passengers at intersections, and in turn, the productivity of the overall network.

  - Congestion, incident detection, transit priority and downstream blockage modules were developed to incorporate recurrent congestion, non-recurrent congestion, transit priority and downstream blockage boundary conditions.

  - The integrated signal control logic was interfaced with a widely used micro-simulation model and tested with different traffic demand and supply conditions for different cases of phase-settings. A relatively big theoretical road network with different geometric configurations was used for testing, providing results in terms of productivity and efficiency for the proposed signal control logic in congested demand cases. The network used for testing is bigger

213

than those reported in the extant literature for TSPs and incident detection.

- Further productivity enhancement cases of pre-timed signal phase settings was identified. The pre-timed signal control logic was converted into an adaptive signal control logic, instead of the typical green extension by actuated signal control.

7.5   Future Research Directions

Future research in the following direction is suggested:

- Improvement of the urban incident detection model:

    Urban incident detection models (GLM, Neuro-Fuzzy and BLM) can be further enhanced to improve performance. The detection model parameters can be further calibrated to reflect various incident locations, duration and severity levels. Also, different models can be employed for different phase settings.

- Inclusion of downstream incident detection strategies:

    It may be beneficial to investigate what happens if a severely affected incident induced phase is not allowed to entertain any new vehicles during the incident. That means, the incident conditions of a downstream exit link are integrated with this signal control logic. Here, the control logic might deter to allow vehicles to enter the downstream incident link by not allowing green to the associated phases of the subject intersection. In this study, this situation was *implicitly* accounted for by downstream blockage boundary

condition, but it may be worth investigating the explicit accounting of downstream incidents.

- Inclusion of network-wide incident clearance strategy:

    A separate module responsible for the network wide incident clearance strategy could be integrated with the developed signal control logic. The network here still refers to the sub-network of this distributed control system whose nucleus is the subject intersection. The incident clearance strategy could be built to react to the possible nature of queue formation due to an incident and according to its severity. Also, it might be worthwhile to include some appropriate rerouting strategies in this sub-network based on the severity of the incident.

- Inclusion of LRT (Light Rail Transit):

    The provision of LRTs could be implemented either as a separate module or inside the currently developed *transit priority module*. LRTs could be given the same status as a high priority bus or it could be given an even higher priority than high priority buses. It is a common practice that the intersection which provides LRT in the middle of a road, typically, omits the left-turning movements for other vehicles. Thus, it is expected that split signal settings would be preferable to an LRT phase in order to enhance productivity output.

- Inclusion of environmental parameter(s):

    From the perspective of sustainable signal control systems, it would also be interesting to see how the control logic performs

with air quality matrices as measure(s) of effectiveness and how the entire logic improves the computation timing of the associated machines compared to other centralized control systems.

- Experiments with the protected phase settings:

    The control logic can be further extended with separate coefficients for the protected left-turning traffic demand. It can also include a probabilistic left-turning estimation model based on the historical traffic count data at the particular intersection. These measures might enhance the performance of the control logic with the protected phase settings in heavily congested demand conditions.

- Experiments with the parameters of the signal control logic:

    The control logic can be further investigated with different parameter values. It would be interesting to assess the logic performance with other possible options, such as how it would behave if the maximum green time is set differently for each of the subject intersections, and what happens if the different phase sets of the same intersection are restricted with various maximum green times based on dominant traffic demands.

- Experiments with arterial coordination:

    The logic could be applied for coordinating along a major arterial corridor similar to all other adaptive signal control systems. It can be done by making alterations to the base logic presented here. This allows the comparative performance of the logic compared to other adaptive control systems in similar operational environments.

- Developing a supervisory control system:

    Each signal control system (either existing base control or adaptive control) works better for specific traffic demand and supply conditions. Logically, there is no single adaptive signal control system that has a one size fits all solution. Therefore, it would be an idea to develop a supervisory interface under which all existing base and developed signal control logics are placed. This supervisory layer would select the best control system based on the prevailing boundary conditions, and traffic demand levels described by the detectors.

REFERENCES

Abdulhai, B. & Ritchie, S. G. (1999). Enhancing the universality and transferability of freeway incident detection using a Bayesian-based neural network. *Transportation Research Part C*, 7(5), 261-280.

Aboudolas, K. ,Papageorgiou M. & Kosmatopoulos.E.(2009).Store-and-forward based methods for the signal control problem in large-scale congested urban road network . *Transport Research Part C,* 17(2),163-174.

Adeli, H. & Samant, A. (2000). An adaptive conjugate gradient neural network-wavelet model for traffic incident detection. *Computer-Aided Civil and Infrastructure Engineering*, 15(4),251.260.

Ahmed, M.S. & Cook, A.R. (1977). Analysis of freeway traffic time-series data using Box- Jenkins techniques. *Transportation Research Record*, No. 722, TRB, National Research Council, pp. 1-9.

Ahmed, M. S. & Cook, A. R. (1980). Time series models for freeway incident detection. *Journal of Transportation Engineering*, 106 (6), ASCE, 731-745.

Ahmed, M. S. & Cook, A. R. (1982). Application of time-series analysis techniques to freeway incident detection. *Transportation Research Board*, No. 841, TRB, National Research Council, pp. 19-21.

Ahmed, F., & Hawas, Y. E., (2012). A threshold-based real-time incident detection system for urban traffic network. *Procedia - Social and Behavioral Sciences,* 48, 1713 – 1722. *Proceedings of the 4th International Conference: Transport Research Arena (TRA) Europe*, Athens, Greece, April 23-26.

Ahmed, F., & Hawas, Y. E., (2013). A fuzzy logic model for real-time incident detection in urban road network. *Proceedings of the 5th International Conference on Agents and Artificial Intelligence (ICAART 2013)*, Barcelona, Spain, February 15-18, 2013.

Ahn, K. & Rakha, H. (2006). Integrating transit signal priority and adaptive traffic signal control. Final report of ITS Center project, The Center for ITS Implementation Research.
URL:
http://www.gmupolicy.net/its/2007%20reports/Integrating%20TSP%20and%20adaptive%20traffic%20signal%20control.pdf, visited on 04-01-2014.

Awadallah, F. (2002). Incident Detection: Selection of Appropriate Technologies and Methodologies. *Road and Transport Research*, 11(2), 50-56.

Balke, K. N. (1993). An evaluation of existing incident detection algorithms. Research Report, FHWA/TX-93/1232-20, Texas Transportation Institute, the Texas A&M University System, College Station, TX, November 1993.

Black, J. & Sreedevi, I. (2001). Automatic incident detection algorithms. ITS Decision Database in PATH,
<http://www.path.berkeley.edu/~leap/TTM/Incident_Manage/Detection/aida.html>, February 2001.

Boillot, F., Midenet, S. & Pierrelee, J. C. (2006). The Real-time urban traffic control system CRONOS: Algorithm and Experiments, *Transportation Research Part C*, 14(1), 18-38.

Brydia, R. E., Johnson, J. D., & Balke, K. N., (2005). An Investigation into the Evaluation and Optimization of the Automatic Incident Detection Algorithm Used in TxDOT Traffic Management System. Texas Transportation Institute, FHWA/TX-06/0-4770-1.

Cai, C., Wong, C. K. & Heydecker, B. G. (2009). Adaptive traffic signal control using approximate dynamic programming, *Transportation Research Part C*, 17(5), 456-474.

Castro-Neto, M., Jeong, Y. S, Jeong, M. K. & Han, L. D. (2009). Online-SVR for short-term traffic flow prediction under typical and atypical traffic conditions. *Expert Systems with Applications*, 36 (3) ,6164–6173.

Chang, E. C. P. & Wang, S. H. (1994). Improved freeway incident detection using fuzzy set theory. *Transportation Research Record*, No. 1453, TRB, National Research Council, pp. 75-82.

Chang, G. L., Wu, J. & Lieu, H. (1994). Real-time incident-responsive corridor control: a successive linear programming approach. In *Proceedings of the Fourth Annual Meeting of IVHS America*, Atlanta, GA, 2, 907–918.

Chassiakos, A. P. & Stephanedes, Y. J. (1993). Smoothing algorithms for incident detection. *Transportation Research Record*, No. 1394, TRB, National Research Council, pp. 8-16.

Chen, S. & Wang, W. (2009). Decision tree learning for freeway automatic incident detection. *Expert Systems with Applications*, 36(2) ,4101–4105.

Chen, S., Wang, W. & Zuylen, H. V. (2009). Construct support vector machine ensemble to detect traffic incident. *Expert Systems with Applications*,36(8), 10976–10986.

Chen, S., Wang, W. & Zuylen, H. V. (2010) A comparison of outlier detection algorithms for ITS data. *Expert Systems with Applications*, 37 (2), 1169–1178.

Cheu, R. L. & Ritchie, S. G. (1995). Automated detection of lane-blocking freeway
incidents using artificial neural networks. *Transportation Research Part C*, 3(6), 371-388.

Collins, J. F., Hopkins, C. M. & Martin, J. A. (1979). Automatic incident detection—TRRL algorithms HIOCC and PATREG. TRRL Supplementary Report, No. 526, Crowthorne, Berkshire, U.K.

Collura, J., Rakha, H., & Gifford, J.(2004). Guidelines for the Planning and Deployment of Emergency Vehicle Preemption and Transit Priority Strategies. *Transportation Research Board, National Research Council*, Washington, D.C.

Cook, A. R. & Cleveland, D. E. (1974). Detection of freeway capacity-reducing incidents by trafficstream measurements. *Transportation Research Record*, No. 495, TRB, National Research Council, pp. 1-11.

Corby, M. J. & Saccomanno, F. F. (1997). Analysis of Freeway Accident Detection. *Transportation Research Record*. Issue 1603, pp 80-89.

Cremer, M. & Schoof, S. (1989). On control strategies for urban traffic corridors. In *Proceedings of the XXX IFAC Conference on Control Computers and Communications in Transportation*, Paris, France, 213–219.

Crenshaw, P. (2000). ACS Lite Presented at the TRB A3A18 Meeting, Midyear Meetings Minutes ,Seattle, Washington, July 9-10, 2000.

Dahal, K., Almejalli, K. & Hossain, M. A. (2012). Decision support for coordinated road traffic control actions ,Decision Support System: URL: http://dx.doi.org/10.1016/j.dss.2012.10.022

D'Ans, G. C. & Gazis, D. C. (1976). Optimal control of oversaturated store-and forward transportation networks. *Transportation Science,* 10(1), 1–19.

Dia, H., & Thomas, K., (2011). Development and evaluation of arterial incident detection models using fusion of simulated probe vehicle and loop detector data. *Information Fusion*, 12(1), 20–27.

Dion, F. & Hellinga, B. (2002).A rule-based real-time traffic responsive signal control system with transit priority: application to an isolated intersection. *Transport Research Part C*, 36(4),325-343.

Donati, F., V. Mauro, G., Roncolini, & M. Vallauri (1984). A hierarchical decentralised traffic light control system. *Proceedings from IFAC 9th World Congress*, Vol. II, 11G/A-1.

Dotoli, M., Fanti, M. P.& Meloni, C. (2006). A signal timing plan formulation for urban traffic control. *Control Engineering Practice*, 14(11), 1297-1311.

Dudek, C.L., Messer, C.J. & Nuckles, N.B. (1974). Incident detection on urban freeway. *Transportation Research Record*, No. 495, TRB, National Research Council, pp. 12-24.

DPE Abu Dhabi (2008). DPE Weekly Report 8, Department of Planning and Economy, Abu Dhabi.

Eichler, M. & Daganzo, C. F. (2006). Bus lanes with intermittent priority: Strategy formulae and an evaluation. *Transportation Research Part B*, 40 (9) , 731–744.

Fambro, D. B. & Ritch, G. P. (1980). Evaluation of an algorithm for detecting urban freeway incidents during low-volume conditions. *Transportation Research Record,* No. 773, TRB, National Research Council, pp. 31-39.

Fehon, K. (2005). North American Development of Adaptive Traffic Signal Systems. *Proceedings of the ITE 2005 Annual Meeting and Exhibit Compendium of Technical Papers*, Melbourne, Australia, Aug. 5–7, pp 17.

Felici, G., Rinaldi, G., Sforza, A.,& Truemper, K.(2006). A logic programming based approach for on-line traffic control. *Transport Research Part C*,14(3), 175-189.

Forbes, G.J. & Hall, F.L. (1990). The applicability of Catastrophe theory in modeling freeway traffic operations. *Transportation Research Part A*, 24 (5), 335-344.

Gartner, N. H. (1982). Demand-Responsive Decentralised Urban Traffic Control, Report DOT/RSPA/DPB-50/81/24, U.S. Department of Transportation, Washington, D.C.

Ghanim, M., Francois, F. & Abu-Lebdeh, G. (2009). Integration of Signal Control and Transit Signal Priority Optimization in Coordinated Network Using Genetic Algorithms and Artificial Neural Networks", Presented at *Transportation Research Board Annual Meeting,* Paper #09-3063, TRB, Washington D.C..

Gursoy, M. B., Xiao, W., & Ozbay, K. (2009). Modeling traffic flow interrupted by incidents *European Journal of Operational Research ,*195(1), 127–138.

Hawas, Y. E. (2004). Development and calibration of route choice utility models: Neuro-Fuzzy approach. *Journal of Transportation Engineering,* ASCE 130 (2), 171–182.

Hawas, Y. E. (2007). A fuzzy-based system for incident detection in urban street networks. *Transportation Research Part C,* 15(2), 69–95.

Hawas, Y. (2011a) .An integrated simulation-based fuzzy logic model for real-time traffic signal control. *Transportmetrica,* 7(4), 247-278.

Hawas, Y (2011b) A simulation-based fuzzy logic model for network real-time signal control and transit preemption, *Proceedings of the International Conference on Fuzzy Computations and Applications*, FCTA, 24-26 October, Paris, France.

Hakimi, S.L., (1969). Analysis and design of communication networks with memory. *Journal of the Franklin Institute,* 287 (1), 1–17.

He, Q., Head, K. L.& Ding, J. (2011). PAMSCOD: Platoon-based Arterial Multi-modal Signal Control with Online Data. *Procedia Social and Behavioral Sciences* 17,462-489,19[th] *International Symposium on Transportation and Traffic Theory*.

Head, K.L., Mirchandani, P.B. & Shepherd, D. (1992). A Hierarchical Framework for Real-Time Traffic Control, *Transportation Research Record* 1360, Transportation Research Board, National Research Council, Washington, D.C., 82–88.

Hellinga, B. & Knapp, G. (2000). Automatic vehicle identification technology-based freeway incident detection. *Transportation Research Record*, No. 1727, TRB, National Research Council, pp. 142-153.

Henry, J. J., Farges, J. L. & Tufal, J. (1983) The PRODYN Real Time Traffic Algorithm, *Proceedings of the IFAC Symposium*, Baden-Baden, Germany.

Hicks, B. & Carter, M. (2000). What Have We Learned About ITS Arterial Management? In What Have We Learned About Intelligent Transportation Systems? Federal Highway Administration, Washington, D.C., Dec. 2000, pp. 45–63.

Hounsell, N. B., McLeod, F. N., & Shrestha, B. P. (2004). Bus priority at traffic signals investigating the options. *Road Transport Information and Control, 2004. RTIC 2004. 12th IEE International Conference*, pp.287 . 294.

Hsiao, C. H., Lin, C.-T. & Cassidy, M. (1994). Application of fuzzy logic and neural networks to automatically detect freeway traffic incidents. *Journal of Transportation Engineering,* 120 (5), ASCE, 753-772.

Hunt, P. B., Robertson, D. I., Bretherton, R. D. & Winton, R. I. (1981). SCOOT— A Traffic Responsive Method of Coordinating Signals," Report TRRL 1014, Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 44.

INFORM (2001), FuzzyTECH 5.5 User Manual.

Ishak, S. S. & Al-Deek, H. M. (1998). Fuzzy ART neural network model for automated detection of freeway incidents. *Transportation Research Record*, No. 1634, TRB, National Research Council, pp. 56-63.

Ivan, J. N., Schofer, J. L., Koppelman, F. S. & Massone, L. L. E. (1995). Real-time data fusion for arterial street incident detection using neural networks. *Transportation Research Record,* No. 1497, TRB, National Research Council, pp. 27-35.

Ivan, J.N. & Chen, S.-R. (1997). Incident detection using vehicle-based and fixed location surveillance. *Journal of Transportation Engineering*,123(3), ASCE, 209-215.

Ivan, J.N. (1997). Neural network representations for arterial street incident detection data fusion. *Transportation Research Part C*, 5(3), 245-254.

Ivan, J. N. & Sethi, V. (1998). Data fusion of fixed detector and probe vehicle data for incident detection. *Computer-Aided Civil and Infrastructure Engineering*, 13(5), 329- 337.

Jin, X, Cheu, R.L. & Srinivassan, D. (2002). Development and adaptation of constructive probabilistic neural network in freeway incident detection. *Transportation Research. Part C*: Emerging Technologies,10(2), 121-147.

Judicky, D. & Robinson, J. (1992).Managing traffic during nonrecurring congestion. *Institute of Transportation Engineers Journal*, 62(3),21-26.

Kay, J. (1992) .Intelligent Vehicle-Highway Systems and Incident Management *Institute of Transportation Engineers Journal*, 62(3),55-57.

Khan, S.I., & Ritchie, S.G. (1998). Statistical and neural classifiers to detect traffic operational problems on urban arterials. *Transportation Research C*, 6(5), 291–314.

Kosmatopoulos, E., Papageorgiou, M., Bielefeldt, C., Dinopoulou, V., Morris, R., Mueck, J., Richards, A. & Weichenmeier, F.(2006).International comparative field evaluation of a traffic-responsive signal control strategy in three cities. *Transport Research Part A* ,40,399-413.

Kosonen, I.(2003).Multi-agent fuzzy signal control based on real-time simulation. *Transport Research Part C* ,11(5),389-403.

Lee, S., Krammes, R.A., & Yen., J., (1998). Arterial fuzzy-logic-based incident detection for signalized diamond interchanges. *Transportation Research C*, 6, 359-377.

Levin, M. & Krause, G.M. (1978). Incident detection: a Bayesian approach. *Transportation Research Record*, No. 682, TRB, National Research Council, pp. 52-58.

Liu, Q. & Xu, J. (2012). Traffic Signal Timing Optimization for Isolated Intersections Based on Differential Evolution Bacteria Foraging Algorithm. *Procedia - Social and Behavioral Sciences* 43,210 – 215, 8th *International Conference on Traffic and Transportation Studies,* Changsha, China, August 1–3, 2012.

Liu, H., Zhang, J. & Cheng, D. (2008). Analytical approach to evaluating transit signal priority. *Journal of Transportation Systems Engineering and Information Technology*, 8(2), 48-57.

Liu, Y. & Chang. G.L. (2011).An arterial signal optimization model for intersections experiencing queue spillback and lane blockage. *Transport Research Part C* ,19(1),130-144.

Liu, Y., Lei, Y., Yi, Q., Jianquan, W. & Huimin, W., (2007). Traffic incident detection algorithm for urban expressways based on probe vehicle data. *Journal of Transportation Systems Engineering & Information Technology*, 8(4), 36-41.

Lo, H.K. (2001). A cell-based traffic control formulation: strategies and benefits of dynamic timing plans. *Transportation Science* ,35 (2), 148–164.

Logi, F. & Ritchie, S. G. (2001). Development and evaluation of a knowledge-based system for traffic congestion and management and control. Transportation Research Part C, 9(6), 433-459.

Lomax, T., Schrank, D. & Eisele, B (2012). TTI's 2012 Urban Mobility Report, Texas A&M Transportation Institute.

Lowrie, P.R, (1982). The Sydney coordinated adaptive control system— principles, methodology, algorithms. In *proceedings of IEE Conference Publication*, United Kingdom, 207, 71-74,

Mahmassani, H.S., Haas, C., Zhou, S. & Peterman, J. (1998). Evaluation of incident detection methodologies. Research Report 1795-1, Center for Transportation Research, University of Texas at Austin, Austin, TX, October 1998, Revised October 1999.

Masters, P.H., Lam, J.K. & Wong, K. (1991). Incident detection algorithms of COMPASS— an advanced traffic management system. *Proceedings of Vehicle Navigation and Information Systems Conference*, Part 1, SAE, Warrendale, PA, October 1991, 295-310.

Mauro, V.& DiTaranto, C. (1990). UTOPIA, *Control, Computers, Communications in Transportation*: Selected Papers from the IFAC Symposium, 245–252.

McKenney. D. & White, T. (2013). Distributed and adaptive traffic signal control within a realistic traffic simulation. *Engineering Application of Artificial Intelligence*, 26(1),574-583.

Mesbah, M., Sarvi, M., Ouveysi, I., & Currie, G.(2011).Optimization of transit priority in the transportation network using a decomposition methodology. *Transport Research Part C*,19(2), 363-373.

Michalopoulos, P. G. (1991). Vehicle detection video through image processing: the Autoscope system. *IEEE Transactions on Vehicular Technology*, 40(1), IEEE, 21 29.

Michalopoulos, P. G., Jacobson, R. D., Anderson, C. A. & DeBruycker, T. B. (1993). Automatic incident detection through video image processing. *Traffic Engineering and Control*, 34 (2), 66-75.

Mirchandani, P. & Head, L. (2001) A Real-Time Traffic Signal Control System: Architecture, Algorithms, and Analysis, *Transportation Research Part C: Emerging Technologies*, 9 (6), 415–432.

Mussa, R.N. & Upchurch, J.E. (2000). Modeling incident detection using vehicle-to roadside communication system. *Journal of the Transportation Research Forum*, 39 (4), 117-127.

Muthuswamy, S., McShane, W.R. & Daniel, J.R. (2007). Evaluation of transit signal priority and optimal signal timing plans on transit and traffic operations. *Transportation Research Record 2034*, TRB, Washington D.C., 2007, 92-102.

Nelson, D. (2000). ITS subsystems and technologies—managing traffic, vehicles and systems. *Intelligent Transportation Primer*, Chapter 14, Institute of Transportation Engineers.

Niittymaki, J. & Maenpaa, M. (2001). The role of fuzzy logic public transport priority in traffic signal control. *Traffic Engineering Control*, 42(1), 22-26.

Parkany, E. A.,(2005). Complete Review of Incident Detection Algorithms & Their Deployment: What Works and What Doesn't. *The New England Transportation Consortium.NETCR37.*

Payne, H. J. (1976). Development and testing of incident detection algorithms, Volume 1: summary of results. Report No. FHWA-RD-76-19, FHWA, Washington D.C., April 1976.

Payne, H. J. & Knobel, H. C. (1976). Development and testing of incident detection algorithms, Volume 2: users guidelines. Report No. FHWA-RD-76-21, FHWA, Washington D.C., April 1976.

Payne, H. J. & Tignor, S. C. (1978). Freeway incident-detection algorithms based on decision trees with states. *Transportation Research Record*, No. 682, TRB, National Research Council, pp. 30-37.

Persaud, B. N., Hall, F. L. & Hall, L. M. (1990) .congestion identification aspects of the mcmaster incident detection algorithm. *Transportation Research Record*, No. 1287, pp 67-74

Petty, K. F., Skabardonis, A. & Varaiya, P. P. (1997). Incident detection with probe vehicles: performance, infrastructure requirements and feasibility. Transportation Systems 1997: *A Proceedings Volume from the 8th IFAC/IFIP/IFORS Symposium*, Chania, Greece, June 16-18, 1, 125-130

Petty, K. F., Ostland, M., Kwon, J, Rice, J. & Bickel, P. J. (2002). A new methodology for evaluating incident detection algorithms. *Transportation Research. Part C*: *Emerging Technologies* , 10(3), 189-204

PTV VISSIM Manual (2012) VISSIM 5.40 User manual, Planung Transport Verkehr, Germany.

Roberg, P. & Abbess, C. R. (1998). Diagnosis and treatment of congestion in central urban areas. *European Journal of Operational Research*, 104(1), 218-230.

Samant, A. & Adeli, H. (2000). Feature extraction for traffic incident detection using wavelet transform and linear discriminant analysis. *Computer-Aided Civil and Infrastructure Engineering*,15(4), 241-250.

Sermons, M. W. & Koppelman, F. S. (1996). Use of vehicle positioning data for arterial incident detection. *Transportation Research Part C,* 4(2),87-96.

Shah, S. A. A., Kim, H., Baek, S., Chang, H. & Ahn, B. H. (2008) .System architecture of a decision support system for freeway incident management in Republic of Korea. *Transportation Research Part A*, 42(5), 799–810.

Shelby, S. G., Bullock, D. M. , Gettman, D. , Ghaman, R.S. , Sabra , Z.A. & Soyke, N. (2008). Overview and performance evaluation of ACS Lite—A low cost adaptive signal control system, No. 08-0334, 87th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 13–17, pp 17.

Singh, M. G., & Tamura, H. (1974). Modelling and hierarchical optimization for oversaturated urban road traffic networks. *International Journal of Control*, 20 (6), 913–934.

Skabardonis, A. & Christofa, E. (2011). Impact of transit signal priority on level of service at signalized intersections. *6ᵗʰ International Symposium on Highway Capacity and Quality of Service*, 28 June-1 July, Stockholm, Sweden.

Slavin, C., Feng, W. Figliozzi, M. & Koonce, P (2013). Statistical study of the impact of adaptive traffic signal control on traffic and transit performance. *Transportation Research Record: Journal of the Transportation Research Board*, 13-4570, pp 117–126.

Smith, H. R., Hemily, B. & Ivanovic, M., (2005). Transit signal priority (TSP): a planning and implementation handbook. United States Department of Transportation.   <http://www.fta.dot.gov/documents/TSPHandbook10-20-05.pdf> (accessed April, 2011).

Srinivasan, D., Cheu, R. L., Poh, Y. P.& Chwee Ng, A. K., (2000). Development of an intelligent technique for traffic network incident detection. *Engineering Applications of Artificial Intelligence* ,13 (3), 311–322.

Stephanedes, Y. J. & Chang, K. K. (1993). Optimal control of freeway corridors. *Journal of Transportation Engineering*,119 (4), 504–514.

Stephanedes, Y. J. & Chassiakos, A. P. (1993a). Application of filtering techniques for incident detection. *Journal of Transportation Engineering*, 119 (1), ASCE, 13-26.

Stephanedes, Y. J. & Chassiakos, A. P. (1993b). Freeway incident detection through filtering. *Transportation Research Part C*, 1(3) , 219-233.

Stevanovic, J., Stevanovic, A., Martin, P. T. & Bauer, T. (2008). Stochastic optimization of traffic control and transit priority settings in VISSIM. *Transportation Research Part C* ,16(3), 332–349.

Stevanovic, A. (2010). Adaptive traffic control systems: domestic and foreign state of practice, National Cooperative Highway Research Program (NCHRP) Synthesis 403, Transportation Research Board.

Tarnoff, P. J. & Parsonson, P. S.(1981). Selecting traffic signal control at individual intersections. NCHRP Report 233, TRB, National Research Council, Washington, D.C., 1981.

Teng, H. & Qi, H. (2003). Application of wavelet technique to freeway incident detection, *Transportation Research Part C*, 11 (3),289– 308.

Thomas, N.E.(1998). Multi-state and multi-sensor incident detection systems for arterial streets. *Transportation Research C*, 6(5-6), 337-357.

Thomas, K., Dia, H. & Cottman, N. (2001). Simulation of arterial incident detection using neural networks. *In the Proceedings of 8th World Congress on ITS*, Sydney.

Toledo, T., Cats, O., Burghout, W. & Koutsopoulos, H.N. (2010). Mesoscopic simulation for transit operations. *Transportation Research Part C* ,18 (6), 896– 908.

Tsai, J. & Case, E.R. (1979). Development of freeway incident detection algorithms by using pattern recognition techniques. *Transportation Research Record*, No. 722, TRB, National Research Council, pp. 113-116.

TSIS-CORSIM Manual (2010). Traffic Software Integrated System-Corridor Simulation 6.2 User Manual, McTrans Center, USA.

UAE MOI (2007). Annual Statistics of Traffic for the year 2007. Ministry of Interior, United Arab Emirates.

UAE MOI (2008). Annual Statistics of Traffic for the year 2007. Ministry of Interior, United Arab Emirates.

Viegas, J. & Lu, B., (2001). Widening the scope for bus priority with intermittent bus lanes. *Transportation Planning and Technology,* 24 (2), 87–110.

Viegas, J., & Lu, B. (2004). The intermittent bus lane signals setting within an area. Transportation Research, Part C, 12(6), 453–469.

Eichler, M. & Daganzo, C.F. (2006). Bus lanes with intermittent priority: Strategy formulae and an evaluation. *Transportation Research Part B* ,40 (9), 731–744.

Viti, F.& Zuylen, H.J.V.(2010) .A probabilistic model for traffic at actuated control signals. *Transport Research Part C,* 18(3),299-310.

Wahlstedt, J. (2011). Impacts of bus priority in coordinated traffic signals. *Procedia Social and Behavioral Sciences* 16, 578–587. *6th International Symposium on Highway Capacity and Quality of Service*, Stockholm, Sweden June 28 – July 1, 2011.

Walters, C. H., Wiles, P. B. & Cooner, S. A. (1999). Incident detection primarily by cellular phones—an evaluation of a system for Dallas, Texas. Preprint CD-ROM, the 78th TRB Annual Meeting, Transportation Research Board, National Research Council, Washington D.C., January 1999.

Wey, W. M. (2000). Model formulation and solution algorithm of traffic signal control in an urban network. *Computers ,Environment and Urban Systems*, 24(4), 355-377.

Wilshire et al. (1985). Traffic Control Systems Handbook, FHWA-IP-85-12.

Xie, X. F., Smith, S. F., Lu, L. & Barlow, G. J. (2012).Schedule-driven intersection control. *Transport Research Part C,* 24,168-189.

Xin, W., McShane, W.R. , Muthuswamy, S. & Chang, J. (2008). An Integrated Real-time Decision Support System for Adaptive Signal Control, *Proceedings of the 15th World Congress on ITS*, New York City, N.Y., Nov. 16–20, pp 9.

Yu, X. H. & Recker, W. W. (2006). Stochastic Adaptive Control Model for Traffic Signal Systems, *Transportation Research Part C,* 14 (4), 263–282.

Yuan, F. & Cheu, R. L. (2003). Incident detection using support vector machines, *Transportation Research Part C*, 11 (3), 309– 328.

 Zhang, K. & Taylor, M.A.P. (2006). Effective arterial road incident detection: a Bayesian network based algorithm. *Transportation Research Part C,* 14 (6), 403–417.

Zheng, X. & Recker ,W. (2013).An adaptive control algorithm for traffic-actuated signals . *Transport Research Part C,* 30,93-115.

Zhou, G., Gan, A & Shen, L.D. (2007). Optimization of adaptive transit signal priority using parallel genetic algorithm, *Tsinghua Science and Technology*, 12 (2), 131-140.

APPENDIX 1

A1.1 Update Module A (*Traffic Regime State*) for Phase ϕ_j:

{

Go to the approach link $L_{i,\varphi_j,u/}$ of ϕ_j;

For any ϕ_j, estimate $\bar{v}^t_{i,\phi_j,u/_{u,m}} = \dfrac{c^{V,t}_{i,\phi_j,u/,4} \times v^{V,t}_{i,\phi_j,u/,4} + c^{V,t}_{i,\phi_j,u/,3} \times v^{V,t}_{i,\phi_j,u/,3}}{c^{V,t}_{i,\phi_j,u/,4} + c^{V,t}_{i,\phi_j,u/,3}}$;

if (ϕ_j is even), then estimate $\bar{v}^t_{i,\phi_j,u/_{m,d}} = \dfrac{c^{V,t}_{i,\phi_j,u/,3} \times v^{V,t}_{i,\phi_j,u/,3} + c^{V,t}_{i,\phi_j,u/,1} \times v^{V,t}_{i,\phi_j,u/,1}}{c^{V,t}_{i,\phi_j,u/,3} + c^{V,t}_{i,\phi_j,u/,1}}$;

if (ϕ_j is odd), then estimate

$$\bar{v}^t_{i,\phi_j,u/_{m,d}} = \dfrac{c^{V,t}_{i,\phi_j,u/,3} \times v^{V,t}_{i,\phi_j,u/,3} + c^{V,t}_{i,\phi_j,u/,5} \times v^{V,t}_{i,\phi_j,u/,5} + c^{V,t}_{i,\phi_j,u/,1} \times v^{V,t}_{i,\phi_j,u/,1}}{c^{V,t}_{i,\phi_j,u/,3} + c^{V,t}_{i,\phi_j,u/,5} + c^{V,t}_{i,\phi_j,u/,1}}$$;

if ($\bar{v}^t_{i,\phi_j,u/_{u,m}} <=0$ OR $\bar{v}^t_{i,\phi_j,u/_{m,d}} <=0$), then

   {

   $\bar{v}^t_{i,\phi_j,u/_{u,m}} =0.01$; // A minimum limit of stalled vehicles

   $\bar{v}^t_{i,\phi_j,u/_{m,d}} =0.01$; // A minimum limit of stalled vehicles

   }

Estimate $\bar{T}_{i,\phi_j,u/} = \dfrac{0.5 l_{i,\phi_j,u/}}{\bar{v}^t_{i,\phi_j,u/_{u,m}}} + \dfrac{0.5 l_{i,\phi_j,u/}}{\bar{v}^t_{i,\phi_j,u/_{m,d}}}$;

// Set a maximum practical travel time limit of 90 minutes to avoid very large travel time.

if ($\bar{T}_{i,\phi_j,u/} >= 90$), then

   {

   $\bar{T}_{i,\phi_j,u/}=90$;

   }

Estimate $T^0_{i,\phi_j,u/} = \dfrac{l_{i,\phi_j,u/}}{v^0_{i,\phi_j,u/}}$;

Estimate $TTI^t_{i,\phi_j,u/} = \dfrac{\bar{T}_{i,\phi_j,u/}}{T^0_{i,\phi_j,u/}}$;

   If ($TTI^t_{i,\phi_j,u/,u} \geq 5$) then // The threshold adopted with $TTI^t_{i,\phi_j,u/,u}$

   {

Set $I^{R,t}_{i,\phi_j,u\prime} = 1$;

}

else

{

Set $I^{R,t}_{i,\phi_j,u\prime} = 0$;

}

Call $V^{t}_{i,\phi_j,u\prime_L}$;

Call $V^{max}_{i,\phi_j,u\prime_L}$;

Estimate $r^{V,t}_{i,\phi_j,u\prime} = \dfrac{V^{t}_{i,\phi_j,u\prime_L}}{V^{max}_{i,\phi_j,u\prime_L}}$;

}

A1.2 Update Approach Link Vehicle Count Function for Phase ϕ_j :

{

Go to the approach link $L_{i,\varphi_j,u'}$ of ϕ_j;

// First, count the total vehicles on the whole approach link

Estimate $V^{max}_{i,\phi_j,u'_L} = \dfrac{(n_{i,\phi_j,e,u'} \times l_{i,\phi_j,e,u'} + n_{i,\phi_j,o,u'} \times l_{i,\phi_j,o,u'})}{l^c}$

//Set some conditions for the 'Standing Vehicle' Counts as estimated error in link vehicle counts. It occurs because of the departure vehicles with the detectors counts of detector 1 and detector 2, while the associated phase is 'red' flagged

if ($I^{R,t}_{i,\phi_j,u'} = 1$), then

{

Set $S^{V,t}_{i,\phi_j,u'}$ = Upper rounded Integer of $(n_{i,\phi_j,e,u'} + n_{i,\phi_j,o,u'})/2$;

}

else

{

Set $S^{V,t}_{i,\phi_j,u'}$ = Lower rounded Integer of $(n_{i,\phi_j,e,u'} + n_{i,\phi_j,o,u'})/2$;

}

if ($C^{V,t}_{i,\phi_j,u',1} + C^{V,t}_{i,\phi_j,u',2} \leq 3$), then

{

Set $S^{V,t}_{i,\phi_j,u'} = 0$;

}

if ($C^{V,t}_{i,\phi_j,u',4} + C^{V,t}_{i,\phi_j,u',1} + C^{V,t}_{i,\phi_j,u',2} = 0$), then

{

Set $S^{V,t}_{i,\phi_j,u'} = 0$;

}

if ($C^{V,t}_{i,\phi_j,u',4} + C^{V,t}_{i,\phi_j,u',5} + C^{V,t}_{i,\phi_j,u',1} + C^{V,t}_{i,\phi_j,u',2} = 0$), then

{

Set $S^{V,t}_{i,\phi_j,u'} = 0$;

}

if $(C^{V,t}_{i,\phi_j,u',2} + C^{V,t}_{i,\phi_j,u',5} = 0)$, then

{

Set $S^{V,t}_{i,\phi_j,u'} = 0$;

}

Estimate $V^{t}_{i,\phi_j,u'_L} = V^{t-1}_{i,\phi_j,u'_L} + C^{V,t}_{i,\phi_j,u',4} - C^{V,t}_{i,\phi_j,u',1} - C^{V,t}_{i,\phi_j,u',2} + S^{V,t}_{i,\phi_j,u'}$

Reset $V^{t}_{i,\phi_j,u'_L} = $ minimum $\{V^{t}_{i,\phi_j,u'_L}, V^{max}_{i,\phi_j,u'_L}\}$

if $(V^{t}_{i,\phi_j,u'_L} \leq 0)$, then

{

Reset $V^{t}_{i,\phi_j,u'_L} \leq 0$

}

// Then, estimate the number of vehicles on the left-storage lanes only

Estimate $V^{max}_{i,\phi_j,u'_o} = \dfrac{(n_{i,\phi_j,o,u'} \times l_{i,\phi_j,o,u'})}{l^c}$

//Set some conditions for the 'Standing Vehicle' Counts as estimated error in link vehicle counts on the left-storage lanes. It occurs because of the departure vehicles with the detectors counts of detector 2, while the associated phase is 'red' flagged

if $(I^{R,t}_{i,\phi_j,u'} = 1)$, then

{

Set $S^{V,t}_{i,\phi_j,u'_o} = $ Upper rounded Integer of $(n_{i,\phi_j,e,u'} + n_{i,\phi_j,o,u'})/2$;

}

else

{

Set $S^{V,t}_{i,\phi_j,u'_o} = 0$;

}

if $(C^{V,t}_{i,\phi_j,u',2} + C^{V,t}_{i,\phi_j,u',5} = 0)$, then

{

Set $S^{V,t}_{i,\phi_j,u'_o} = 0$;

}

if $(C^{V,t}_{i,\phi_j,u',2} = C^{V,t}_{i,\phi_j,u',5})$, then

{

Set $S^{V,t}_{i,\phi_j,u'_o} = 0$;

}

Estimate $V^t_{i,\phi_j,u'_o} = V^{t-1}_{i,\phi_j,u'_o} + C^{V,t}_{i,\phi_j,u',5} - C^{V,t}_{i,\phi_j,u',2} + S^{V,t}_{i,\phi_j,u'_o}$

Reset $V^t_{i,\phi_j,u'_o} = \text{minimum } \{V^t_{i,\phi_j,u'_o}, V^{max}_{i,\phi_j,u'_o}\}$

if $(V^t_{i,\phi_j,u'_o} \leq 0)$, then

{

Reset $V^t_{i,\phi_j,u'_o} = 0$;

}

Set $V^t_{i,\phi_j,u'_e} = V^t_{i,\phi_j,u'_L} - V^t_{i,\phi_j,u'_o}$;

}

A1.3 Update Module B (*Transit Signal Priority*) for Phase ϕ_j:

{

// Call the ' Function of priority criteria'

Initialize high priority bus count, $C_{i,\phi_j,u/}^{p,t}=0$;

Initialize normal priority bus count, $C_{i,\phi_j,u/}^{b,t}=0$;

Go to the approach link $L_{i,\varphi_j,u/}$ of ϕ_j;

for (Each of the *buses* on $L_{i,\varphi_j,u/}$ of ϕ_j, where $\phi_j \in \Phi_k$)

{

Get the bus of Bus ID $b_{i,\phi_j,u/}$;

if (the bus $b_{i,\phi_j,u/}$ is not bound to any bus stoppage on the link and is bound to the signal), then

 {

  Estimate $l_{i,\phi_j u/,}^{b}$;

   if ($l_{i,\phi_j u/,}^{b} <= 0.5 * l_{i,\phi_j,u/}$) then

    {

     Estimate $T_{i,\phi_j,u/}^{b} = \dfrac{l_{i,\phi_j u/}^{b}}{\bar{v}_{i,\phi_j,u/_{m,d}}^{t}}$;

    }

   else

    {

     Estimate $T_{i,\phi_j,u/}^{b} = \dfrac{(l_{i,\phi_j u/}^{b}-0.5\, l_{i,\phi_j,u/})}{\bar{v}_{i,\phi_j,u/_{u,m}}^{t}} + \dfrac{0.5\, l_{i,\phi_j,u/}}{\bar{v}_{i,\phi_j,u/_{m,d}}^{t}}$;

    }

  if ($g_{i,\Phi_k}^{\max} \neq g_{i,\Phi_k}^{\min}$), then

  {

   if ($T_{i,\phi_j,u/}^{b} <= \Delta g_{i,\Phi_k}$) then

   {

   Set $P_{i,\phi_j,u/}^{b} = 1$;

   }

else

{

Set $P^b_{i,\phi_j,u\prime} = 0$;

}

}

else

{

Set $P^b_{i,\phi_j,u\prime} = 0$;

}

if ($P^b_{i,\phi_j,u\prime} = 1$) then

{

Increase $C^{p,t}_{i,\phi_j,u\prime}$;

}

else

{

Increase $C^{b,t}_{i,\phi_j,u\prime}$;

}

}

}

If ($C^{p,t}_{i,\phi_j,u\prime} \geq 1$) then

{

Set $I^{P,t}_{i,\phi_j,u\prime} = 1$;

}

else

{

Set $I^{P,t}_{i,\phi_j,u\prime} = 0$;

}

}

A1.4 Update Car Count Function for Phase ϕ_j :

{

Go to the approach link $L_{i,\varphi_j,u/}$ of ϕ_j;

Call V^t_{i,ϕ_j,u'_e};

Call V^t_{i,ϕ_j,u'_o};

Call $C^{b,t}_{i,\phi_j,u/}$; // From Module B

Call $C^{p,t}_{i,\phi_j,u/}$; //From Module B

    if (ϕ_j is even)

    {

    Estimate $C^{b,t}_{i,\phi_j,u/} = V^t_{i,\phi_j,u'_e} - C^{b,t}_{i,\phi_j,u/} - C^{p,t}_{i,\phi_j,u/}$;

    }

    else

    {

    Estimate $C^{b,t}_{i,\phi_j,u/} = V^t_{i,\phi_j,u'_o} - C^{b,t}_{i,\phi_j,u/} - C^{p,t}_{i,\phi_j,u/}$;

    }

}

A1.5 Update Module C (*Downstream Blockage*) for Phase ϕ_j :

{

Go to the approach link $L_{i,\varphi_j,u/}$ of ϕ_j;

Call V^t_{i,ϕ_j,u'_e};

Call V^t_{i,ϕ_j,u'_o};

if (ϕ_j is even), then

{

Set $V^t_{i,\phi_j,u/} = V^t_{i,\phi_j,u'_e}$;

}

else

{

Set $V^t_{i,\phi_j,u/} = V^t_{i,\phi_j,u'_o}$;

}

// Now estimate $V^s_{i,\phi_j,u/}$.

If (ϕ_j is even) then,

{

For actuated type signals:

Set $V^s_{i,\phi_j,u/} = $ Integer of $\{(q_{i,\phi_j,e} \times n_{i,\phi_j,e,u/} \times \Delta g_{i,\Phi_k})/3600\}$;

For pre-timed type signals:

Set $V^s_{i,\phi_j,u/} = $ Integer of $\{(q_{i,\phi_j,e} \times n_{i,\phi_j,e,u/} \times g_{i,\Phi_k})/3600\}$;

}

else

{

For the actuated type signals:

Set $V^s_{i,\phi_j,u/} = $ Integer of $\{(q_{i,\phi_j,o} \times n_{i,\phi_j,o,u/} \times \Delta g_{i,\Phi_k})/3600\}$;

For the pre-timed type signals:

Set $V^s_{i,\phi_j,u/} = $ Integer of $\{(q_{i,\phi_j,o} \times n_{i,\phi_j,o,u/} \times g_{i,\Phi_k})/3600\}$;

}

Estimate $d^t_{i,\phi_j,u/} = $ min $\{V^t_{i,\phi_j,u/}, V^s_{i,\phi_j,u/}\}$;

Go to the exit link $L_{i,\varphi_j,d/}$ of ϕ_j;

Call $V_{i,\phi_j,d/}^{max}$;

Call $V_{i,\phi_j,d/}^{t}$;

Estimate, $S_{i,\phi_jd/,}^{t}=V_{i,\phi_j,d/}^{max} - V_{i,\phi_j,d/}^{t}$;

      If $(d_{i,\phi_j,u/}^{t} > S_{i,\phi_jd/}^{t})$ then

      {

      Set $I_{i,\phi_j,d/}^{B,t} = 1$;

      }

      else

      {

      Set $I_{i,\phi_j,d/}^{B,t} = 0$;

      }

}

A1.6 Update Exit Link Vehicle Count Function of Module C for Phase ϕ_j :

{

Go to the downstream exit link $L_{i,\varphi_j,d/}$ of ϕ_j;

Estimate $V^{max}_{i,\phi_j,d/} = \frac{(n_{i,\phi_j,e,d/} \times l_{i,\phi_j,e,d/} + n_{i,\phi_j,e,d/} \times l_{i,\phi_j,e,d})}{l^c}$

//Set some conditions for the 'Standing Vehicle' Counts as estimated error in downstream exit link vehicle counts. It occurs because of the departure vehicles with the detectors counts of detector 1 and detector 2 while the vehicles stop on these. However, the Module C does not know the information if the downstream junction of the downstream exit link is signalized or un-signalized. Also, it does not know the information of the 'traffic regime status' of the downstream exit link.

Set $S^{V,t}_{i,\phi_j,u/} = $ Lower rounded Integer of $(n_{i,\phi_j,e,u/} + n_{i,\phi_j,o,u/})/2$;

if $(C^{V,t}_{i,\phi_j,d/,1} + C^{V,t}_{i,\phi_j,d/,2} \leq 3)$, then

{

Set $S^{V,t}_{i,\phi_j,d/} = 0$;

}

if $(C^{V,t}_{i,\phi_j,d/,1} + C^{V,t}_{i,\phi_j,d/,2} + C^{V,t}_{i,\phi_j,d/,4} = 0)$, then

{

Set $S^{V,t}_{i,\phi_j,d/} = 0$;

}

if $(C^{V,t}_{i,\phi_j,d/,1} + C^{V,t}_{i,\phi_j,d/,2} + C^{V,t}_{i,\phi_j,d/,4} + C^{V,t}_{i,\phi_j,d/,5} = 0)$, then

{

Set $S^{V,t}_{i,\phi_j,d/} = 0$;

}

if $(C^{V,t}_{i,\phi_j,d/,2} + C^{V,t}_{i,\phi_j,d/,5} = 0)$, then

{

Set $S_{i,\phi_j,d^/}^{V,t} = 0;$

}

Estimate $V_{i,\phi_j,d^/}^t = V_{i,\phi_j,d^/}^{t-1} + C_{i,\phi_j,d^/,4}^{V,t} - C_{i,\phi_j,d^/,1}^{V,t} - C_{i,\phi_j,d^/,2}^{V,t} + S_{i,\phi_j,d^/}^{V,t}$

Reset $V_{i,\phi_j,d^/}^t = \text{minimum } \{V_{i,\phi_j,d^/}^t, V_{i,\phi_j,d^/}^{max}\}$

}

A1.7 Update Module D (*Incident Status*) for Phase ϕ_j :

{

Go to the approach link $L_{i,\varphi_j,d\prime}$ of ϕ_j;

if (time, t = End of incident time interval, θ) then

{

Estimate $\Delta C_{i,\phi_j,u\prime,d}^{\theta,t}$ and set $X_{1,i,\phi_j}^t = \Delta C_{i,\phi_j,u\prime,d}^{\theta,t}$;

Estimate $\Delta C_{i,\phi_j,u\prime,m}^{\theta,t}$ and set $X_{2,i,\phi_j}^t = \Delta C_{i,\phi_j,u\prime,m}^{\theta,t}$;

Estimate $\Delta C_{i,\phi_j,u\prime,u}^{\theta,t}$ and set $X_{3,i,\phi_j}^t = \Delta C_{i,\phi_j,u\prime,u}^{\theta,t}$;

Estimate $\Delta v_{i,\phi_j,u\prime,d}^{\theta,t}$ and set $X_{4,i,\phi_j}^t = \Delta v_{i,\phi_j,u\prime,d}^{\theta,t}$;

Estimate $\Delta v_{i,\phi_j,u\prime,m}^{\theta,t}$ and set $X_{5,i,\phi_j}^t = \Delta v_{i,\phi_j,u\prime,m}^{\theta,t}$;

Estimate $\Delta v_{i,\phi_j,u\prime,u}^{\theta,t}$ and set $X_{6,i,\phi_j}^t = \Delta v_{i,\phi_j,u\prime,u}^{\theta,t}$;

Set $X_7 = \theta$;

}

Estimate $p_{i,\phi_j,u\prime}^{\theta,t} = \frac{e^{(bX)}}{1+e^{bX}}$;

If ($p_{i,\phi_j,u\prime}^{\theta,t} \geq 0.5$) then

{

Set $I_{i,\phi_j,u\prime}^{N,t} = 1$;

}

else

```
            {
            Set $I_{i,\phi_j,u\prime}^{N,t} = 0$;

            }

}
```

A1.8 Update Node Signal State of Intersection _i_:

{

Set Current Time, t = simulation clock second

Go to the intersection (i.e., node) i;

for (each phase ϕ_j at intersection _i_ at time _t_);

    {

      if (Current time, t = End of detector data aggregation time interval, Δt),

      then

          {

            Update Module A for phase ϕ_j;

            Update Approach Link Vehicle Count Function for phase

            ϕ_j;

            Update Module C for phase ϕ_j;

            Update Exit Link Vehicle Count Function for phase ϕ_j;

          }

      if (Current time, t = End of incident prediction time interval, θ), then

          {

            Update Module D for phase ϕ_j;

          }

      Update Module B for phase ϕ_j;

      Update Car Count Function for phase ϕ_j;

      }

// Initialize the node signal state

        if (Current Time, t <=1), then

          {

// Start with a specific phase set

        For Dual Phase Operation Settings:

            Current Phase Set, $\Phi_c = \Phi_4$;

            Optimum Phase Set, $\Phi_o = \Phi_4$;

        For Split Phase Operation Settings:

            Current Phase Set, $\Phi_c = \Phi_3$;

            Optimum Phase Set, $\Phi_o = \Phi_3$;

For Protected Phase Operation Settings:

$$\text{Current Phase Set, } \Phi_c = \Phi_1;$$

$$\text{Optimum Phase Set, } \Phi_o = \Phi_1;$$

}

if $((t^g_{i,\Phi_c} < g^{max}_{i,\Phi_k})$ AND $(\Phi_c = \Phi_o)$ AND $(P^y_{i,\Phi_c} = 1)$ AND $(P^r_{i,\Phi_c} = 1))$, then

{

Set Φ_c as Green;

Increase t^g_{i,Φ_c}: $t^g_{i,\Phi_c} = t^g_{i,\Phi_c} + 1$;

// Now, check for optimum phase set at the end of minimum green time or at the end of each extended green time interval of a phase set

if $((t^g_{i,\Phi_c} = g^{min}_{i,\Phi_k}))$ OR $((t^g_{i,\Phi_c} > g^{min}_{i,\Phi_k})$ AND $(t^g_{i,\Phi_c} \% \Delta g = 0))$

{

Initialize and estimate Z^t_{i,Φ_c} for the current Φ_c.

Set $\Phi_o = \Phi_c$;

Set $Z^t_{i,\Phi_o} = Z^t_{i,\Phi_c}$;

for (Each of the *s* candidate phase sets of Ψ_c, where $\Phi_c \in \Psi_c$)

{

Go to phase set Φ^{k,Ψ_c} , where *k=1,2,..s*

Estimate Z^t_{i,Φ_k} for this phase set Φ^{k,Ψ_c} ;

if $(Z^t_{i,\Phi_k} > Z^t_{i,\Phi_o})$, then

{

Set $\Phi_{c*1} = \Phi^{k,\Psi_c}$;

Set $Z^t_{i,\Phi_o} = Z^t_{i,\Phi_k}$;

}

}

Set $\Phi_n = \Phi_o$;

Reset $\Phi_o = \Phi_{c*1}$;

if $(\Phi_c \neq \Phi_o)$, then

// This check if current phase set to go for next time step until maximum green

$$\{$$

Reset $t^g_{i,\Phi_c}=0;$

Reset $P^y_{i,\Phi_c}=0;$

Keep $P^r_{i,\Phi_c}=1;$

$$\}$$

// Start of 2nd highest Z value Phase Set Identification

Initialize $\Phi_{c*2}=\Phi_6;$ // Using call next phase function

Initialize, $Z^t_{i,\Phi_{c*2}}= 0.0;$

for (Each of the s candidate phase sets of Ψ_c, where $\Phi_c \in \Psi_c$)

$$\{$$

Go to phase set Φ^{k,Ψ_c} , where $k=1,2,...s$

Estimate Z^t_{i,Φ_k} for this phase set Φ^{k,Ψ_c} ;

if (($Z^t_{i,\Phi_k} <= Z^t_{i,\Phi_o}$) AND ($Z^t_{i,\Phi_k}>= Z^t_{i,\Phi_{c*2}}$) AND ($\Phi_c \neq \Phi^{k,\Psi_c}$)), then

$$\{$$

Set $\Phi_{c*2}=\Phi^{k,\Psi_c};$

Set $Z^t_{i,\Phi_{c*2}}=Z^t_{i,\Phi_k};$

$$\}$$

$$\}$$

// Set condition here for second highest set.

if ((($g^{max}_{i,\Phi_k}- t^g_{i,\Phi_c}$) $<= \Delta g_{i,\Phi_k}$) AND ($\Phi_c= \Phi_o$)), then

$$\{$$

Reset $\Phi_o= \Phi_{c*2}$;

Reset $t^g_{i,\Phi_c}=0;$

Reset $P^y_{i,\Phi_c}=0;$

252

$$\text{Keep } P^r_{i,\Phi_c}=1;$$

}

}

}

// End of green signals

// Start of yellow signals

else if $((t^y_{i,\Phi_c} <= y_{i,\Phi_k})$ AND $(\Phi_c \neq \Phi_o)$ AND $(P^y_{i,\Phi_c} =0)$ AND $(P^r_{i,\Phi_c}=1))$, then

{

Set Φ_c to Yellow Transition;

Increase $t^y_{i,\Phi_c}: t^y_{i,\Phi_c} = t^y_{i,\Phi_c} +1;$

if $(t^y_{i,\Phi_c} = y_{i,\Phi_k})$, then

{

Reset $t^y_{i,\Phi_c} = 0;$

Reset $P^r_{i,\Phi_c}=0;$

}

}

// Start of red signals

else if $((t^r_{i,\Phi_c} <= r_{i,\Phi_k})$ AND $(\Phi_c \neq \Phi_o)$ AND $(P^y_{i,\Phi_c} =0)$ AND $(P^r_{i,\Phi_c}=0))$, then

{

Set Φ_c to Red Transition;

Increase $t^r_{i,\Phi_c}: t^r_{i,\Phi_c} = t^r_{i,\Phi_c} +1;$

if $(t^r_{i,\Phi_c} = r_{i,\Phi_k})$, then

{

Reset $t^r_{i,\Phi_c} = 0;$

Reset $P^y_{i,\Phi_c}=1;$

Reset $P^r_{i,\Phi_c}=1;$

Reset $\Phi_c = \Phi_o;$

}

}

}

APPENDIX 2

A2.1 Ahmed & Hawas (2012)

A Threshold-Based Real-Time Incident Detection System for Urban Traffic Networks

Faisal Ahmed[a,*], Yaser E. Hawas[b]

[a]Ph.D. Candidate, Department of Civil and Environmental Engineering, College of Engineering, United Arab Emirates (UAE) University, Al Ain, Post Box: 17777, United Arab Emirates.

[b]Professor, Department of Civil and Environmental Engineering, College of Engineering, United Arab Emirates (UAE) University, Al-Ain, P.O. Box 17777, United Arab Emirates.

Abstract

As incident detection on a typical busy urban road link or intersection still demands more efficient algorithms, this paper introduces a methodology that can be used to characterize the various traffic patterns (incident or no incident) using typical link passage detectors. Offline urban incident scenarios are generated using a microscopic simulation model assuming varying traffic link flows, signal green phase and cycle times, link lengths. Similar scenarios are also generated for non-incident cases. Three detectors were assumed on each link to extract traffic measures. Comparative numerical statistical analyses were conducted to identify the traffic measures (such as the average speed and flow) that are likely to be affected by the incidents. And further analysis was conducted to quantify the most probable thresholds to be used in the proposed urban incident detection model. The proposed model is validated using simulation data. The performance of the proposed model is assessed using dynamic performance indicators such as the success rate of detecting an incident at a specific cycle time, and the false alarm rate.

© 2012 Published by Elsevier Ltd. Selection and/or peer review under responsibility of the Programme Committee of the Transport Research Arena 2012

Keywords: Urban incident detection model; detector; average speed; regression; detection rate; false alarm rate

1. Introduction

Handfuls of research have been developed and incidents detections algorithms for freeways and urban expressway or tunnels are already there with the commercial traffic control systems. On the other hand, detecting an incident on an urban road link or intersection is very difficult to estimate. Urban roads and intersections are interrupted basically by cross-roads, entry-exit to/from the arterial link, pedestrian cross-walk and traffic control signal systems within very short space and time intervals. The traffic dynamics of the recurrent congested urban link and intersection is very similar to the sudden incident scenario. This makes it difficult to distinguish between an incident and non-incident case with the related traffic parameters. Apparently, the developed research in this area is not that significant and therefore, this paper strives to fill up some of this research gaps.

This paper describes the development of a threshold-based offline urban incident detection model that tries to detect the incident status of each analysis time-step of the incident(s) occurred on a link of a pre-timed signal network. Here, the analysis time step is taken as the cycle time of the downstream signalized intersection of the subject link. The used approach is to develop some simple regression models using the extracted traffic measures data from the fixed detectors.

*Corresponding Author. Tel: +971 3 767 3332, Fax: +971 3 767 3354,
E-mail address: Faisal_Ahmed@uaeu.ac.ae

A Fuzzy Logic Model for Real-time Incident Detection in Urban Road Network

Faisal Ahmed and Yaser E. Hawas

Department of Civil and Environmental Engineering, COE, United Arab Emirates (UAE) University, Al Ain, U.A.E.

Abstract: Incident detection systems for the urban traffic network are still lacking efficient algorithms or models for better performance. This paper presents a new urban incident detection system based on the application of Fuzzy Logic modeling. Offline urban incident and corresponding non-incident scenarios are generated using a microscopic simulation model assuming varying traffic link flows, phase timing, cycle times, and link lengths. The traffic measures are extracted from three detectors on each link. Statistical significance analysis was utilized to identify the significant input variables to be used in developing the Neuro-fuzzy model. A set of data was generated and used for training of the proposed Neuro-fuzzy model, while another set was used for validation. The performance of the proposed model is assessed using the success and the false alarm rates of detecting an incident at a specific cycle time.

1 INTRODUCTION

The loop detector-based freeway incident detection algorithms in literature could be generally categorized into adopted analytical and heuristic-based techniques (Parkany, 2005). Notable roadway detector-based recent urban incident detection models are mostly based on statistical regression (Ahmed and Hawas, 2012), Bayesian network (Zhang and Taylor, 2006) and fuzzy logic modeling (Hawas, 2007) techniques. Non-parametric optimization technique (Liu et al., 2007) and discriminant analysis (Sermons and Koppelman, 1996) was used for the probe-vehicle based urban incident detection system. Neural network models were also developed (Dia and Thomas, 2011) using both loop detector and probe-vehicle data.

Typically, the focus of these algorithms was primarily on estimating the performance measures using the percentage of the total number of incidents detected or falsely identified incidents for the simulated duration where the whole incident as a single unit. These algorithms do not particularly account for the true start or the terminating times of individual incidents as a criterion of evaluation. Moreover, these do not consider the effects of the link lengths of the approaches, the hourly traffic volumes, the signal settings and the cycle times of

the intersections. This study strives to fill in some of these research gaps of urban incident detection areas for more efficient detection model.

This study assumes that the duration of an incident is divided into smaller time steps and the algorithm is operated repeatedly each (shorter time resolution) step to detect incidents. The proposed fuzzy-model is capable of identifying whether there is an incident or not during each time step. The simulation period may be divided to hundreds of such shorter time steps. With this approach the actual incident start and clearance time could be identified to a great extent.

Therefore, this paper comes up with a new form of urban incident detection model using fuzzy-logic. The model detects the incident status each time step, under various signal cycle times, link lengths and traffic volumes combinations.

2 METHODOLOGY

The conceptual assumption is that the average detectors' readings in the case of incident may significantly vary from the counter readings in the case of no incident. A micro-simulation based methodology is adopted. A typical pre-timed urban intersection network that consists of four links of

465

APPENDIX 3

Table A3.1: Comparative productivity performance of the proposed control system(s) (in *Bus Trips*)

	Demand Case A						
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	1	54	54	Yes	54	Yes
	Protected Actuated	2	54	54	Yes	54	Yes
	Protected Pre-timed	3	54	54	Yes	54	Yes
	Split Actuated	4	54	54	Yes	54	Yes
	Split Pre-timed	5	54	54	Yes	54	Yes
Big	Dual Actuated	6	54	54	Yes	54	Yes
	Protected Actuated	7	54	54	Yes	54	Yes
	Protected Pre-timed	8	54	54	Yes	54	Yes
	Split Actuated	9	54	54	Yes	54	Yes
	Split Pre-timed	10	54	54	Yes	54	Yes
Mix	Dual Actuated	11	54	54	Yes	54	Yes
	Protected Actuated	12	54	54	Yes	54	Yes
	Protected Pre-timed	13	54	54	Yes	54	Yes
	Split Actuated	14	54	54	Yes	54	Yes
	Split Pre-timed	15	54	54	Yes	54	Yes
	Demand Case B						
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	16	90	89	No	88	No
	Protected Actuated	17	90	90	Yes	90	Yes
	Protected Pre-timed	18	85	90	Yes	90	Yes
	Split Actuated	19	90	90	Yes	90	Yes

Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
	Split Pre-timed	20	84	90	Yes	90	Yes
Big	Dual Actuated	21	86	84	No	89	Yes
	Protected Actuated	22	86	90	Yes	90	Yes
	Protected Pre-timed	23	75	90	Yes	90	Yes
	Split Actuated	24	86	90	Yes	90	Yes
	Split Pre-timed	25	81	89	Yes	89	Yes
Mix	Dual Actuated	26	88	87	No	86	No
	Protected Actuated	27	88	90	Yes	90	Yes
	Protected Pre-timed	28	84	90	Yes	90	Yes
	Split Actuated	29	88	90	Yes	90	Yes
	Split Pre-timed	30	81	90	Yes	90	Yes
Demand Case C							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	31	89	89	Yes	89	Yes
	Protected Actuated	32	89	90	Yes	90	Yes
	Protected Pre-timed	33	83	90	Yes	90	Yes
	Split Actuated	34	88	90	Yes	90	Yes
	Split Pre-timed	35	76	90	Yes	90	Yes
Big	Dual Actuated	36	86	85	No	85	No
	Protected Actuated	37	86	90	Yes	87	Yes
	Protected Pre-timed	38	80	89	Yes	89	Yes
	Split Actuated	39	86	90	Yes	90	Yes
	Split Pre-timed	40	76	89	Yes	90	Yes
Mix	Dual Actuated	41	87	87	Yes	88	Yes
	Protected Actuated	42	91	90	No	90	No
	Protected Pre-timed	43	84	90	Yes	90	Yes
	Split Actuated	44	87	90	Yes	90	Yes
	Split Pre-timed	45	85	90	Yes	90	Yes

Demand Case D								
					Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)		*Bus Trips*	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	46	108		108	Yes	108	Yes
	Protected Actuated	47	108		107	No	92	No
	Protected Pre-timed	48	106		108	Yes	108	Yes
	Split Actuated	49	108		108	Yes	108	Yes
	Split Pre-timed	50	107		108	Yes	108	Yes
Big	Dual Actuated	51	107		108	Yes	108	Yes
	Protected Actuated	52	108		98	No	91	No
	Protected Pre-timed	53	106		108	Yes	102	No
	Split Actuated	54	108		108	Yes	108	Yes
	Split Pre-timed	55	99		108	Yes	108	Yes
Mix	Dual Actuated	56	108		108	Yes	108	Yes
	Protected Actuated	57	108		98	No	90	No
	Protected Pre-timed	58	105		107	Yes	102	No
	Split Actuated	59	107		108	Yes	108	Yes
	Split Pre-timed	60	105		108	Yes	108	Yes
Demand Case E1								
					Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)		*Bus Trips*	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	61	160		159	No	160	Yes
	Protected Actuated	62	159		128	No	87	No
	Protected Pre-timed	63	148		124	No	119	No
	Split Actuated	64	146		161	Yes	162	Yes
	Split Pre-timed	65	140		158	Yes	158	Yes

| Network grid type | Phase settings (Control Type) | Model ID | CORSIM (*Bus Trips*) | Logic with IM | | Logic w/o IM | |
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Big	Dual Actuated	66	156	158	Yes	157	Yes
	Protected Actuated	67	154	143	No	109	No
	Protected Pre-timed	68	141	157	Yes	127	No
	Split Actuated	69	140	158	Yes	158	Yes
	Split Pre-timed	70	141	155	Yes	158	Yes
Mix	Dual Actuated	71	155	157	Yes	156	Yes
	Protected Actuated	72	156	114	No	100	No
	Protected Pre-timed	73	141	136	No	110	No
	Split Actuated	74	143	156	Yes	156	Yes
	Split Pre-timed	75	140	155	Yes	155	Yes

Demand Case E2							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	76	158	155	No	157	No
	Protected Actuated	77	156	115	No	71	No
	Protected Pre-timed	78	143	131	No	97	No
	Split Actuated	79	149	159	Yes	159	Yes
	Split Pre-timed	80	137	153	Yes	155	Yes
Big	Dual Actuated	81	147	157	Yes	154	Yes
	Protected Actuated	82	149	136	No	123	No
	Protected Pre-timed	83	137	149	Yes	124	No
	Split Actuated	84	142	155	Yes	159	Yes
	Split Pre-timed	85	139	147	Yes	153	Yes
Mix	Dual Actuated	86	156	153	No	153	No
	Protected Actuated	87	156	116	No	96	No
	Protected Pre-timed	88	143	137	No	102	No
	Split Actuated	89	147	154	Yes	154	Yes
	Split Pre-timed	90	143	150	Yes	157	Yes

Demand Case F1							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	91	208	218	Yes	205	No
	Protected Actuated	92	242	130	No	93	No
	Protected Pre-timed	93	165	139	No	103	No
	Split Actuated	94	184	158	No	194	Yes
	Split Pre-timed	95	153	190	Yes	221	Yes
Big	Dual Actuated	96	250	255	Yes	257	Yes
	Protected Actuated	97	245	238	No	154	No
	Protected Pre-timed	98	215	194	No	158	No
	Split Actuated	99	224	238	Yes	238	Yes
	Split Pre-timed	100	223	231	Yes	238	Yes
Mix	Dual Actuated	101	201	186	No	203	Yes
	Protected Actuated	102	227	130	No	116	No
	Protected Pre-timed	103	192	167	No	113	No
	Split Actuated	104	184	170	No	170	No
	Split Pre-timed	105	172	197	Yes	207	Yes
Demand Case F2							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	106	167	207	Yes	197	Yes
	Protected Actuated	107	246	128	No	97	No
	Protected Pre-timed	108	161	147	No	105	No
	Split Actuated	109	179	148	No	194	Yes

	Split Pre-timed	110	176	163	No	210	Yes
Big	Dual Actuated	111	250	247	No	249	No
	Protected Actuated	112	253	180	No	158	No
	Protected Pre-timed	113	207	204	No	150	No
	Split Actuated	114	232	232	Yes	240	Yes
	Split Pre-timed	115	227	238	Yes	239	Yes
Mix	Dual Actuated	116	188	210	Yes	211	Yes
	Protected Actuated	117	229	137	No	118	No
	Protected Pre-timed	118	174	175	No	138	No
	Split Actuated	119	187	173	No	177	No
	Split Pre-timed	120	154	204	Yes	209	Yes

Table A3.2: Comparative productivity performance of the proposed control system(s) (in *Person Trips*)

				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	(*Person Trips*)	Similar or Improvement	(*Person Trips*)	Similar or Improvement
Demand Case A							
Small	Dual Actuated	1	6608	6466	No	6499	No
	Protected Actuated	2	6678	6448	No	6502	No
	Protected Pre-timed	3	6552	6396	No	6447	No
	Split Actuated	4	6641	6527	No	6532	No
	Split Pre-timed	5	6430	6463	Yes	6472	Yes
Big	Dual Actuated	6	6566	6413	No	6433	No
	Protected Actuated	7	6501	6361	No	6398	No
	Protected Pre-timed	8	6373	6323	No	6335	No
	Split Actuated	9	6525	6469	No	6474	No
	Split Pre-timed	10	6452	6403	No	6391	No
Mix	Dual Actuated	11	6589	6454	No	6464	No
	Protected Actuated	12	6615	6445	No	6458	No
	Protected Pre-timed	13	6520	6354	No	6424	No
	Split Actuated	14	6634	6502	No	6502	No
	Split Pre-timed	15	6490	6444	No	6492	Yes

Demand Case B							
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	(*Person Trips*)	Similar or Improvement	(*Person Trips*)	Similar or Improvement
Small	Dual Actuated	16	17680	17412	No	17391	No
	Protected Actuated	17	17835	17492	No	17424	No
	Protected Pre-timed	18	17344	17319	No	17381	Yes
	Split Actuated	19	17850	17407	No	17482	No
	Split Pre-timed	20	17260	17281	Yes	17332	Yes
Big	Dual Actuated	21	17536	17227	No	17444	No
	Protected Actuated	22	17500	17313	No	17369	No
	Protected Pre-timed	23	16786	17131	Yes	17193	Yes
	Split Actuated	24	17370	17380	Yes	17421	Yes
	Split Pre-timed	25	16822	17147	Yes	17198	Yes
Mix	Dual Actuated	26	17665	17440	No	17331	No
	Protected Actuated	27	17783	17466	No	17474	No
	Protected Pre-timed	28	17234	17320	Yes	17381	Yes
	Split Actuated	29	17745	17466	No	17479	No
	Split Pre-timed	30	17123	17245	Yes	17316	Yes

Demand Case C							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	Logic with IM		Logic w/o IM	
				Person Trips	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	31	28124	27933	No	27979	No
	Protected Actuated	32	27955	27892	No	27853	No
	Protected Pre-timed	33	27158	27653	Yes	27670	Yes
	Split Actuated	34	27952	27736	No	27738	No
	Split Pre-timed	35	27011	27477	Yes	27530	Yes
Big	Dual Actuated	36	27701	27497	No	27550	No
	Protected Actuated	37	27582	26965	No	26366	No
	Protected Pre-timed	38	26737	27093	Yes	27131	Yes
	Split Actuated	39	27550	27368	No	27484	No
	Split Pre-timed	40	26554	27057	Yes	27203	Yes
Mix	Dual Actuated	41	27701	27484	No	27549	No
	Protected Actuated	42	27968	26722	No	27083	No
	Protected Pre-timed	43	27009	27154	Yes	27270	Yes
	Split Actuated	44	27838	27363	No	27401	No
	Split Pre-timed	45	27184	27091	No	27152	No

Demand Case D							
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	*Person Trips*	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	46	42134	41889	No	42001	No
	Protected Actuated	47	41913	37653	No	32741	No
	Protected Pre-timed	48	40829	41174	Yes	41000	Yes
	Split Actuated	49	41490	41371	No	41423	No
	Split Pre-timed	50	40839	41125	Yes	41238	Yes
Big	Dual Actuated	51	41135	41046	No	41112	No
	Protected Actuated	52	41131	34678	No	29518	No
	Protected Pre-timed	53	39888	39596	No	36775	No
	Split Actuated	54	40708	40269	Yes	40507	Yes
	Split Pre-timed	55	39577	40045	Yes	40304	Yes
Mix	Dual Actuated	56	41210	40963	No	41158	No
	Protected Actuated	57	41385	32880	No	29321	No
	Protected Pre-timed	58	40009	38961	No	37108	No
	Split Actuated	59	40988	41159	Yes	40469	No
	Split Pre-timed	60	40107	40022	No	40258	Yes

Demand Case E1							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	Logic with IM		Logic w/o IM	
				Person Trips	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	61	57722	57678	No	57756	Yes
	Protected Actuated	62	56789	36683	No	26436	No
	Protected Pre-timed	63	53181	44480	No	41277	No
	Split Actuated	64	53668	55391	Yes	55972	Yes
	Split Pre-timed	65	51713	55202	Yes	55743	Yes
Big	Dual Actuated	66	56064	56277	Yes	56321	Yes
	Protected Actuated	67	55266	37554	No	29736	No
	Protected Pre-timed	68	51204	49388	No	37371	No
	Split Actuated	69	52905	53818	Yes	54299	Yes
	Split Pre-timed	70	52278	53562	Yes	54407	Yes
Mix	Dual Actuated	71	55488	55474	No	55747	Yes
	Protected Actuated	72	55568	32577	No	26919	No
	Protected Pre-timed	73	50697	44734	No	33124	No
	Split Actuated	74	52225	53084	Yes	53628	Yes
	Split Pre-timed	75	51045	53038	Yes	53780	Yes

Demand Case E2							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	Logic with IM		Logic w/o IM	
				Person Trips	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	76	57069	56353	No	56370	No
	Protected Actuated	77	56019	29198	No	19706	No
	Protected Pre-timed	78	51562	43584	No	31008	No
	Split Actuated	79	54181	54808	Yes	55730	Yes
	Split Pre-timed	80	50715	53221	Yes	54481	Yes
Big	Dual Actuated	81	55477	55626	Yes	55267	No
	Protected Actuated	82	54705	32050	No	26424	No
	Protected Pre-timed	83	50350	47062	No	32592	No
	Split Actuated	84	52896	53336	Yes	54372	Yes
	Split Pre-timed	85	51392	51833	Yes	53006	Yes
Mix	Dual Actuated	86	55354	54085	No	53985	No
	Protected Actuated	87	55333	29345	No	21908	No
	Protected Pre-timed	88	51641	43758	No	29796	No
	Split Actuated	89	53482	52522	No	53569	Yes
	Split Pre-timed	90	51775	51053	No	52037	Yes

Demand Case F1							
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	*Person Trips*	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	91	63723	63221	No	60109	No
	Protected Actuated	92	71796	29724	No	20624	No
	Protected Pre-timed	93	54502	35620	No	24738	No
	Split Actuated	94	57000	42199	No	53137	No
	Split Pre-timed	95	48484	53451	Yes	60920	Yes
Big	Dual Actuated	96	75051	76010	Yes	75607	Yes
	Protected Actuated	97	72204	68646	No	27714	No
	Protected Pre-timed	98	62776	45675	No	31456	No
	Split Actuated	99	66492	65509	No	66932	Yes
	Split Pre-timed	100	65523	67507	Yes	68646	Yes
Mix	Dual Actuated	101	53859	52387	No	55312	Yes
	Protected Actuated	102	65168	29129	No	22636	No
	Protected Pre-timed	103	55069	39074	No	25456	No
	Split Actuated	104	54860	46048	No	47046	No
	Split Pre-timed	105	49036	53207	Yes	56142	Yes

Demand Case F2							
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	*Person Trips*	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	106	63723	59202	No	57761	No
	Protected Actuated	107	72681	27243	No	18266	No
	Protected Pre-timed	108	47588	40342	No	24536	No
	Split Actuated	109	51719	39023	No	54276	Yes
	Split Pre-timed	110	52365	46326	No	57879	Yes
Big	Dual Actuated	111	74838	71664	No	71430	No
	Protected Actuated	112	74297	32867	No	26358	No
	Protected Pre-timed	113	62506	47608	No	29405	No
	Split Actuated	114	67947	65443	No	68068	Yes
	Split Pre-timed	115	66121	66854	Yes	68222	Yes
Mix	Dual Actuated	116	52655	57614	Yes	55542	Yes
	Protected Actuated	117	66811	28004	No	21068	No
	Protected Pre-timed	118	50905	40708	No	27652	No
	Split Actuated	119	55633	47068	No	49105	No
	Split Pre-timed	120	45484	51511	Yes	54839	Yes

Table A3.3: Comparative efficiency performance of the proposed control system(s) (in *Average Delay/Person*)

Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Demand Case A							
Small	Dual Actuated	1	78	193.6	No	195.7	No
	Protected Actuated	2	91.5	213.7	No	203.1	No
	Protected Pre-timed	3	172.3	235.4	No	233.4	No
	Split Actuated	4	101.4	168.9	No	162.8	No
	Split Pre-timed	5	243	205.1	Yes	198.8	Yes
Big	Dual Actuated	6	79.4	191.8	No	190.6	No
	Protected Actuated	7	89.3	225.5	No	216.9	No
	Protected Pre-timed	8	183.1	266.7	No	251.9	No
	Split Actuated	9	97.7	161.9	No	155.3	No
	Split Pre-timed	10	226.5	218.7	Yes	204.7	Yes
Mix	Dual Actuated	11	77.5	198	No	199.5	No
	Protected Actuated	12	88.1	205.9	No	199.5	No
	Protected Pre-timed	13	170.2	240.8	No	227.9	No
	Split Actuated	14	98.6	163.5	No	163.5	No
	Split Pre-timed	15	228.5	208.8	Yes	201	Yes

	Demand Case B						
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	16	136.2	206.3	No	203.4	No
	Protected Actuated	17	138	204	No	201.7	No
	Protected Pre-timed	18	261.4	237.8	Yes	230.6	Yes
	Split Actuated	19	134.2	202.3	No	197.4	No
	Split Pre-timed	20	285	246	Yes	238.3	Yes
Big	Dual Actuated	21	137.3	203.1	No	200.3	No
	Protected Actuated	22	137.9	223.9	No	211.4	No
	Protected Pre-timed	23	262.4	279.6	No	263.8	No
	Split Actuated	24	139.3	204.6	No	192.2	No
	Split Pre-timed	25	275.3	267.3	Yes	250.2	Yes
Mix	Dual Actuated	26	136.9	207.2	No	205.8	No
	Protected Actuated	27	139.6	215.8	No	208.6	No
	Protected Pre-timed	28	253.1	255.7	No	247.7	Yes
	Split Actuated	29	137.8	205	No	195	No
	Split Pre-timed	30	276.1	259.3	Yes	245.3	Yes

Demand Case C							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	31	176.7	206.9	No	207.1	No
	Protected Actuated	32	173.6	223.9	No	224	No
	Protected Pre-timed	33	295.7	266.4	Yes	261.4	Yes
	Split Actuated	34	176.5	240.8	No	238.1	No
	Split Pre-timed	35	307.7	282.6	Yes	275.2	Yes
Big	Dual Actuated	36	177.1	210.7	No	209.1	No
	Protected Actuated	37	179.2	269.9	No	246.5	No
	Protected Pre-timed	38	291.2	307.5	No	295.8	No
	Split Actuated	39	184.4	247.9	No	231.2	No
	Split Pre-timed	40	319.4	304.6	Yes	281.5	Yes
Mix	Dual Actuated	41	179.8	216.6	No	212.6	No
	Protected Actuated	42	176.8	250.7	No	243.9	No
	Protected Pre-timed	43	302.2	289.7	Yes	280.9	Yes
	Split Actuated	44	182	250.2	No	237.9	No
	Split Pre-timed	45	304.8	299.2	Yes	281	Yes

				Logic with IM		Logic w/o IM	
Demand Case D
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	46	207.3	225.3	No	221	No
	Protected Actuated	47	209.1	285.7	No	256.1	No
	Protected Pre-timed	48	327	294.4	Yes	280.5	Yes
	Split Actuated	49	247.6	282.8	No	273.1	No
	Split Pre-timed	50	330.8	316.4	Yes	301.2	Yes
Big	Dual Actuated	51	210.6	225.6	No	218.9	No
	Protected Actuated	52	220.2	338.1	No	271.1	No
	Protected Pre-timed	53	347.1	342.4	Yes	310.1	Yes
	Split Actuated	54	251.8	301.8	No	275	No
	Split Pre-timed	55	343	340.4	Yes	309.2	Yes
Mix	Dual Actuated	56	214.2	237.9	No	229.7	No
	Protected Actuated	57	220.1	337.3	No	299.6	No
	Protected Pre-timed	58	352.8	339.1	Yes	305.5	Yes
	Split Actuated	59	253.2	294	No	283.8	No
	Split Pre-timed	60	341.1	337.3	Yes	313	Yes

				Demand Case E1				
					Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]		[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	61	233		234	No	230	Yes
	Protected Actuated	62	237.6		443	No	346.6	No
	Protected Pre-timed	63	417.9		381.9	Yes	370.1	Yes
	Split Actuated	64	364		370.7	No	341.3	Yes
	Split Pre-timed	65	418.3		394.1	Yes	360.7	Yes
Big	Dual Actuated	66	238		236.4	Yes	229.1	Yes
	Protected Actuated	67	267.2		414.3	No	305.4	No
	Protected Pre-timed	68	453.4		427.4	Yes	320.6	Yes
	Split Actuated	69	364.3		387.5	No	352.8	Yes
	Split Pre-timed	70	419.9		412	Yes	363.6	Yes
Mix	Dual Actuated	71	271.3		281	No	270.2	Yes
	Protected Actuated	72	269.8		458.3	No	382.1	No
	Protected Pre-timed	73	467		464	Yes	376.5	Yes
	Split Actuated	74	379.6		419.1	No	382.1	No
	Split Pre-timed	75	443.9		442	Yes	397.6	Yes
				Demand Case E2				
					Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]		[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	76	278.4		279.1	No	279.9	No
	Protected Actuated	77	282.5		624.2	No	444.7	No
	Protected Pre-timed	78	513.6		573.7	No	437.3	Yes
	Split Actuated	79	373.2		418.5	No	362.8	Yes

Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
	Split Pre-timed	80	494.4	519.3	No	448	Yes
Big	Dual Actuated	81	288.4	273.9	Yes	276.4	Yes
	Protected Actuated	82	305.5	502.6	No	356.2	No
	Protected Pre-timed	83	548.6	565.4	No	382.1	Yes
	Split Actuated	84	377.8	436.8	No	366.1	Yes
	Split Pre-timed	85	509.6	518.8	No	452.3	Yes
Mix	Dual Actuated	86	306.3	332.8	No	326	No
	Protected Actuated	87	300.9	646.4	No	439.2	No
	Protected Pre-timed	88	512	621	No	470.8	Yes
	Split Actuated	89	376.2	469.6	No	407.4	No
	Split Pre-timed	90	499.3	556.7	No	496.8	Yes

<div align="center">Demand Case F1</div>

Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	91	568.2	539.6	Yes	536.6	Yes
	Protected Actuated	92	491.4	752.8	No	407	Yes
	Protected Pre-timed	93	732.6	653.5	Yes	451.6	Yes
	Split Actuated	94	676.7	976.6	No	1030.3	No
	Split Pre-timed	95	697.6	923	No	825.3	No
Big	Dual Actuated	96	469.4	461.2	Yes	451.4	Yes
	Protected Actuated	97	528.8	785.6	No	462.3	Yes
	Protected Pre-timed	98	829.2	726.8	Yes	448.1	Yes
	Split Actuated	99	721.1	869.1	No	830.8	No
	Split Pre-timed	100	756.9	836.4	No	785.6	No
Mix	Dual Actuated	101	581.8	595.2	No	593.8	No
	Protected Actuated	102	476.9	770.6	No	523.5	No
	Protected Pre-timed	103	747.3	815.5	No	581.7	Yes
	Split Actuated	104	686.7	896.6	No	809	No
	Split Pre-timed	105	674.4	867.1	No	820.8	No

				Logic with IM		Logic w/o IM	
Demand Case F2							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	106	568.2	736	No	730.1	No
	Protected Actuated	107	497.4	965.3	No	451.9	Yes
	Protected Pre-timed	108	817.5	1090.5	No	607.3	Yes
	Split Actuated	109	717.1	1030.5	No	1017.4	No
	Split Pre-timed	110	752.6	943.9	No	853.7	No
Big	Dual Actuated	111	515.7	566.2	No	572.3	No
	Protected Actuated	112	521.9	758.2	No	511.7	Yes
	Protected Pre-timed	113	897.6	895	Yes	520.6	Yes
	Split Actuated	114	702.9	860.2	No	797.1	No
	Split Pre-timed	115	805.9	907.9	No	840.7	No
Mix	Dual Actuated	116	591.1	752.1	No	709.8	No
	Protected Actuated	117	483.7	1031.7	No	516.3	No
	Protected Pre-timed	118	805.7	1018.5	No	649.4	Yes
	Split Actuated	119	690.7	887.8	No	888.9	No
	Split Pre-timed	120	715.5	897.5	No	896.7	No

Table A3.4: Comparative efficiency performance of the proposed control system(s) (in *Average Trip Time/Person*)

Demand Case A							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	1	157.5	277.6	No	279.8	No
	Protected Actuated	2	176.1	297.6	No	287.1	No
	Protected Pre-timed	3	256.6	319.3	No	317.4	No
	Split Actuated	4	185.9	253	No	247.1	No
	Split Pre-timed	5	326.8	289.1	Yes	282.9	Yes
Big	Dual Actuated	6	248.3	359.7	No	358.6	No
	Protected Actuated	7	258.1	393	No	384.7	No
	Protected Pre-timed	8	351.1	433.9	No	419.4	No
	Split Actuated	9	266.4	330.2	No	323.6	No
	Split Pre-timed	10	394.7	386.7	Yes	372.6	Yes
Mix	Dual Actuated	11	204	323.9	No	325.5	No
	Protected Actuated	12	214.8	331.7	No	325.6	No
	Protected Pre-timed	13	296.4	366.3	No	353.8	No
	Split Actuated	14	225.6	289.6	No	289.6	No
	Split Pre-timed	15	354.9	334.6	Yes	327	Yes
Demand Case B							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	16	226.9	297.1	No	294.3	No
	Protected Actuated	17	228.1	294.5	No	292.3	No
	Protected Pre-timed	18	351.9	328.2	Yes	321.1	Yes

Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM [*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	Logic w/o IM [*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
	Split Actuated	19	224.2	292.8	No	287.9	No
	Split Pre-timed	20	375.7	336.4	Yes	328.8	Yes
Big	Dual Actuated	21	318.7	384.6	No	380.5	No
	Protected Actuated	22	318.4	403.5	No	391.2	No
	Protected Pre-timed	23	445.8	459	No	443.3	Yes
	Split Actuated	24	319.7	384.2	No	372	No
	Split Pre-timed	25	456.5	447	Yes	430	Yes
Mix	Dual Actuated	26	273	343.2	No	342	No
	Protected Actuated	27	274.9	351.1	No	344	No
	Protected Pre-timed	28	388.8	390.8	No	382.9	Yes
	Split Actuated	29	273.1	340.3	No	330.4	No
	Split Pre-timed	30	412.5	394.4	Yes	380.5	Yes
Demand Case C							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM [*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	Logic w/o IM [*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	31	272.4	302.6	No	302.7	No
	Protected Actuated	32	267.5	319.4	No	319.5	No
	Protected Pre-timed	33	390.1	361.9	Yes	356.8	Yes
	Split Actuated	34	270.5	336.3	No	333.6	No
	Split Pre-timed	35	403	378	Yes	370.6	Yes
Big	Dual Actuated	36	367.4	401	No	399.5	No
	Protected Actuated	37	367.2	458.5	No	435.6	No
	Protected Pre-timed	38	480.1	496.4	No	484.8	No
	Split Actuated	39	372.2	436.8	No	420.2	No
	Split Pre-timed	40	509	493.5	Yes	470.3	Yes
Mix	Dual Actuated	41	322.7	359.3	No	355.3	No
	Protected Actuated	42	317.2	392.5	No	385.9	No
	Protected Pre-timed	43	443.4	431.6	Yes	423	Yes
	Split Actuated	44	323.1	392.4	No	380.1	No
	Split Pre-timed	45	445.8	441	Yes	423	Yes

Demand Case D							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	46	304.7	322.6	No	318.4	No
	Protected Actuated	47	303.8	382	No	352.9	No
	Protected Pre-timed	48	421.6	391.5	Yes	377.7	Yes
	Split Actuated	49	342.2	380	No	370.3	No
	Split Pre-timed	50	425.3	413.5	Yes	372.1	Yes
Big	Dual Actuated	51	404.9	419.6	No	413	No
	Protected Actuated	52	409.9	531.7	No	463.1	No
	Protected Pre-timed	53	536.7	535.8	Yes	503.3	Yes
	Split Actuated	54	441	495.4	No	468.8	No
	Split Pre-timed	55	533.4	533.9	No	502.8	Yes
Mix	Dual Actuated	56	360.2	383.9	No	375.7	No
	Protected Actuated	57	362.7	482.2	No	443.8	No
	Protected Pre-timed	58	495.3	484.7	Yes	451	Yes
	Split Actuated	59	395.8	436.3	No	429.6	No
	Split Pre-timed	60	483.6	482.9	Yes	458.7	Yes
Demand Case E1							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	61	328	329.1	No	325	Yes
	Protected Actuated	62	330.3	535.2	No	440.4	No
	Protected Pre-timed	63	510.8	477	Yes	464.9	Yes
	Split Actuated	64	457.2	465.1	No	435.8	Yes
	Split Pre-timed	65	511.6	488.7	Yes	455.5	Yes

Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Big	Dual Actuated	66	428.3	426.4	Yes	419.4	Yes
	Protected Actuated	67	453.2	597.1	No	489	No
	Protected Pre-timed	68	639.9	614.6	Yes	507	Yes
	Split Actuated	69	551.4	576.5	No	542.1	Yes
	Split Pre-timed	70	606.6	601.4	Yes	552.9	Yes
Mix	Dual Actuated	71	414.2	423.7	No	413	Yes
	Protected Actuated	72	409.5	598.2	No	520.6	No
	Protected Pre-timed	73	607	606.2	Yes	516.8	Yes
	Split Actuated	74	519.9	561.1	No	524.3	No
	Split Pre-timed	75	584.2	584	Yes	540	Yes
Demand Case E2							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	76	373.5	374.3	No	374.9	No
	Protected Actuated	77	375.7	714.4	No	537.6	No
	Protected Pre-timed	78	607	667.6	No	532.1	Yes
	Split Actuated	79	466.7	512.9	No	457.5	Yes
	Split Pre-timed	80	588.2	613.9	No	542.8	Yes
Big	Dual Actuated	81	480.3	463.8	Yes	466.7	Yes
	Protected Actuated	82	492.5	680.2	No	530.1	No
	Protected Pre-timed	83	736	753.1	No	563.8	Yes
	Split Actuated	84	565.1	626.1	No	555.3	Yes
	Split Pre-timed	85	696.8	708.8	No	641.8	Yes
Mix	Dual Actuated	86	449.1	475.5	No	468.7	No
	Protected Actuated	87	440.9	783.3	No	573.8	No
	Protected Pre-timed	88	652.5	762.7	No	611.4	Yes
	Split Actuated	89	516.8	611.6	No	549.8	No
	Split Pre-timed	90	639.9	698.8	No	639.6	Yes

Demand Case F1							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	91	658.9	629.4	Yes	627	Yes
	Protected Actuated	92	581.8	839	No	493.2	Yes
	Protected Pre-timed	93	824.5	742.1	Yes	539.6	Yes
	Split Actuated	94	768	1064.6	No	1119.1	No
	Split Pre-timed	95	789.1	1012.8	No	913.9	No
Big	Dual Actuated	96	650.7	642.3	Yes	632.3	Yes
	Protected Actuated	97	708.8	966.7	No	622	Yes
	Protected Pre-timed	98	1009.1	899.2	Yes	612.6	Yes
	Split Actuated	99	901.5	1048.2	No	1010.8	No
	Split Pre-timed	100	936.8	1017.8	No	966.7	No
Mix	Dual Actuated	101	716.7	731	No	728.8	Yes
	Protected Actuated	102	612	900.4	No	648.7	No
	Protected Pre-timed	103	882.6	946.1	No	711.7	Yes
	Split Actuated	104	822.8	1032.3	No	945.6	No
	Split Pre-timed	105	809.2	1001.9	No	955.7	No
Demand Case F2							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	106	658.9	825.6	No	820.3	No
	Protected Actuated	107	587.8	1049.5	No	532.4	Yes
	Protected Pre-timed	108	907.9	1179.1	No	694.1	Yes
	Split Actuated	109	807.3	1119.4	No	1107	No
	Split Pre-timed	110	843.1	1033.8	No	942.6	No

Big	Dual Actuated	111	697.5	747.1	No	752.7	No
	Protected Actuated	112	702.4	918.8	No	666.6	Yes
	Protected Pre-timed	113	1079.2	1067.1	Yes	684.9	Yes
	Split Actuated	114	883.7	1040.1	No	977.3	No
	Split Pre-timed	115	986.2	1087.8	No	1021.1	No
Mix	Dual Actuated	116	727	886.6	No	843	No
	Protected Actuated	117	619.4	1156.7	No	636.5	No
	Protected Pre-timed	118	942.5	1148.0	No	774.8	Yes
	Split Actuated	119	827.1	1023.6	No	1025.4	No
	Split Pre-timed	120	851.9	1030.6	No	1030.5	No

Table A3.5: Comparative productivity performance of the proposed control system(s) (in *Bus Trips*) for various incident conditions

Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Demand Case D (with Lane 2 Incident)							
Small	Dual Actuated	121	108	108	Yes	108	Yes
	Split Actuated	122	108	108	Yes	108	Yes
	Split Pre-timed	123	107	108	Yes	108	Yes
Big	Dual Actuated	124	106	108	Yes	107	Yes
	Split Actuated	125	105	108	Yes	108	Yes
	Split Pre-timed	126	104	108	Yes	108	Yes
Mix	Dual Actuated	127	108	108	Yes	108	Yes
	Split Actuated	128	105	108	Yes	108	Yes
	Split Pre-timed	129	104	108	Yes	108	Yes
Demand Case E1 (with Lane 2 Incident)							
Small	Dual Actuated	130	159	160	Yes	160	Yes
	Split Actuated	131	146	161	Yes	162	Yes
	Split Pre-timed	132	144	156	Yes	160	Yes
Big	Dual Actuated	133	156	157	Yes	158	Yes
	Split Actuated	134	142	158	Yes	160	Yes
	Split Pre-timed	135	140	155	Yes	158	Yes
Mix	Dual Actuated	136	153	158	Yes	158	Yes
	Split Actuated	137	145	156	Yes	157	Yes
	Split Pre-timed	138	140	154	Yes	154	Yes

Demand Case F1 (with Lane 2 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	139	213	205	No	218	Yes
	Split Actuated	140	184	152	No	198	Yes
	Split Pre-timed	141	156	200	Yes	226	Yes
Big	Dual Actuated	142	255	256	Yes	257	Yes
	Split Actuated	143	227	224	No	230	Yes
	Split Pre-timed	144	223	235	Yes	240	Yes
Mix	Dual Actuated	145	193	191	No	201	Yes
	Split Actuated	146	194	169	No	177	No
	Split Pre-timed	147	168	196	Yes	210	Yes
Demand Case D (with Lane 3 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	148	108	108	Yes	108	Yes
	Split Actuated	149	108	108	Yes	108	Yes
	Split Pre-timed	150	107	108	Yes	108	Yes
Big	Dual Actuated	151	108	108	Yes	108	Yes
	Split Actuated	152	105	108	Yes	108	Yes
	Split Pre-timed	153	104	108	Yes	108	Yes
Mix	Dual Actuated	154	108	108	Yes	108	Yes
	Split Actuated	155	108	108	Yes	108	Yes
	Split Pre-timed	156	105	108	Yes	108	Yes

Demand Case E1 (with Lane 3 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	157	159	160	Yes	160	Yes
	Split Actuated	158	149	162	Yes	161	Yes
	Split Pre-timed	159	144	157	Yes	159	Yes
Big	Dual Actuated	160	157	156	No	157	Yes
	Split Actuated	161	142	159	Yes	159	Yes
	Split Pre-timed	162	141	156	Yes	158	Yes
Mix	Dual Actuated	163	155	156	Yes	155	Yes
	Split Actuated	164	143	157	Yes	156	Yes
	Split Pre-timed	165	141	155	Yes	156	Yes
Demand Case F1 (with Lane 3 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Bus Trips*)	Logic with IM		Logic w/o IM	
				Bus Trips	Similar or Improvement	*Bus Trips*	Similar or Improvement
Small	Dual Actuated	166	211	212	Yes	222	Yes
	Split Actuated	167	174	155	No	192	Yes
	Split Pre-timed	168	148	169	Yes	198	Yes
Big	Dual Actuated	169	253	252	No	259	Yes
	Split Actuated	170	228	236	Yes	236	Yes
	Split Pre-timed	171	229	243	Yes	242	Yes
Mix	Dual Actuated	172	187	199	Yes	200	Yes
	Split Actuated	173	192	163	No	172	No
	Split Pre-timed	174	181	190	Yes	209	Yes

Table A3.6: Comparative productivity performance of the proposed control system(s) (in *Person Trips*) for various incident conditions

Demand Case D (with Lane 2 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	Logic with IM		Logic w/o IM	
				Person Trips	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	121	42144	41765	No	41798	No
	Split Actuated	122	41474	41342	No	41431	No
	Split Pre-timed	123	40812	41090	Yes	41211	Yes
Big	Dual Actuated	124	41109	41092	No	41118	Yes
	Split Actuated	125	40616	40278	No	40491	No
	Split Pre-timed	126	39796	40018	Yes	40355	Yes
Mix	Dual Actuated	127	41225	41055	No	41205	No
	Split Actuated	128	40944	40236	No	40474	No
	Split Pre-timed	129	40055	39984	No	40210	Yes
Demand Case E1 (with Lane 2 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	Logic with IM		Logic w/o IM	
				Person Trips	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	130	57692	57775	Yes	57845	Yes
	Split Actuated	131	53392	55450	Yes	56017	Yes
	Split Pre-timed	132	51902	55224	Yes	55847	Yes
Big	Dual Actuated	133	56084	56246	Yes	56430	Yes
	Split Actuated	134	52995	53840	Yes	54430	Yes
	Split Pre-timed	135	52237	53684	Yes	54420	Yes
Mix	Dual Actuated	136	55358	55662	Yes	55917	Yes
	Split Actuated	137	52395	53098	Yes	53782	Yes
	Split Pre-timed	138	50859	53042	Yes	53737	Yes

Demand Case F1 (with Lane 2 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	Logic with IM		Logic w/o IM	
				Person Trips	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	139	63700	61842	No	63643	No
	Split Actuated	140	56836	40730	No	54642	No
	Split Pre-timed	141	49015	54844	Yes	61485	Yes
Big	Dual Actuated	142	75830	75645	No	75923	Yes
	Split Actuated	143	66534	64662	No	66763	Yes
	Split Pre-timed	144	65712	67192	Yes	69013	Yes
Mix	Dual Actuated	145	52140	52954	Yes	54402	Yes
	Split Actuated	146	55480	46006	No	49382	No
	Split Pre-timed	147	50673	51314	Yes	56713	Yes
Demand Case D (with Lane 3 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	Logic with IM		Logic w/o IM	
				Person Trips	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	148	42081	42030	No	41956	No
	Split Actuated	149	41476	41354	No	41465	No
	Split Pre-timed	150	40836	41155	Yes	41234	Yes
Big	Dual Actuated	151	41178	41078	No	41128	No
	Split Actuated	152	40646	40260	No	40481	No
	Split Pre-timed	153	39778	39997	Yes	40352	Yes
Mix	Dual Actuated	154	41226	41026	No	41114	No
	Split Actuated	155	41004	40264	No	40549	No
	Split Pre-timed	156	40069	39984	No	40258	Yes

Demand Case E1 (with Lane 3 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	Logic with IM		Logic w/o IM	
				Person Trips	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	157	57676	57679	Yes	57807	Yes
	Split Actuated	158	53771	55498	Yes	55913	Yes
	Split Pre-timed	159	52290	55160	Yes	55810	Yes
Big	Dual Actuated	160	56112	56196	Yes	56313	Yes
	Split Actuated	161	52996	53828	Yes	54357	Yes
	Split Pre-timed	162	52297	53668	Yes	54373	Yes
Mix	Dual Actuated	163	55464	55505	Yes	55553	Yes
	Split Actuated	164	52278	53200	Yes	53792	Yes
	Split Pre-timed	165	50973	52990	Yes	53806	Yes
Demand Case F1 (with Lane 3 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM (*Person Trips*)	Logic with IM		Logic w/o IM	
				Person Trips	Similar or Improvement	*Person Trips*	Similar or Improvement
Small	Dual Actuated	166	65671	63268	No	66091	Yes
	Split Actuated	167	57535	40190	No	52247	No
	Split Pre-timed	168	47369	49261	Yes	57199	Yes
Big	Dual Actuated	169	75124	75366	Yes	76265	Yes
	Split Actuated	170	66740	65780	No	67092	Yes
	Split Pre-timed	171	65810	67866	Yes	68939	Yes
Mix	Dual Actuated	172	51867	54437	Yes	55221	Yes
	Split Actuated	173	55982	44419	No	46894	No
	Split Pre-timed	174	52056	51395	No	56559	Yes

Table A3.7: Comparative efficiency performance of the proposed control system(s) (in *Average Delay/Person*) for various incident conditions

Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
Demand Case D (with Lane 2 Incident)							
				[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	121	206.8	248.8	No	247.2	No
	Split Actuated	122	249	282	No	272.3	No
	Split Pre-timed	123	331.5	318.4	Yes	302.6	Yes
Big	Dual Actuated	124	209.4	225.7	No	219.7	No
	Split Actuated	125	251.4	300.4	No	274.9	No
	Split Pre-timed	126	341.2	339.4	Yes	309.7	Yes
Mix	Dual Actuated	127	214.3	235.3	No	226.6	No
	Split Actuated	128	252.1	301.1	No	282.4	No
	Split Pre-timed	129	342.6	341.4	Yes	313.7	Yes
Demand Case E1 (with Lane 2 Incident)							
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	130	232.8	234.4	No	223.2	Yes
	Split Actuated	131	363.9	370.7	No	340.5	Yes
	Split Pre-timed	132	415.2	394.9	Yes	359	Yes
Big	Dual Actuated	133	236.8	237.2	No	229.7	Yes
	Split Actuated	134	363.3	388.4	No	350.3	Yes
	Split Pre-timed	135	418.6	406.2	Yes	364.7	Yes
Mix	Dual Actuated	136	274.2	278.2	No	266.9	Yes
	Split Actuated	137	375.5	418.9	No	380.9	No
	Split Pre-timed	138	442.5	439.8	Yes	398.7	Yes

Demand Case F1 (with Lane 2 Incident)							
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	139	557.8	558.1	No	557.5	Yes
	Split Actuated	140	682.7	865.5	No	1047.9	No
	Split Pre-timed	141	698.4	882.7	No	804.6	No
Big	Dual Actuated	142	479.1	453.4	Yes	446.4	Yes
	Split Actuated	143	720.6	870.5	No	840.8	No
	Split Pre-timed	144	758.2	839.5	No	785.7	No
Mix	Dual Actuated	145	569.7	605.9	No	582.3	No
	Split Actuated	146	672.8	828.2	No	921	No
	Split Pre-timed	147	708.7	776.3	No	834.5	No
Demand Case D (with Lane 3 Incident)							
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	148	206.2	224.4	No	223	No
	Split Actuated	149	249.2	282.8	No	271.7	No
	Split Pre-timed	150	330	316.1	Yes	302.4	Yes
Big	Dual Actuated	151	210.3	223.5	No	219.3	No
	Split Actuated	152	250.7	301.8	No	277	No
	Split Pre-timed	153	341.2	339.8	Yes	308.4	Yes
Mix	Dual Actuated	154	214	237.2	No	230	No
	Split Actuated	155	252.4	299.1	No	281.3	No
	Split Pre-timed	156	344	339.8	Yes	314	Yes

Demand Case E1 (with Lane 3 Incident)							
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	157	233.9	235.6	No	226.2	Yes
	Split Actuated	158	362.1	370.2	No	344.6	Yes
	Split Pre-timed	159	414.6	395.5	Yes	359.2	Yes
Big	Dual Actuated	160	239.4	236.6	Yes	229.3	Yes
	Split Actuated	161	362	391.7	No	353.3	Yes
	Split Pre-timed	162	417.8	408.3	Yes	363.3	Yes
Mix	Dual Actuated	163	270.4	280.8	No	270.5	No
	Split Actuated	164	379.4	415.8	No	380.3	No
	Split Pre-timed	165	441.4	439.1	Yes	396.5	Yes
Demand Case F1 (with Lane 3 Incident)							
				Logic with IM		Logic w/o IM	
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Delay/ Person* (in Sec)]	[*Average Delay/ Person* (in Sec)]	Similar or Reduction	[*Average Delay/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	166	564.9	569.6	No	578.9	No
	Split Actuated	167	683.4	839	No	1054.9	No
	Split Pre-timed	168	680.8	867.8	No	800.7	No
Big	Dual Actuated	169	472.9	457.4	Yes	447.9	Yes
	Split Actuated	170	715.1	870.7	No	829.3	No
	Split Pre-timed	171	756.6	822.2	No	781.7	No
Mix	Dual Actuated	172	581.3	661.2	No	608.4	No
	Split Actuated	173	693.3	791.6	No	810.1	No
	Split Pre-timed	174	742.6	801.4	No	843.1	No

Table A3.8: Comparative efficiency performance of the proposed control system(s) (in *Average Trip Time/Person*) for various incident conditions

				Demand Case D (with Lane 2 Incident)				
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	121	304.2	346.1	No	344.5	No
	Split Actuated	122	343.6	379.2	No	369.5	No
	Split Pre-timed	123	426	415.5	Yes	399.8	Yes
Big	Dual Actuated	124	403.9	419.8	No	414	No
	Split Actuated	125	441.1	494.1	No	468.8	No
	Split Pre-timed	126	530.7	532.9	No	503.4	Yes
Mix	Dual Actuated	127	360.4	381.3	No	372.7	No
	Split Actuated	128	395	446.8	No	428.3	No
	Split Pre-timed	129	485.3	487	No	459.4	Yes
				Demand Case E1 (with Lane 2 Incident)				
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	130	327.9	329.4	No	318.2	Yes
	Split Actuated	131	457.1	465.1	No	434.9	Yes
	Split Pre-timed	132	508.2	489.7	Yes	453.6	Yes
Big	Dual Actuated	133	427.1	427.4	No	419.9	Yes
	Split Actuated	134	550.2	577.4	No	539.4	Yes
	Split Pre-timed	135	605.4	595.6	Yes	554	Yes
Mix	Dual Actuated	136	417.3	420.8	No	409.6	Yes
	Split Actuated	137	515.6	560.9	No	523	No

	Split Pre-timed	138	582.7	582	Yes	541.2	Yes

Demand Case F1 (with Lane 2 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	139	648	648.8	No	647.5	Yes
	Split Actuated	140	773.9	954.8	No	1136.8	No
	Split Pre-timed	141	789.8	971.7	No	893.3	No
Big	Dual Actuated	142	660	634.4	Yes	627.5	Yes
	Split Actuated	143	900.6	1051.2	No	1021.9	No
	Split Pre-timed	144	938.1	1020.1	No	966.5	No
Mix	Dual Actuated	145	704.9	741.4	No	717.1	No
	Split Actuated	146	807.8	963.4	No	1057.6	No
	Split Pre-timed	147	845.1	910.9	No	969.2	No

Demand Case D (with Lane 3 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				Average Trip Time/ Person (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	148	303.6	321.8	No	320.3	No
	Split Actuated	149	343.8	380	No	368.9	No
	Split Pre-timed	150	424.5	413.2	Yes	399.5	Yes
Big	Dual Actuated	151	404.4	417.5	No	413.4	No
	Split Actuated	152	440.4	495.4	No	470.8	No
	Split Pre-timed	153	530.7	533.3	No	502.1	Yes
Mix	Dual Actuated	154	360	383.1	No	376	No
	Split Actuated	155	394.8	444.8	No	427.1	No
	Split Pre-timed	156	486.5	485.4	Yes	459.8	Yes

Demand Case E1 (with Lane 3 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	157	328.9	330.6	No	321.2	Yes
	Split Actuated	158	455.1	464.5	No	439.1	Yes
	Split Pre-timed	159	507.7	490.3	Yes	453.9	Yes
Big	Dual Actuated	160	429.6	427	Yes	419.6	Yes
	Split Actuated	161	548.9	580.6	No	542.5	Yes
	Split Pre-timed	162	604.5	597.6	Yes	552.6	Yes
Mix	Dual Actuated	163	413.3	423.6	No	413.5	No
	Split Actuated	164	519.7	557.7	No	522.6	No
	Split Pre-timed	165	581.6	581.2	Yes	538.7	Yes
Demand Case F1 (with Lane 3 Incident)							
Network grid type	Phase settings (Control Type)	Model ID	CORSIM [*Average Trip Time/ Person* (in Sec)]	Logic with IM		Logic w/o IM	
				Average Trip Time/ Person (in Sec)]	Similar or Reduction	[*Average Trip Time/ Person* (in Sec)]	Similar or Reduction
Small	Dual Actuated	166	655.8	660	No	669.5	No
	Split Actuated	167	775.6	927.8	No	1143.4	No
	Split Pre-timed	168	772.6	958.3	No	890.2	No
Big	Dual Actuated	169	653.9	638.7	Yes	628.8	Yes
	Split Actuated	170	895	1050.1	No	1009.7	No
	Split Pre-timed	171	935.7	1001.8	No	962.3	No
Mix	Dual Actuated	172	717.4	796.3	No	743.5	No
	Split Actuated	173	828.7	927.1	No	946.1	No
	Split Pre-timed	174	877.5	936.3	No	978.1	No
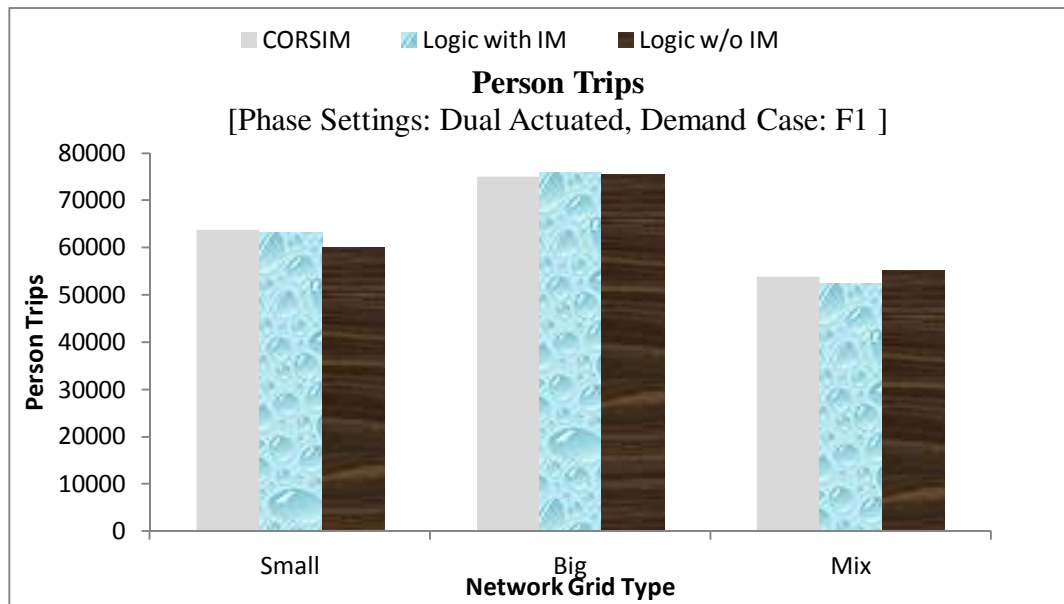
Figure A3.1: Performance (in *Person Trips*) of Dual Actuated Setting in Demand
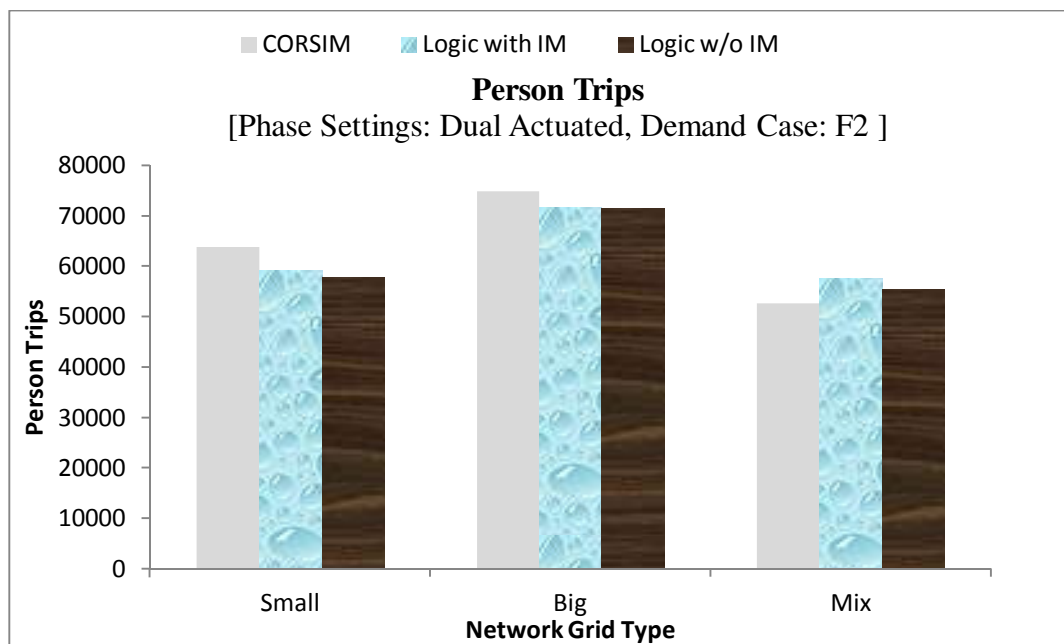
Case F1

Figure A3.2: Performance (in *Person Trips*) of Dual Actuated Setting in Demand
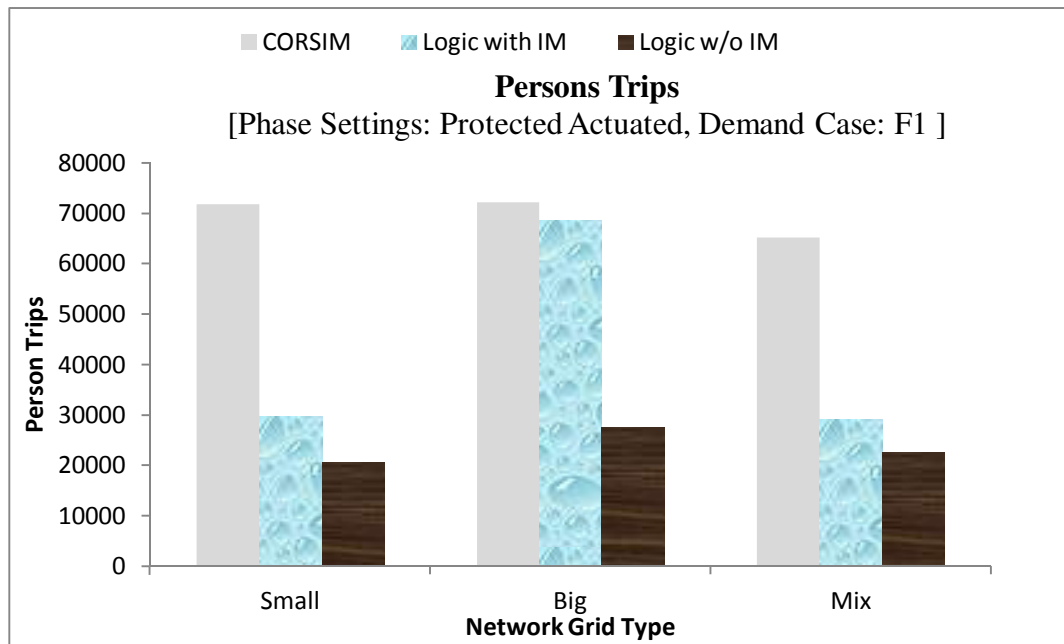
Case F2

Figure A3.3: Performance (in *Person Trips*) of Protected Actuated Setting in
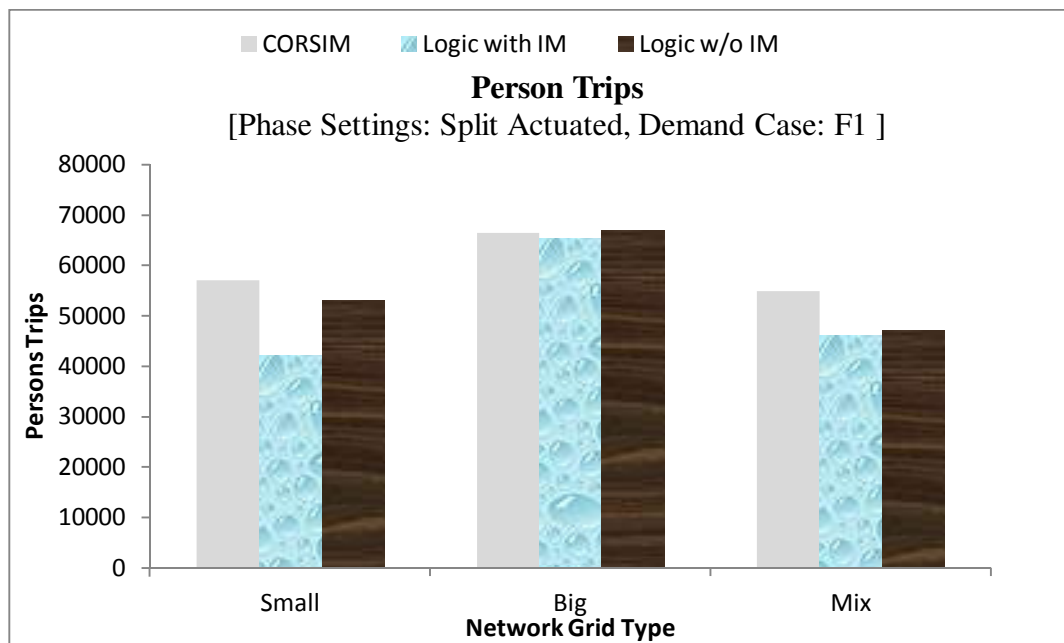
Demand Case F1

Figure A3.4: Performance (in *Person Trips*) of Split Actuated Setting in Demand

Case F1

297
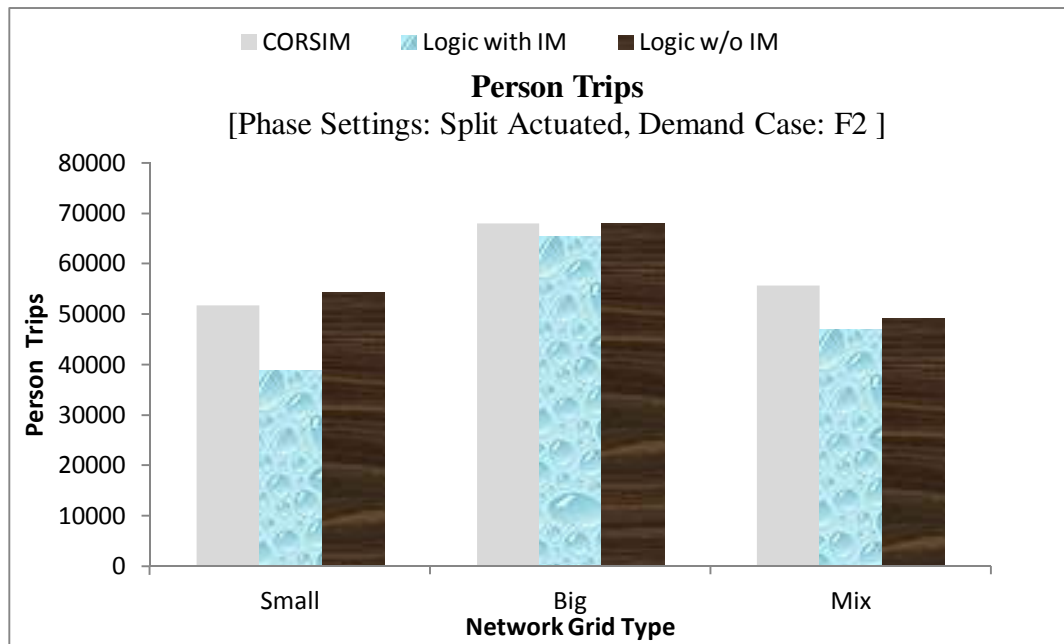
Figure A3.5: Performance (in *Person Trips*) of Split Actuated Setting in Demand
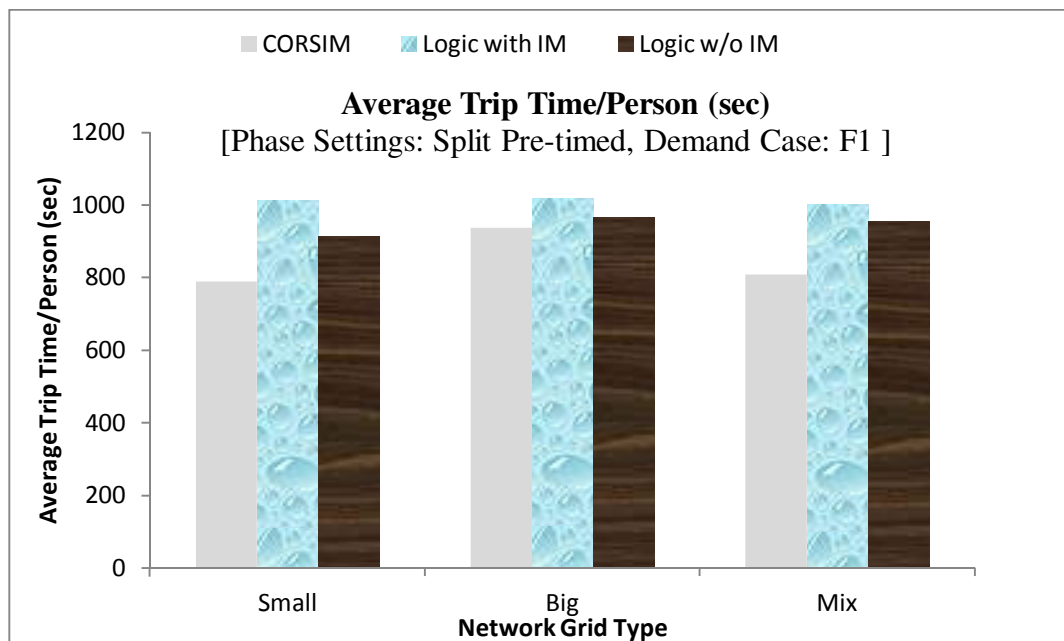
Case F2

Figure A3.6: Performance (in *Average Trip Time/Person*) of Split Pre-timed

Setting in Demand Case F1
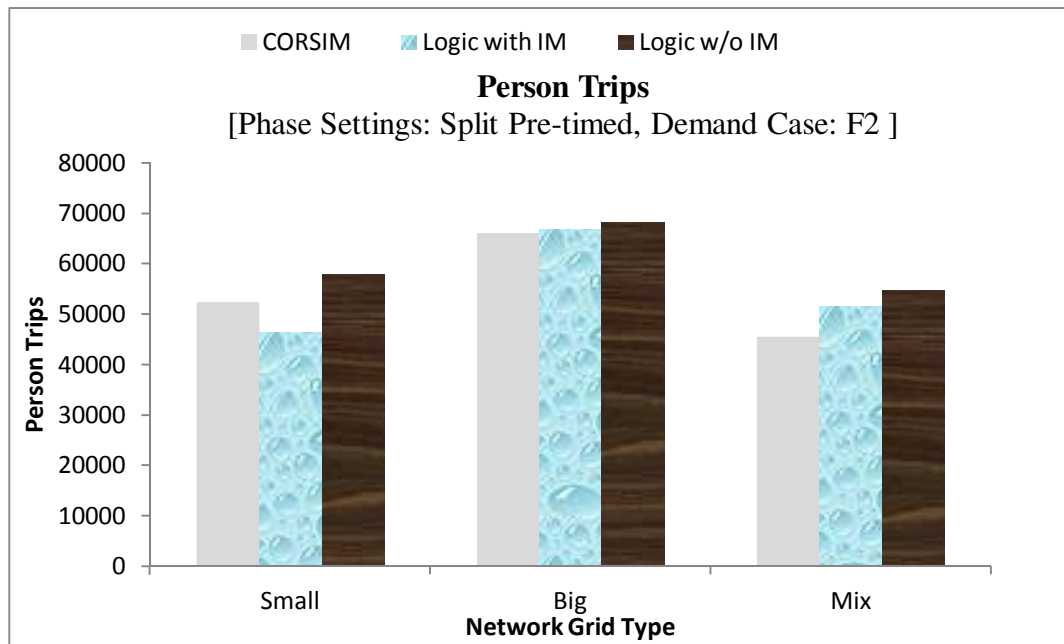
Figure A3.7: Performance (in *Person Trips*) of Split Pre-timed Setting in Demand

Case F2

APPENDIX 4
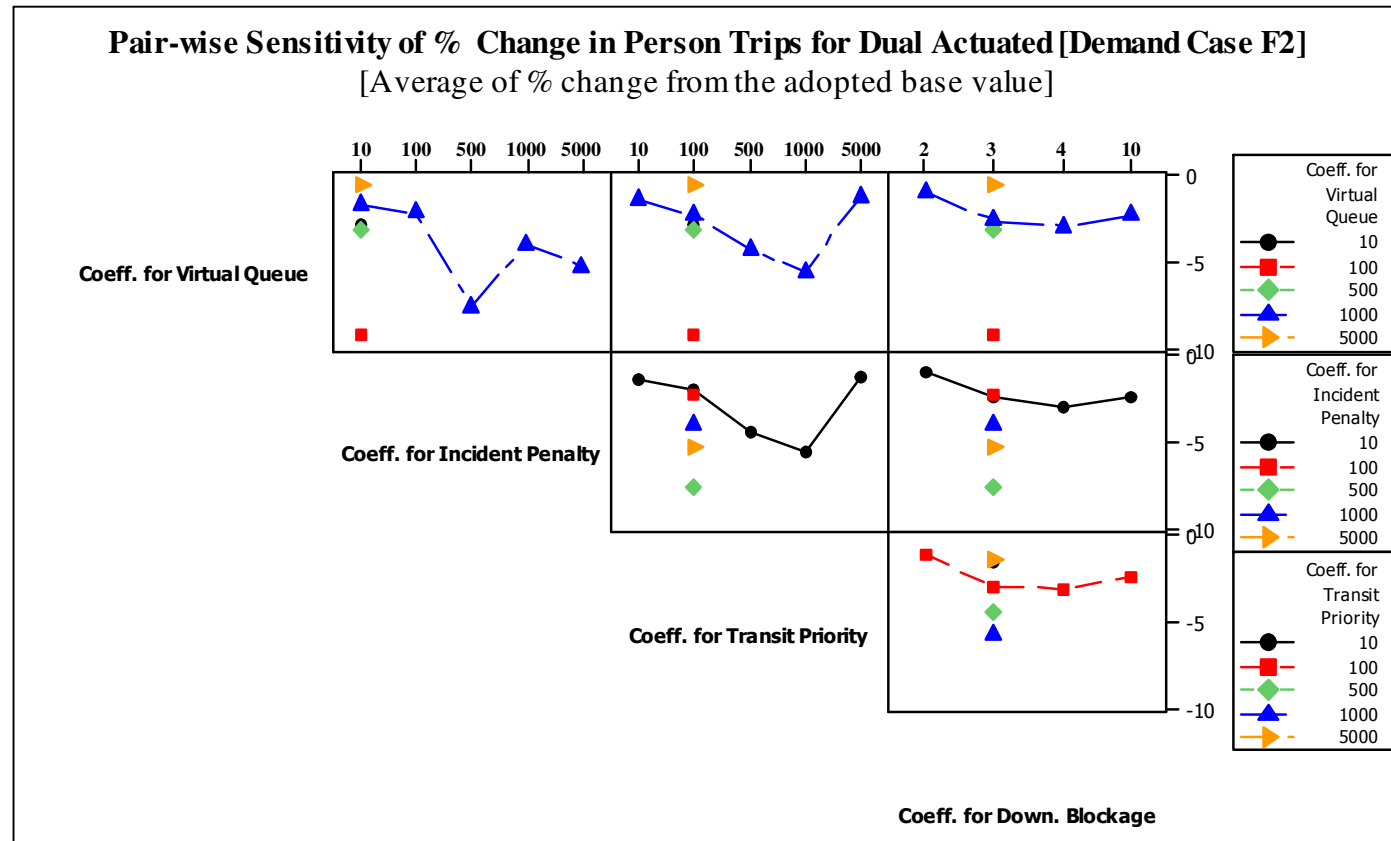
Figure A4.1: Coefficients Sensitivity Patterns (% Change of *Person Trips*) for Dual Actuated Control (Demand Case F2)
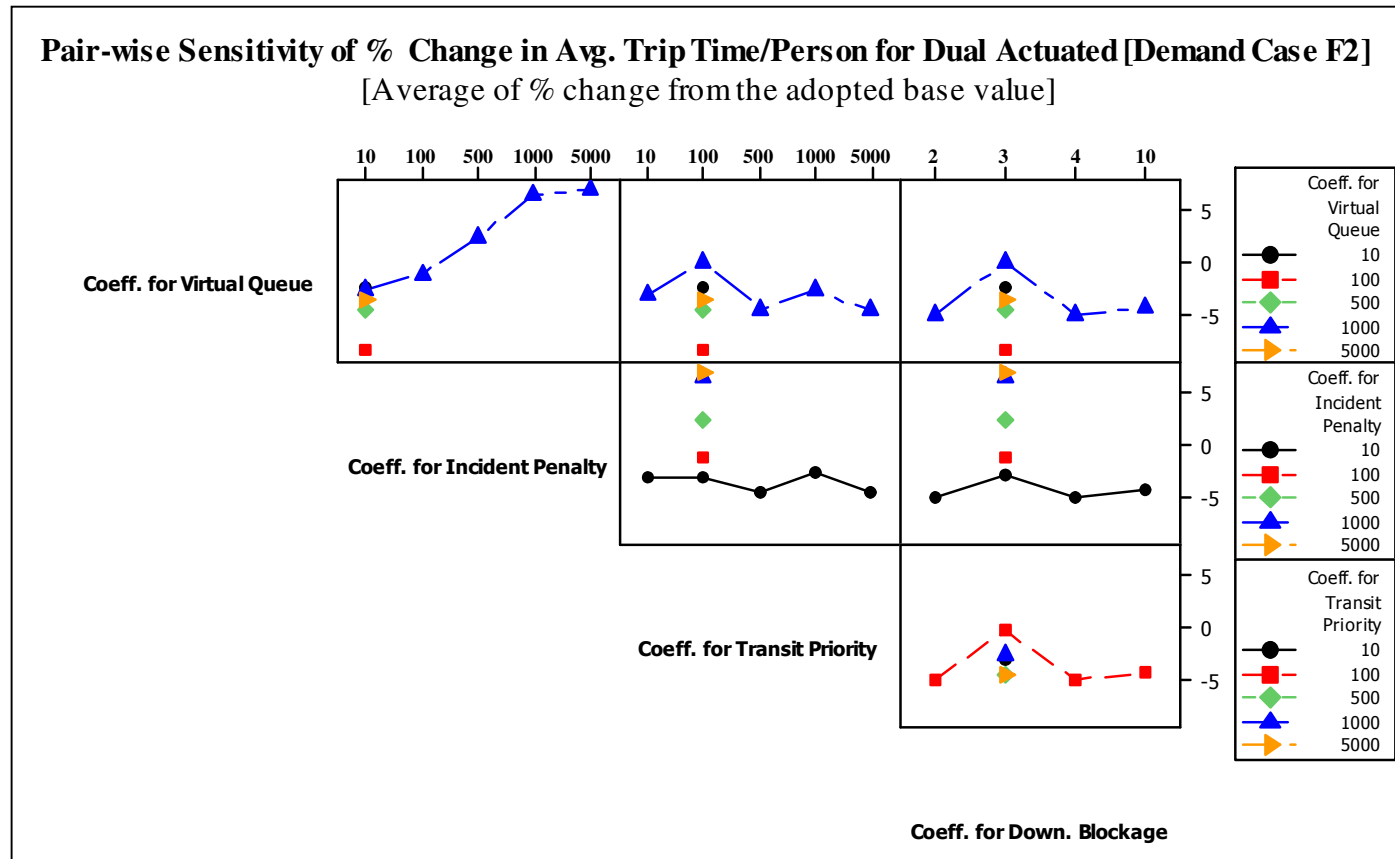
Figure A4.2: Coefficients Sensitivity Patterns (% Change of *Average Trip Time/Person*) for Dual Actuated Control (Demand Case F2)
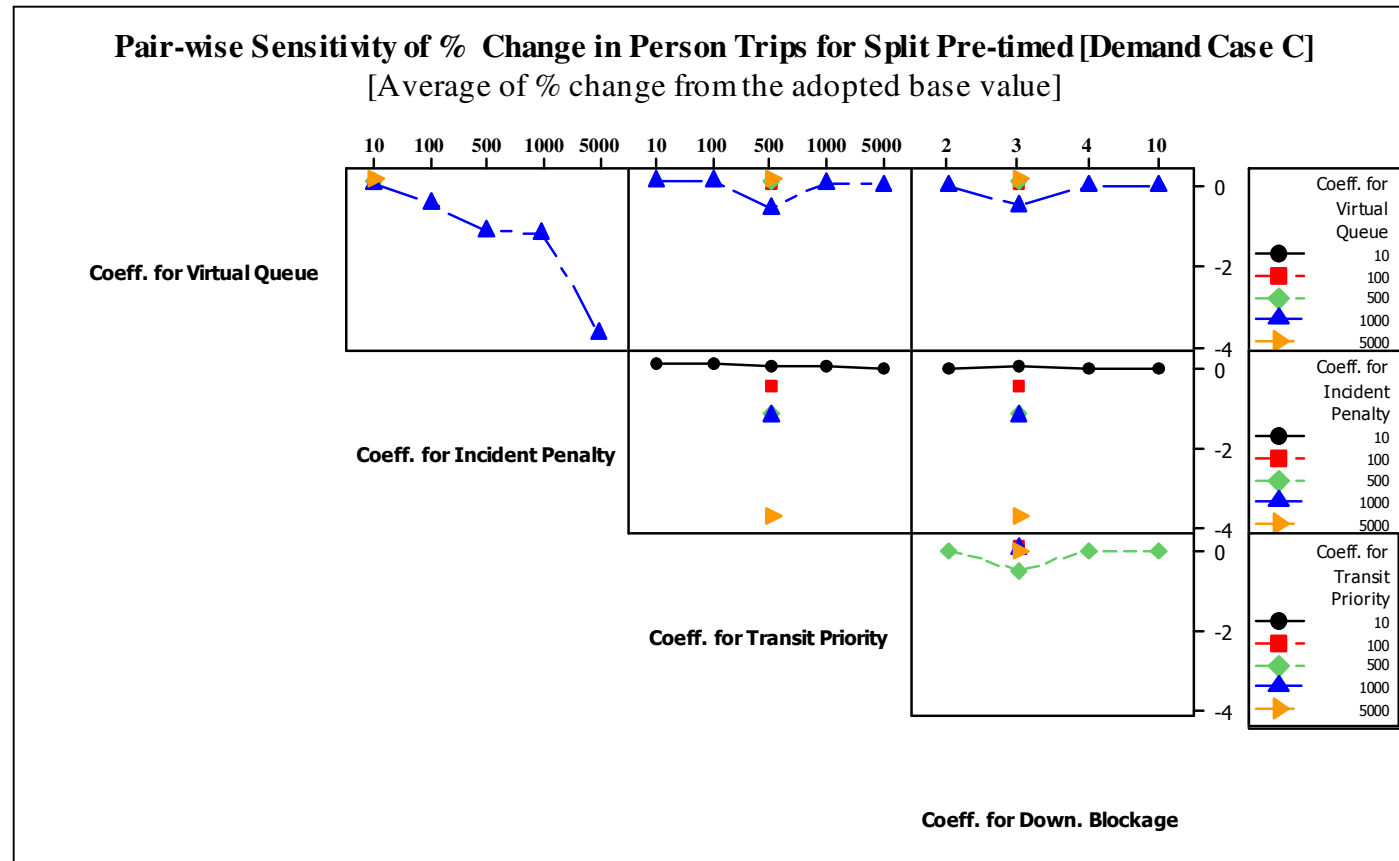
Figure A4.3: Coefficients Sensitivity Patterns (% Change of *Person Trips*) for Split Pre-timed Control (Demand Case C)
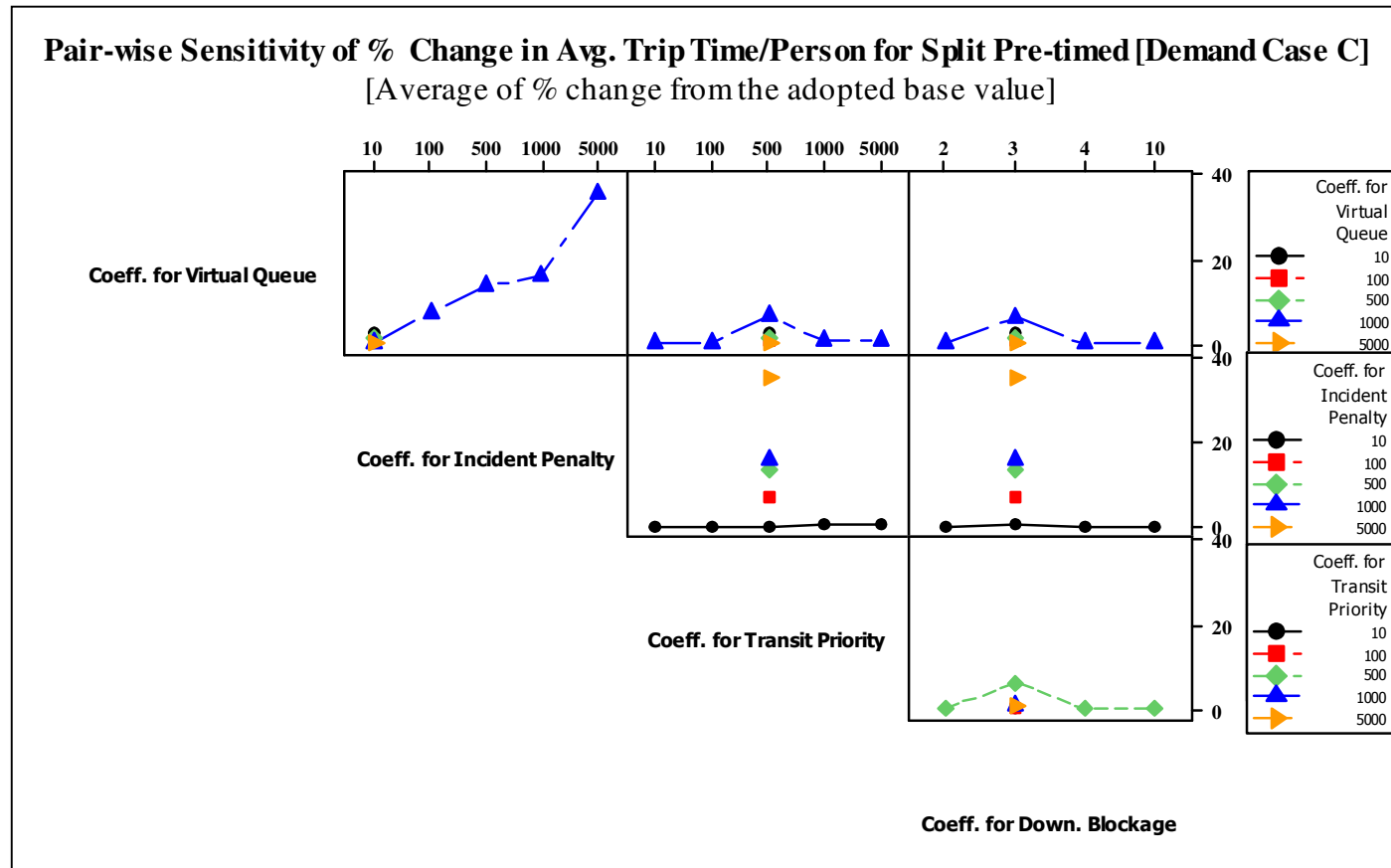
Figure A4.4: Coefficients Sensitivity Patterns (% Change of *Average Trip Time/Person*) for Split Pre-timed Control (Demand Case C)
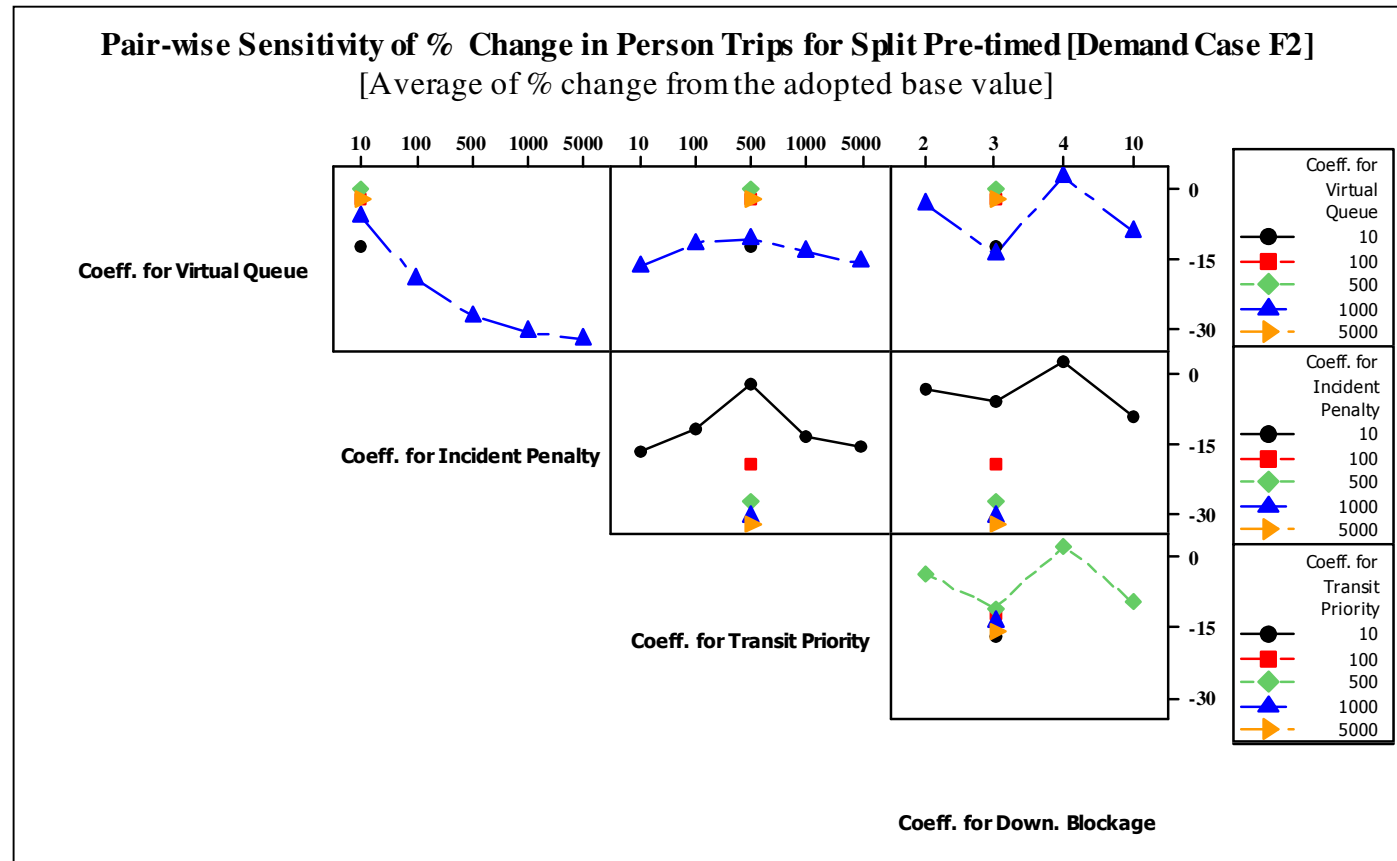
Figure A4.5: Coefficients Sensitivity Patterns (% Change of *Person Trips*) for Split Pre-timed Control (Demand Case F2)
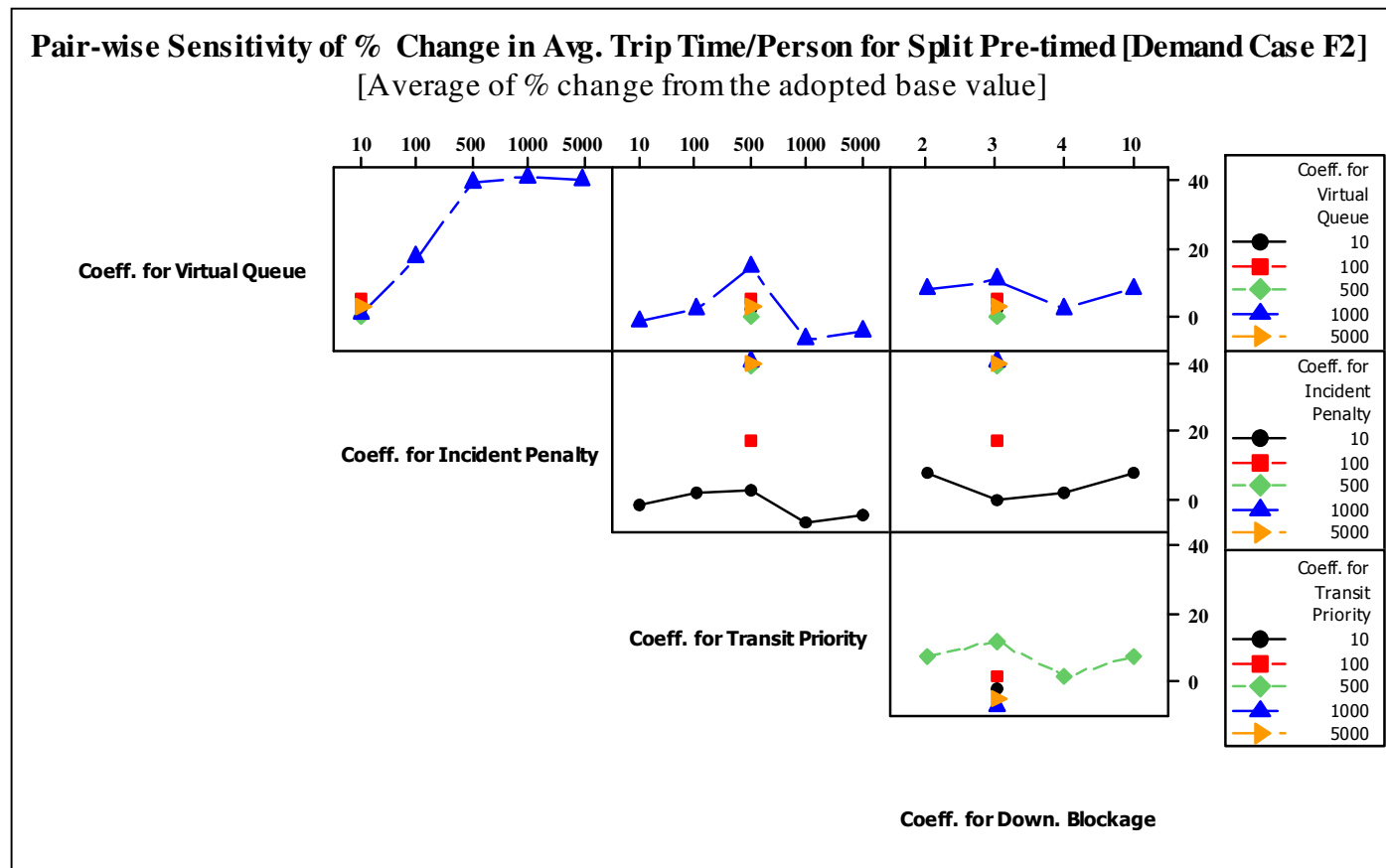
Figure A4.6: Coefficients Sensitivity Patterns (% Change of *Average Trip Time/Person*) for Split Pre-timed Control (Demand Case F2)
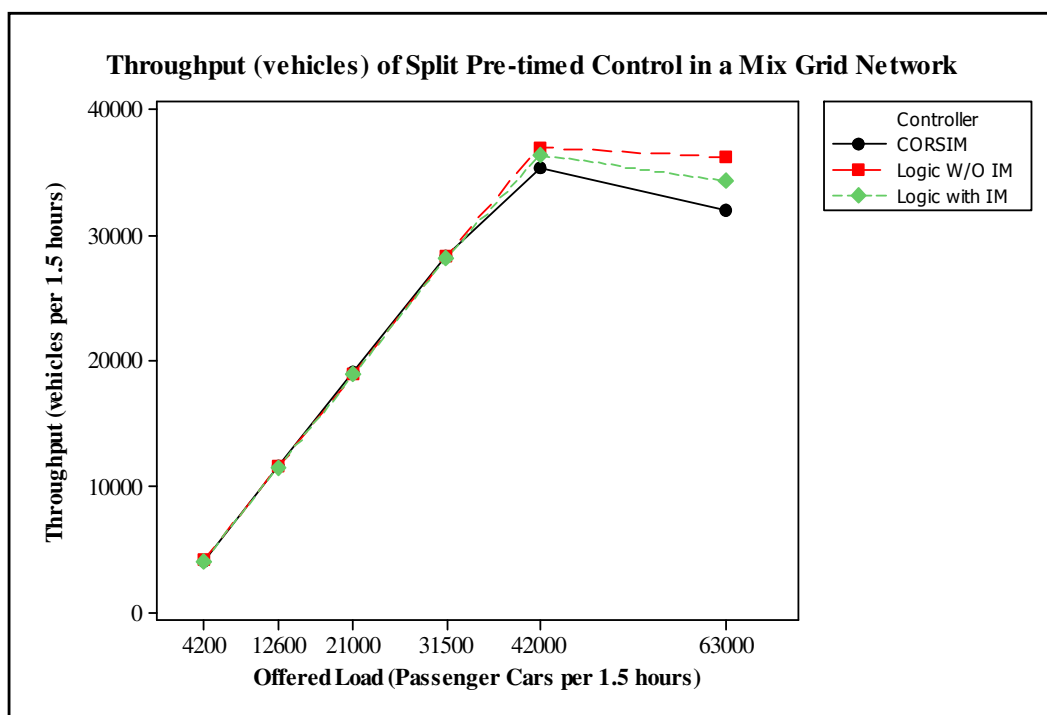
Figure A4.7: Offered load versus throughput for Split Pre-timed in mix grid network
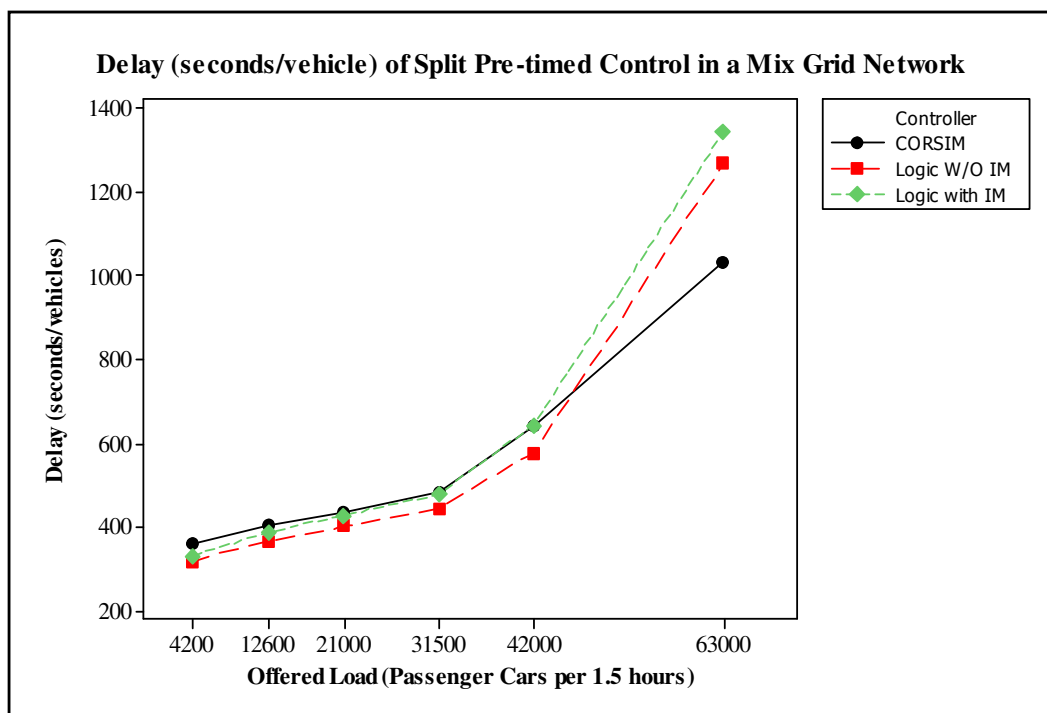
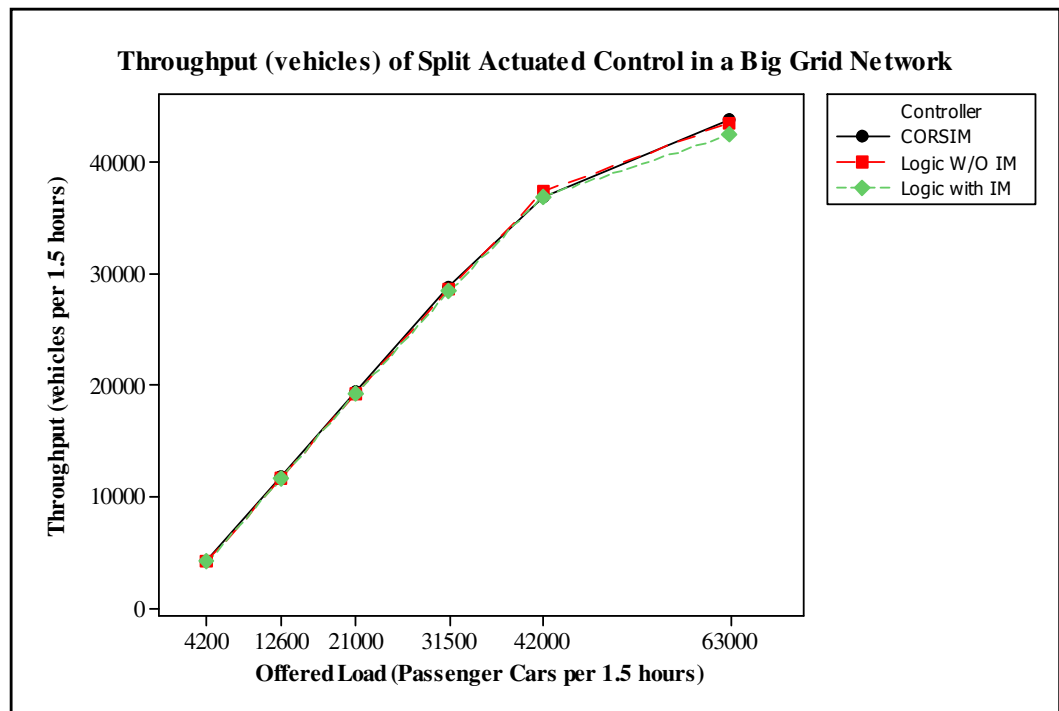Figure A4.8: Offered load versus delay for Split Pre-timed in mix grid network
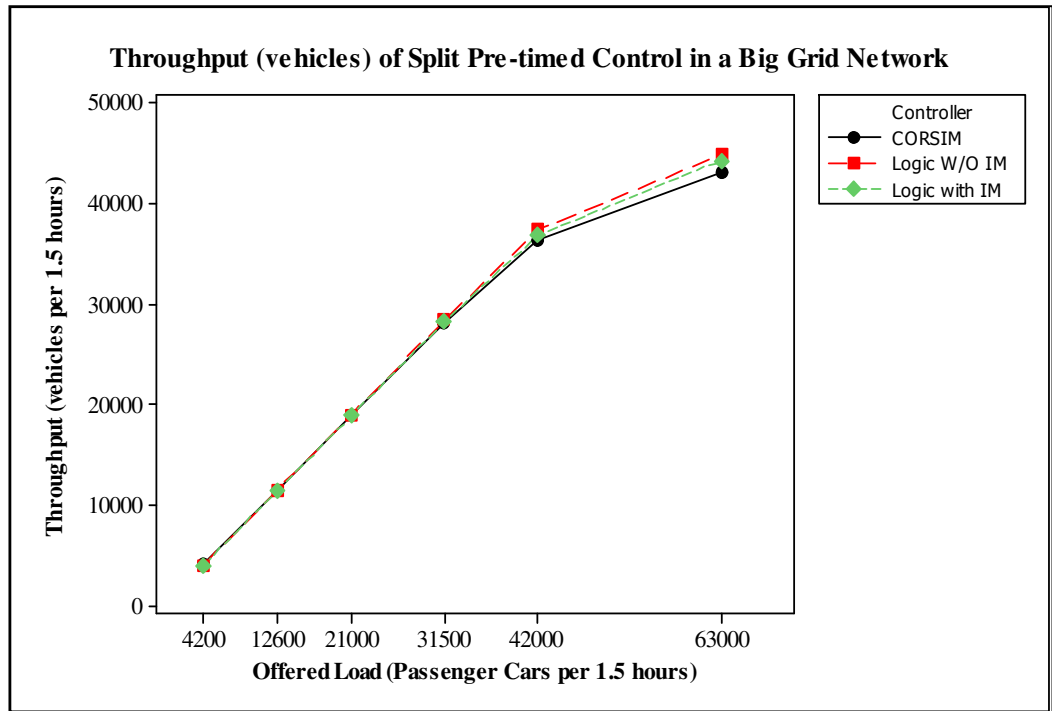
Figure A4.9: Offered load versus throughput for Split Pre-timed in big grid
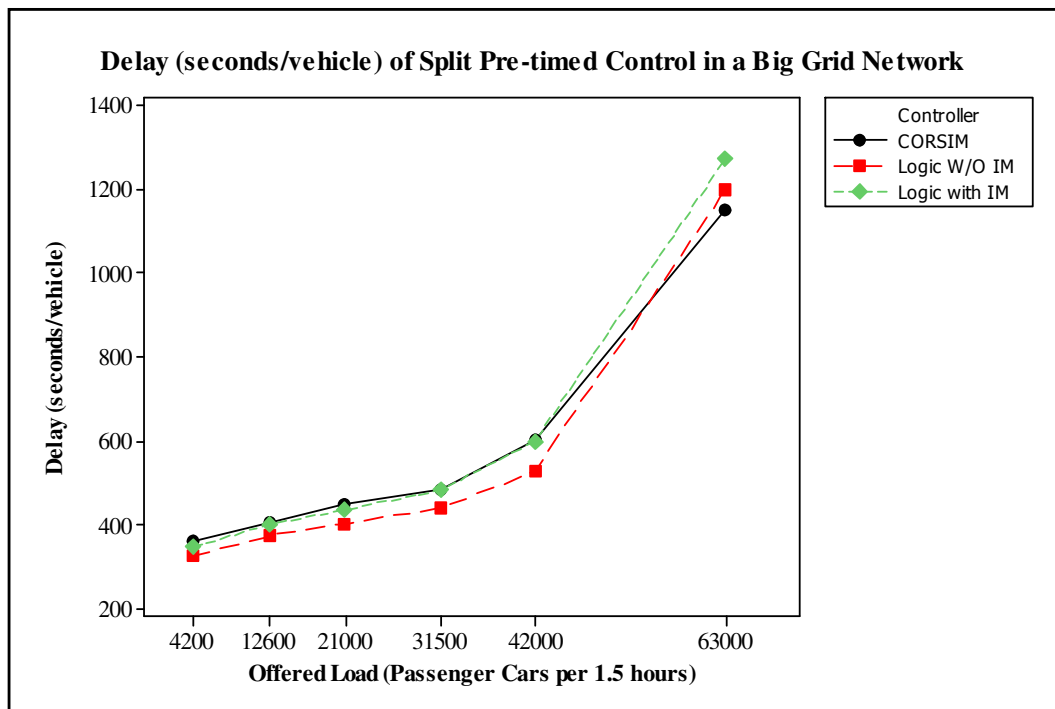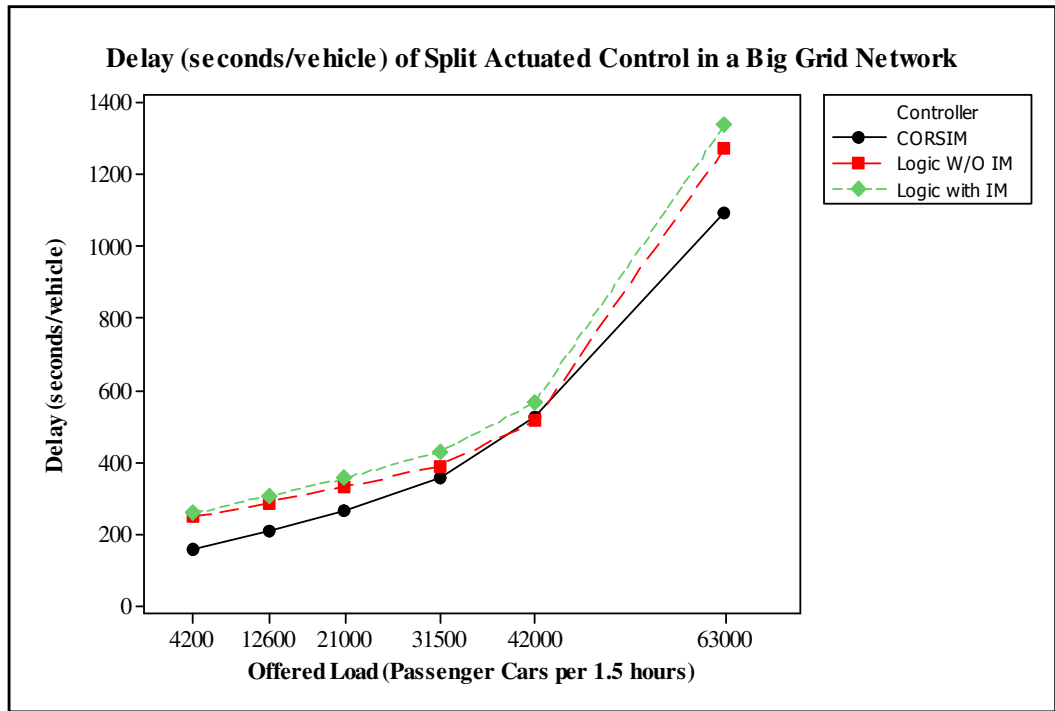
network

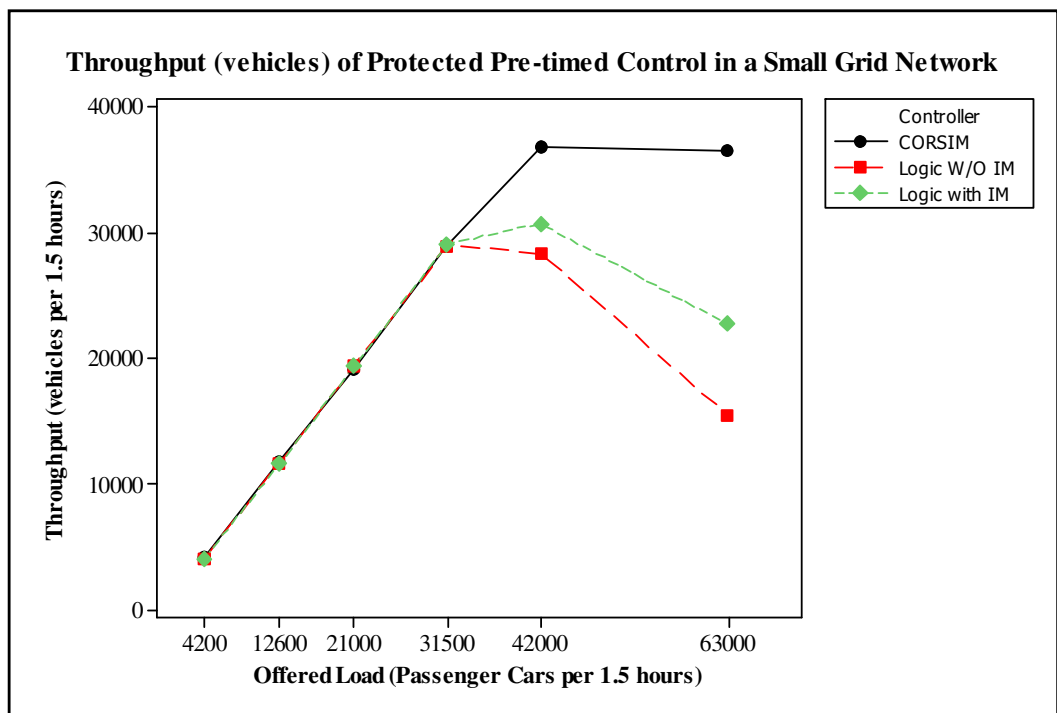Figure A4.10: Offered load versus delay for Split Pre-timed in big grid network
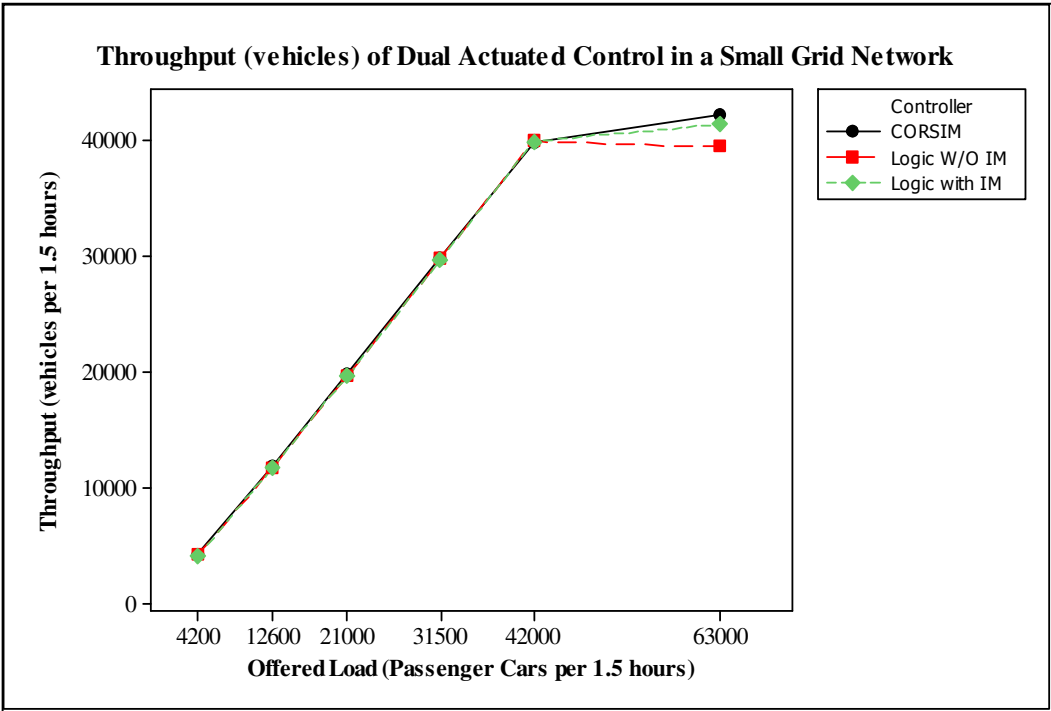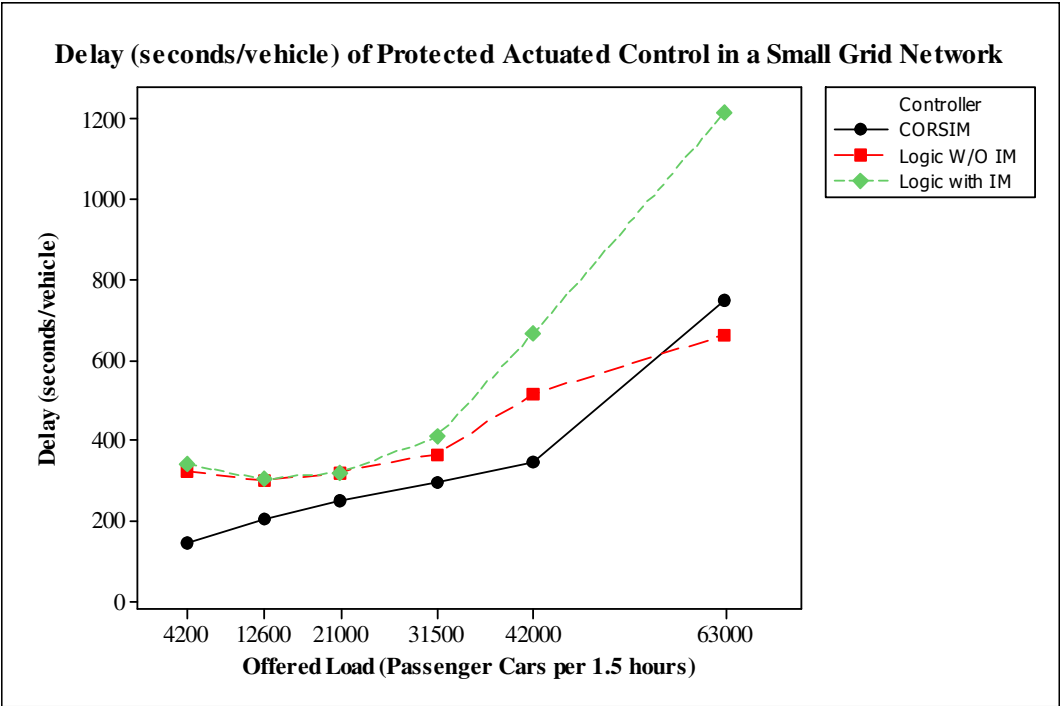
Figure A4.11: Offered load versus throughput for Dual Actuated in small grid
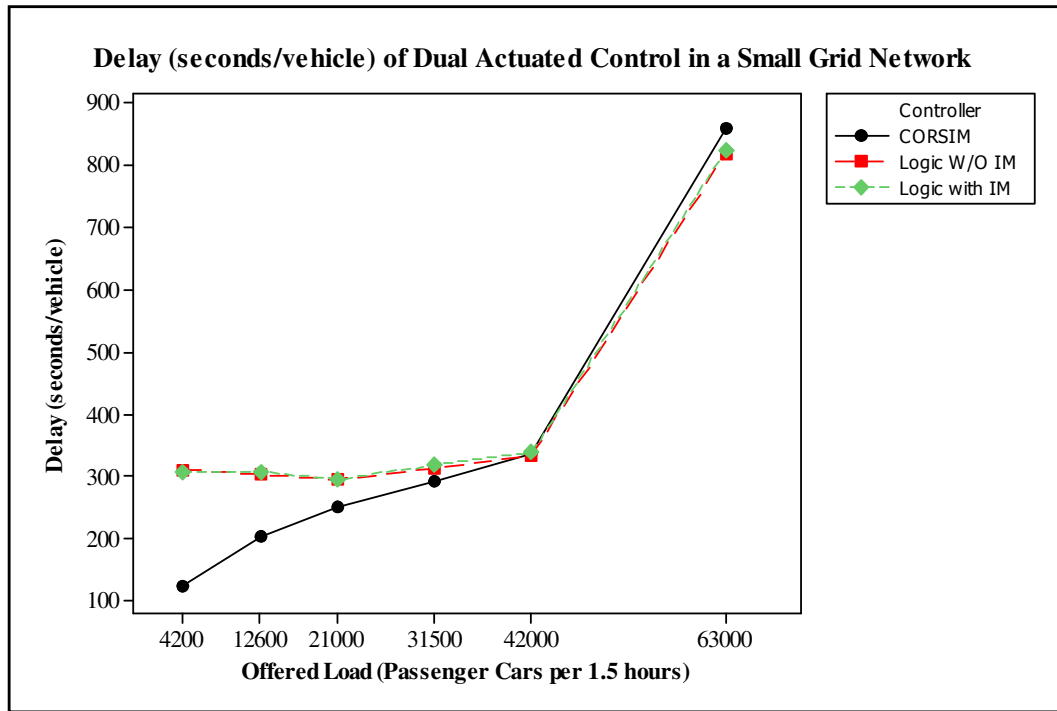
network

Figure A4.12: Offered load versus delay for Dual Actuated in small grid network
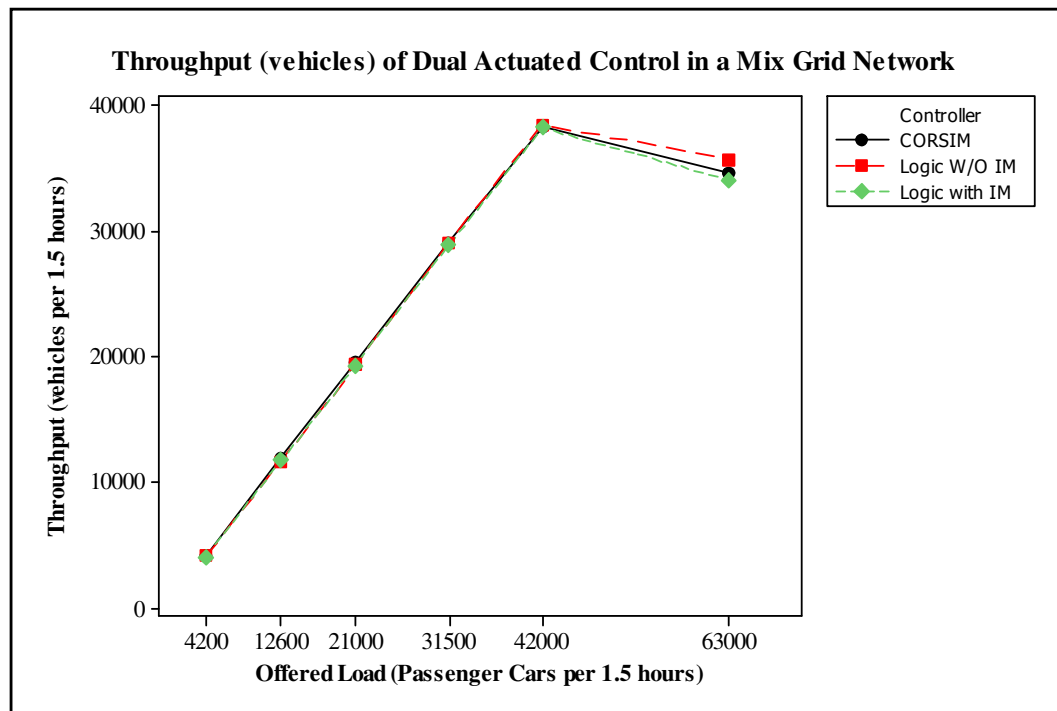
Figure A4.13: Offered load versus throughput for Dual Actuated in mix grid
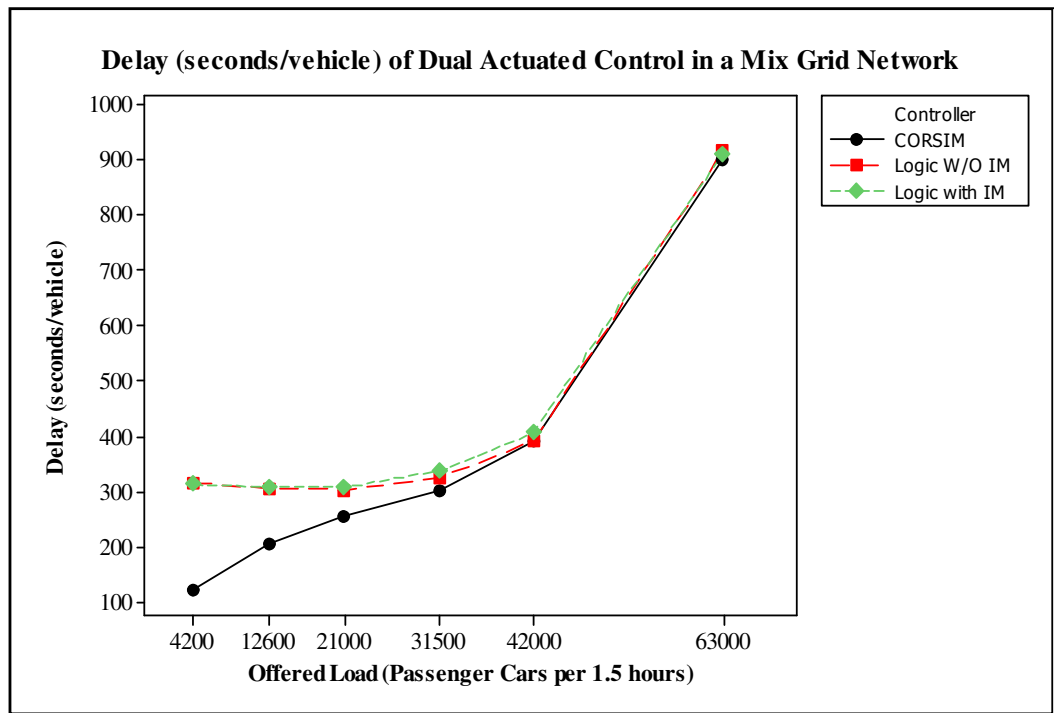
network

Figure A4.14: Offered load versus delay for Dual Actuated in mix grid network
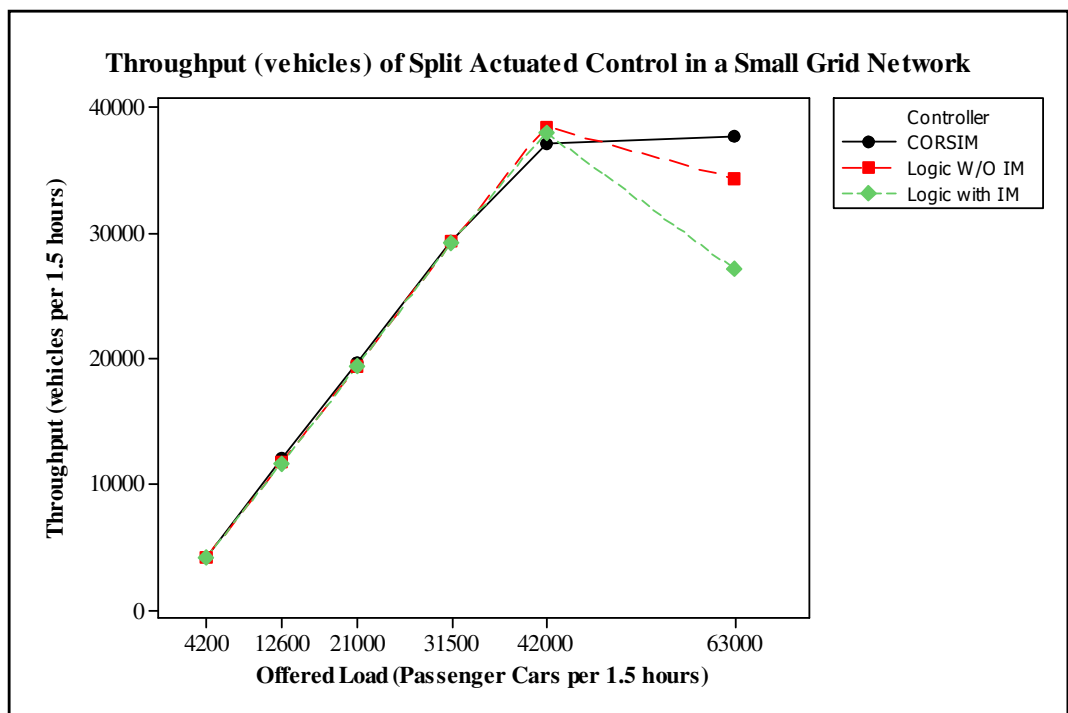
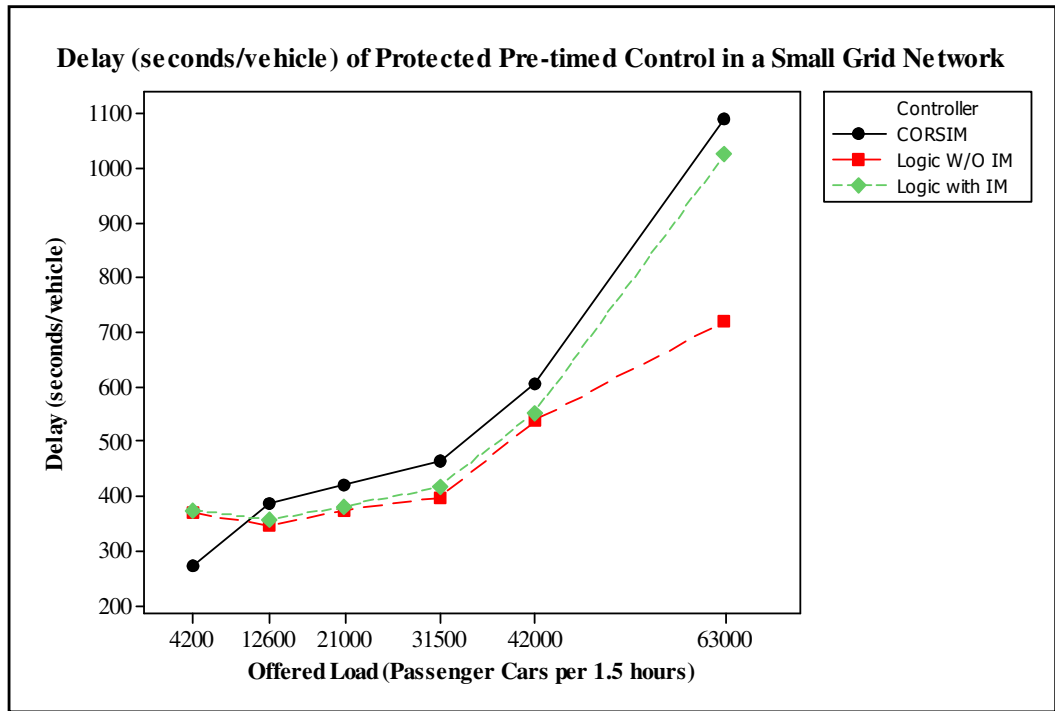Figure A4.15: Offered load versus throughput for Split Actuated in small grid

network

311
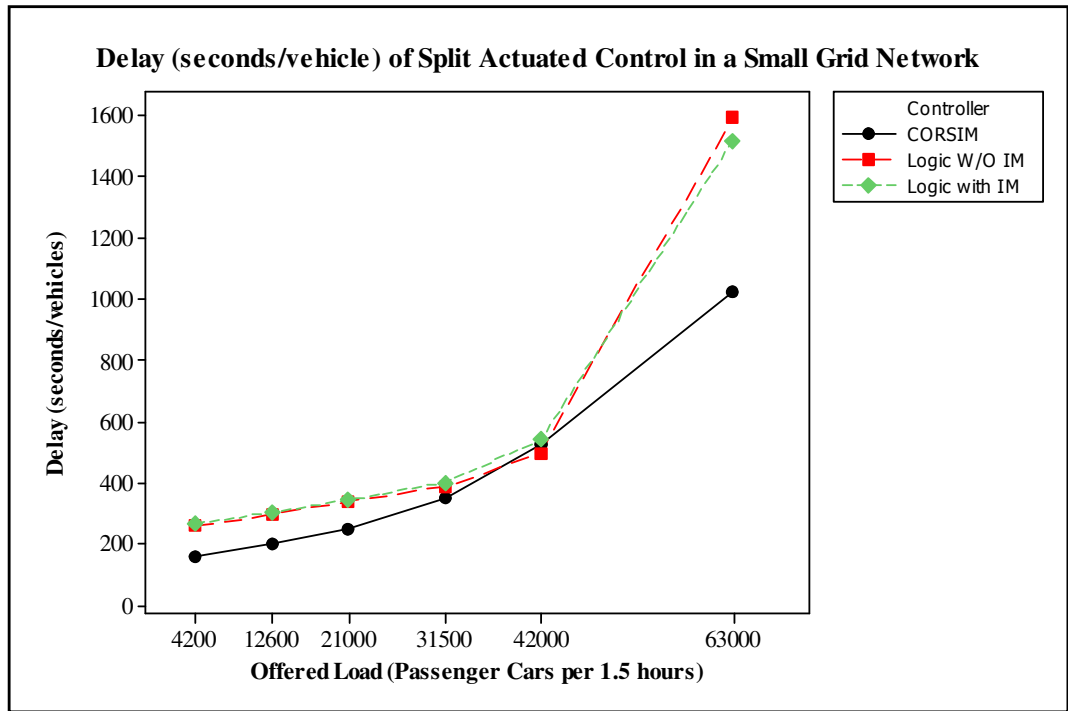
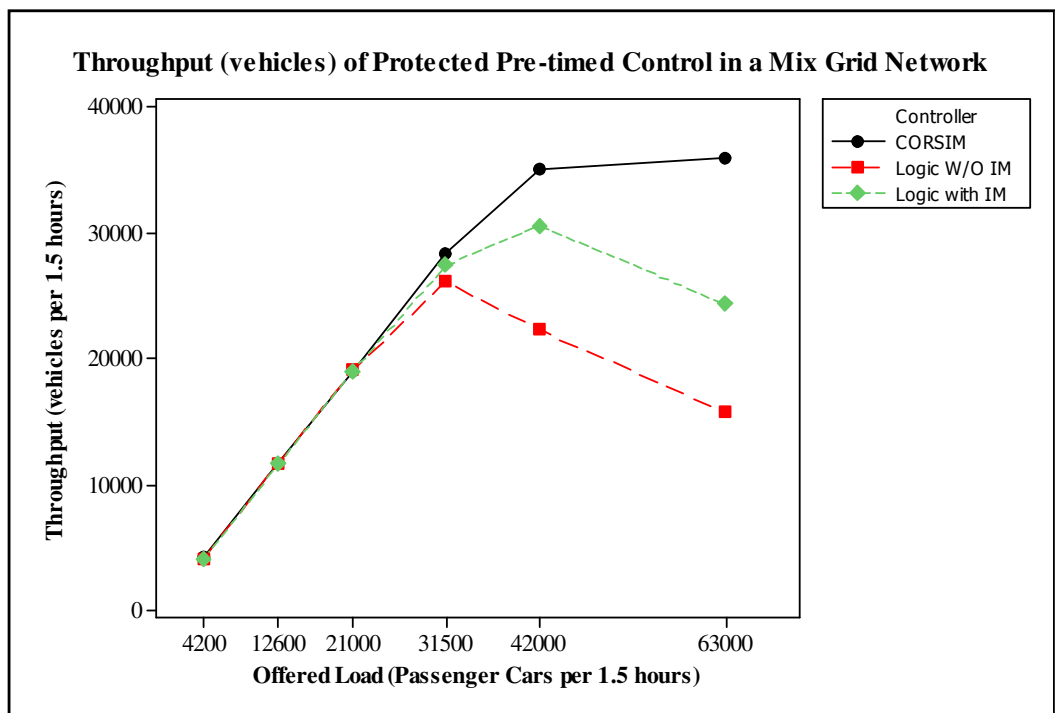Figure A4.16: Offered load versus delay for Split Actuated in small grid network
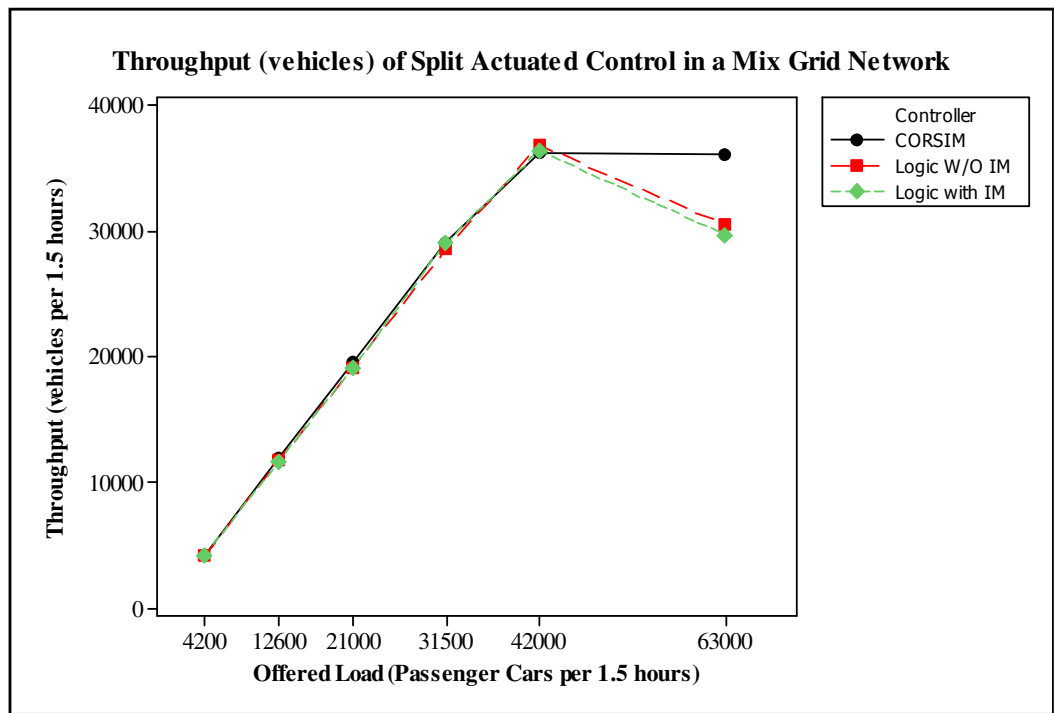
Figure A4.17: Offered load versus throughput for Split Actuated in mix grid
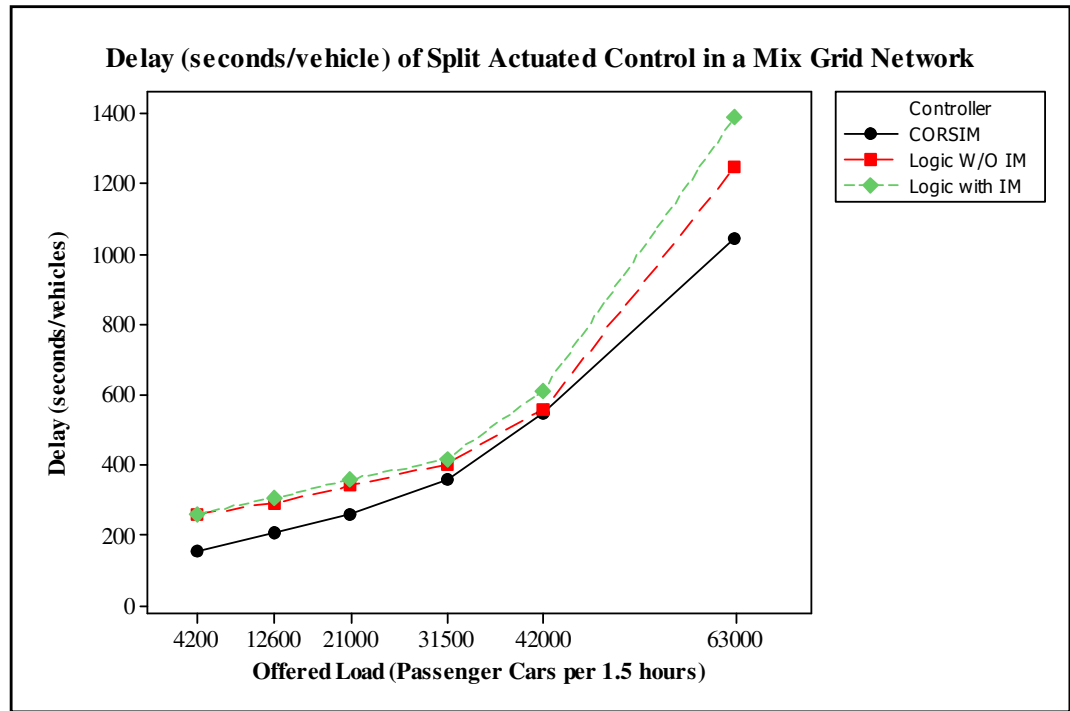
network

Figure A4.18: Offered load versus delay for Split Actuated in mix grid network

Figure A4.19: Offered load versus throughput for Split Actuated in big grid

network

Figure A4.20: Offered load versus delay for Split Actuated in big grid network

Figure A4.21: Offered load versus throughput for Protected Pre-timed in small

grid network

Figure A4.22: Offered load versus delay for Protected Pre-timed in small grid

network

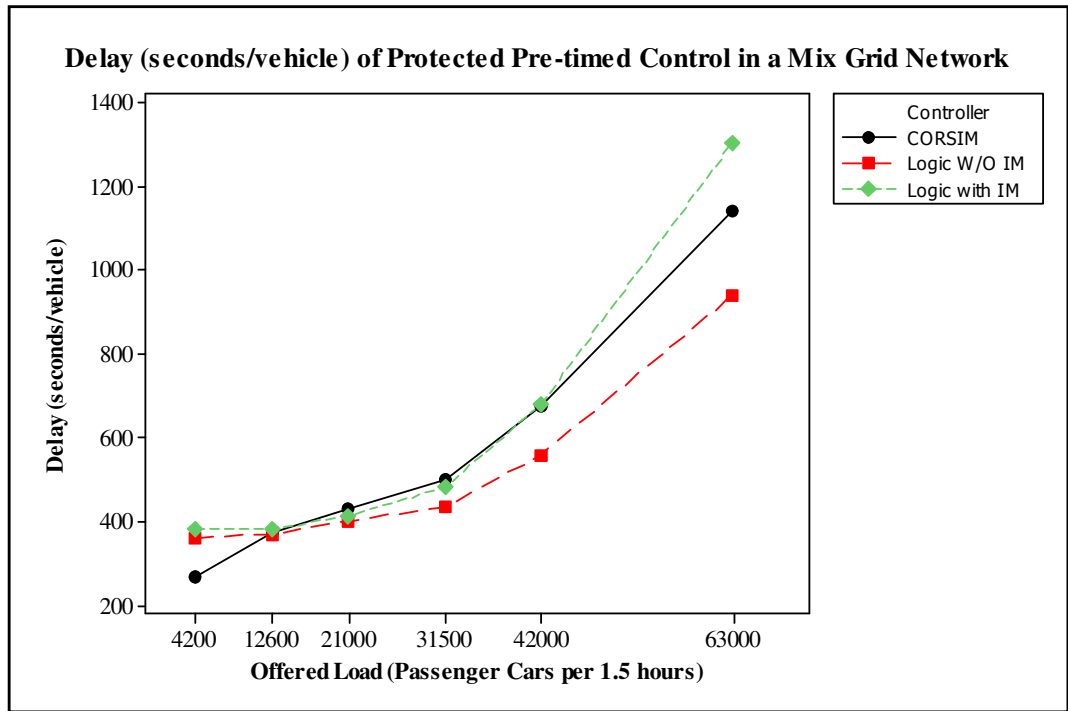Figure A4.23: Offered load versus throughput for Protected Pre-timed in mix grid

network

Figure A4.24: Offered load versus delay for Protected Pre-timed in mix grid
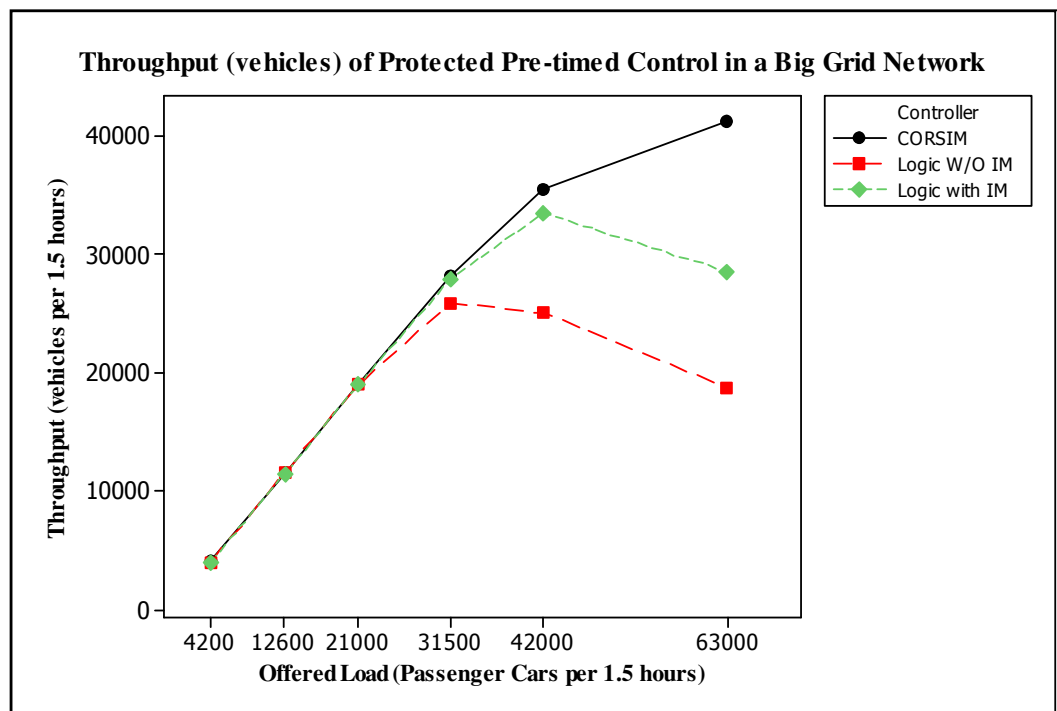
network

Figure A4.25: Offered load versus throughput for Protected Pre-timed in big grid
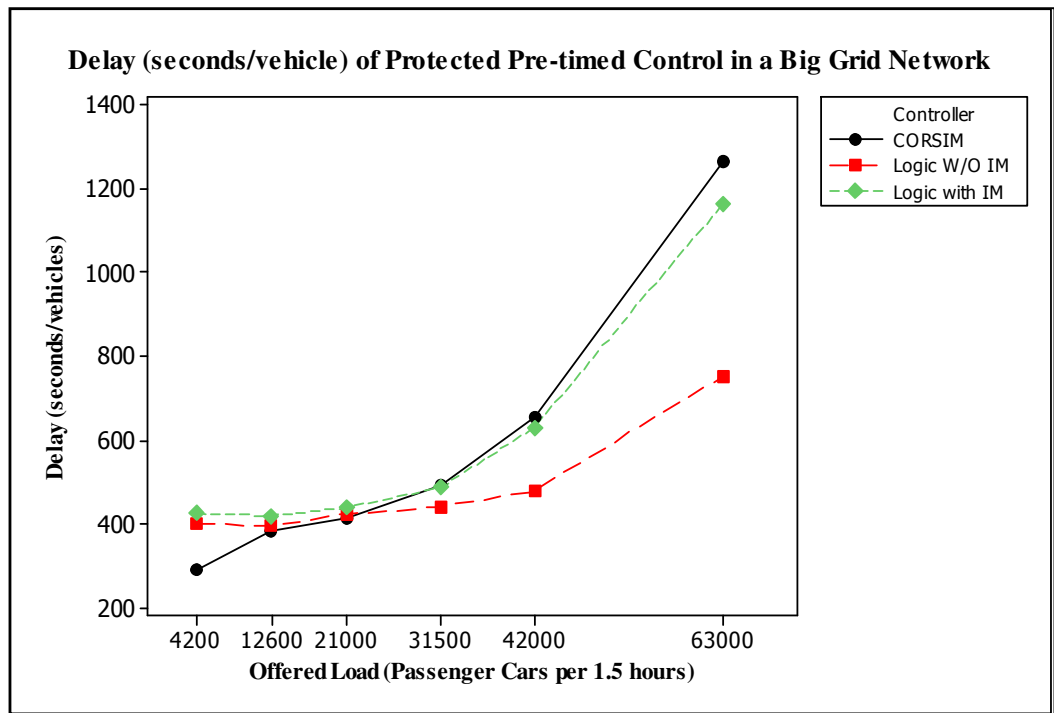
network

Figure A4.26: Offered load versus delay for Protected Pre-timed in big grid

network