MODELLING OF TRAFFIC CONTROL DELAYS AT PRIORITY JUNCTIONS USING ARTIFICIAL NEURAL NETWORK

MOHAMMAD ALI SAHRAEI

A thesis submitted in fulfilment of the
requirements for the award of degree of
Doctor of Philosophy (Civil Engineering)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

APRIL 2018

TO MY BELOVED MOTHER FOR HER
ENDLESS LOVE AND SUPPORT

ACKNOWLEDGEMENT

Firstly, I am thankful to God for completing this PhD project successfully. This project could not have been written without help of my supervisor, **Prof. Dr. Othman Che Puan** who encouraged and challenged me through my academic program.

I would like to express my special gratitude and thanks my mother for her kindness, patience and support me, and to my sisters Mahya, Modil, and Fatemeh for encourage me through thick and thin. Without all of you I will not be able to stand where I am today.

Thanks to my friends especially my best friend Babak Ziaei for his help and view at various occasions. Also, I would like to express my appreciation to those who have given me either direct or indirect assistance in this project.

Eventually, I hope that this thesis will be advantageous in the future.

ABSTRACT

Traffic delay is an essential aspect taken into consideration in the evaluation of operational performance of priority junctions. Delay is typically described as the excess time taken in a transportation facility in comparison to that of a reference value. Although, there are several methods available for the estimation of traffic control delay, they can lead to different results. A comparative analysis for the estimation of the control delay using the American highway capacity manual and the Malaysian highway capacity manual showed that the theoretical models are not consistent with actual delays observed from sites. This implies that both theoretical models are not directly capable of analysing control delay at priority junctions in Malaysia. This study was carried out to model traffic control delays at priority junctions using Artificial Neural Network (ANN). In this study, data were sampled from eight priority junctions of various configurations. Data pertaining to the analysis of critical gap, follow-up time, and control delay were collected using video camera recording technique. The study was divided into two phases comprising analysis of field data, and the development of ANN and mathematical models using MATLAB software. In the course of data analysis, the research recognized and estimated various variables that influence control delay. To generate the model, an ANN with two hidden layers and several sizes of neurons in the hidden layers were developed. Several mathematical models for estimation of control delay with a reasonable accuracy were developed using the outputs from the ANN model. Findings from this research showed that the range of conflicting flow is from 130 to 2470 veh/h and 120 to 2300 pcu/h, the values of control delays predicted are 3-37 sec/veh and 4-43 sec/pcu, respectively. Accordingly, the minimum and maximum values of traffic control delay occurred for both left- and right-turning vehicles from the minor roads. The modelling results showed that the values of control delay for right-turning manoeuvre from minor road at junction with four lanes major/two lanes minor road were higher than other junctions. This is due to queue delays and stops delay behind the stop line, in order to select an appropriate gap on the major road in the far and near side. Delay values for right-turning manoeuvre from major road at junction with four lanes major/four lanes minor road were greater than other junctions. The analysis revealed that heavy vehicles had the lowest effect on the proposed models, with an increase from 10% to 50%, resulting in the values of control delay to increase from 1% to 3%. On the contrary, the movement flow and conflicting flow had the highest impact, with an increase from 10% to 50% whereby the control delay could increase to 44%. The statistical analyses revealed that the delay estimated using the formula acquired from the ANN model and those from the field studies are equal.

ABSTRAK

Kelewatan lalu lintas adalah salah satu aspek penting yang diambil kira dalam penilaian prestasi operasi persimpangan keutamaan. Kelewatan biasanya digambarkan sebagai masa berlebihan yang diambil dari kemudahan pengangkutan berbanding dengan nilai rujukan. Walaupun terdapat beberapa kaedah yang tersedia untuk menganggarkan kelewatan kawalan lalulintas ianya boleh menyebabkan keputusan yang berbeza. Analisis perbandingan untuk menganggarkan kelewatan kawalan menggunakan manual kapasiti lebuh raya Amerika dan manual kapasiti lebuh raya Malaysia menunjukkan bahawa model teori tidak selaras dengan kelewatan sebenar yang dilihat dari lapangan. Ini menunjukkan bahawa kedua-dua model teori tidak mampu menganalisis kelewatan kawalan pada persimpangan keutamaan di Malaysia. Kajian ini dijalankan untuk pemodelan kelewatan kawalan lalu lintas di persimpangan keutamaan menggunakan Rangkaian Neural Buatan (ANN). Dalam kajian ini, data telah diambil dari lapan persimpangan utama pelbagai konfigurasi. Data yang berkaitan dengan analisis jurang kritikal, masa tindakan susulan, dan kelewatan kawalan dikumpulkan menggunakan teknik rakaman kamera video. Kajian ini dibahagikan kepada dua fasa yang terdiri daripada analisis data lapangan dan pembangunan ANN dan model matematik menggunakan perisian MATLAB. Dalam menjalankan analisis data, penyelidikan mengenal pasti dan menganggarkan pelbagai pembolehubah yang mempengaruhi kelewatan kawalan. Untuk menghasilkan model, ANN dengan dua lapisan tersembunyi dan beberapa saiz neuron dalam lapisan tersembunyi telah dibangunkan. Beberapa model matematik untuk menganggarkan kelewatan kawalan dengan ketepatan yang munasabah telah dibangunkan menggunakan output daripada model ANN. Dapatan kajian ini menunjukkan bahawa dalam julat aliran bertentangan antara 130 hingga 2470 kend/jam dan 120 hingga 2300 ukp/jam, nilai kelewatan kawalan masing-masing diramalkan hampir 3-37 saat/kend dan 4-43 saat/ukp. Oleh itu, nilai minimum dan maksimum kelewatan kawalan lalu lintas berlaku untuk masing-masing kenderaan membelok kiri dan kanan dari jalan kecil. Hasil pemodelan menunjukkan bahawa nilai-nilai kelewatan kawalan untuk pergerakan membelok kanan dari jalan kecil di persimpangan dengan empat lorong jalan utama/dua lorong jalan kecil lebih tinggi daripada persimpangan lain. Ini disebabkan oleh kelewatan barisan dan juga kelewatan berhenti di belakang garisan berhenti untuk memilih jarak sesuai di jalan utama pada jarak jauh dan dekat. Nilai kelewatan untuk membelok kanan dari jalan utama di persimpangan dengan empat lorong utama/empat lorong jalan kecil adalah lebih besar daripada persimpangan lain. Analisis menunjukkan bahawa kenderaan berat mempunyai kesan terendah terhadap model yang dicadangkan, iaitu dengan peningkatan daripada 10% hingga 50% menyebabkan nilai kelewatan kawalan meningkat dari 1% hingga 3%. Sebaliknya, aliran pergerakan dan aliran bertentangan mempunyai kesan tertinggi dengan peningkatan dari 10% hingga 50% di mana kelewatan kawalan boleh meningkat sehingga 44%. Analisis statistik mendedahkan bahawa kelewatan yang dianggarkan menggunakan formula yang diperoleh dari model ANN dan mereka dari kajian lapangan sama.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ANN	-	Artificial neural network
AWSC	-	All Way Stop Controlled
BP	-	backpropagation algorithm
CI	-	Computational Intelligence
CDF	-	Cumulative Distribution Function
h	-	hour
HCM	-	Highway Capacity Manual
km	-	kilometre
MSE	-	Mean Squared Error
MHCM	-	Malaysia Highway Capacity Manual
M/M/1	-	Markovian (random) arrivals/Markovian service rate/one
M/G/1	-	Markovian (random) arrivals/generally distributed service times/one
Mph	-	mile per hour
MLP	-	Multilayer Perceptron
P_{HV}	-	proportion of heavy vehicles
pcu	-	passenger car unit
RSS	-	Residual Sum of Squares
sec	-	second
sec/veh	-	second/vehicle
TWSC	-	Two Way Stopped Control
US	-	United States
veh	-	vehicle
veh/h	-	vehicle/hour

LIST OF SYMBOLS

A_x	-	Adjustment factor for movement x
b	-	Bias vector
$c_{m,x}$	-	Capacity of movement x
$c_{p,x}$	-	Potential capacity of movement x
CF	-	Conflict Flow rate
CG	-	Critical gap
d_Q	-	Desired output vector
D	-	Control delay
D_L	-	Control Delay (left-turning from minor road)
D_R	-	Control Delay (right-turning from minor road)
$D_{R\text{-}M}$	-	Control Delay (right-turning from major road)
Fa(t)	-	PDFs of the accepted gap
Fr(t)	-	PDFs of the rejected gap
F_t	-	Follow-up time
O_q	-	Output vector
P_{HV}	-	Proportion of heavy vehicles (i.e. large lorry + bus)
P_m	-	Proportion of motorcycle
P_L	-	Proportion of lorry (i.e. lorry + large van)
$t_{c,x}$	-	Critical gap for movement x
$t_{f,x}$	-	Follow-up time
T	-	Analysis time period
TF_L	-	Traffic Flow on minor road (left-turning from minor road)
TF_R	-	Traffic Flow on minor road (right-turning from minor road)

TF_{R-M}	-	Traffic Flow on major road (right-turning from major road)
$v_{c,x}$	-	Conflicting flow rate for movement x
V_x	-	Flow rate for movement x
$v_{c,x}$	-	Conflict flow
W	-	Weight matrix

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Delay is generally identified as the excess time taken in a transportation facility in comparison to that of a reference value. In this regard, it is the distinction between the time it would consume to traverse a road section under ideal situations and the real travel time. Accordingly, delay is generally taken into consideration as one of the most significant evaluation of the efficiency of priority junctions as recognized by road users.

Generally there are two principal types of priority T-junctions, i.e. the All Ways Stop-Controlled (AWSC) and Two-Way Stop-Controlled (TWSC) (Brilon *et al.*, 1997). The Highway Capacity Manual (HCM) and Malaysia Highway Capacity Manual (MHCM) explained that a three-leg junction could also be considered as a specific form of TWSC junctions, as long as the single minor street is controlled by a stop sign (TRB, 2000, TRB, 2010, MHCM, 2011).

The control of vehicles at priority junctions is a complicated and highly interactive process since each motorist generates their own individual decisions to perform the important manoeuvre, affected by his or her perceptions of speed, distance, as well as their car's performance (Kaysi and Abbany, 2007). Each motorist must also find a safe time for the movement to view existing traffic and traffic signs. Consequently, priority junctions generate a particular issue for potential accidents of vehicles which is appearing from minor road, as well as right-turning manoeuvre from major road as the priority of vehicles is for the ones from the major road (Brilon *et al.*, 1997).

Several models can be found in the literature review for calculating different kind of delay. In this regard, one of the initial delay method appears to be that of (Tanner, 1962). This author suggested one of the initial formulas which was attempted to utilize queuing theory and a steady state situation for calculating the delays at priority junctions. Troutbeck (1986) created a model for estimation of the delay at priority junctions as a function of the subsequent factors: a form factor that quantifies the impact of queuing in the minor road, the minor road flow rate was low, and also based on the degree saturation of the minor road.

Al-Omari & Benekohal (1999) created two distinct methods for calculating service delay and queue delay. I. Kaysi & Alam (2000) examined the effect of motorist behaviour on delay including impatience, experience, and also aggressiveness at priority junctions. Tapio (2004) formulated relationships between traffic flow and delay on the minor streets, while Chodur (2005) examined delay models at priority junctions on urban area. In addition, there are several researchers (Khattak and Jovanis, 1990, Heidemann, 1991, Kyte et al., 1991, Madanat et al., 1994, Tian Zongzhong, 1997, Akcelik et al., 1998a) who attempted to estimate the values of delays throughout different movement at priority junctions. In this case, a complete literature review is provided in Chapter 2.

This study concentrates on the control delay at priority junctions i.e. TWSC, for vehicle movement from minor road, as well as right-turning manoeuvre from major road. In this regard, first, a model of control delay is developed using Artificial Neural Network (ANN) with MATLAB software. Then, several mathematical formulas based on different categories and movements at TWSC junction are extracted from network.

1.2 Problem statement

Most of the above researches were carried out in different countries where geometry, traffic characteristics, traffic rules and also driving behaviour are different from those in Malaysia. In addition, the Transportation Research Board (TRB) (2010) in Highway Capacity Manual (HCM), as well as Malaysia Highway Capacity Manual (MHCM) (2011) provides a procedure for calculating control delay at priority junctions. In order to show that the existing models are not able to estimate the values of control delays at priority junctions, comparative analysis are performed in Chapter 4 between actual control delays and existing models (i.e. HCM's and MHCM's models). Generally, the analysis displays that the calculated control delays utilizing mentioned models are substantially different from the observed data.

More specifically, although the MHCM is provided and edited under Malaysia traffic and geometric characteristics, it cannot estimate the values of control delays in comparison to the actual data at priority junctions precisely. Because, the process is depending on the techniques followed from the United States Highway Capacity Manual. Under these conditions, the outcomes of the delay analysis probably are not directly transferable to a geographic region distinct from that in which they have been acquired. Consequently, there is evidence that local circumstances needs to be examined to present appropriate models to estimate control delay at priority junctions.

1.3 Aim and objective

The aim of the study is to develop an ANN model of traffic control delays at priority junctions for Malaysia traffic conditions. The delay model must be capable of representing and investigating the magnitudes of control delays to drivers at the minor approach and also to the right-turning drivers from major road.

The following objectives are defined in order to achieve the aim of the study:

(i) To collect and analyse the relevant traffic data at priority junctions for model development and validation purposes.

(ii) To assess and evaluate the current practices of junction delay assessment methods and their application to the local traffic.

(iii) To develop mathematical delay models and application graphs for estimating delay at priority junction for ranges of traffic flows.

1.4 Scope of study

Basically, the scope of this study consists of two factors; site study data collection and evaluation of the data gathered. The study sites utilized for the data gathering are selected around Johor Bahru States, Malaysia. The junctions are divided into three categories comprising of four lanes major/four lanes minor, four lanes major/two lanes minor, and two lanes major/two lanes minor road. They are selected such that junctions with diverse rates of traffic flow conditions, compositions, and geometric features. In terms of data collection, several parameters are extracted from site studies including traffic flow rate on major and minor road, gap acceptance, and also control delay.

In terms of data evaluation, it is separated into two stages: first, analysis of field data using Excel software, and then development of ANN and mathematical models. In the first stage, some parameters including follow-up time and critical gap are evaluated and then observed control delay is compared with those depending on each of HCM's model and MHCM's model in order to show the existing models are not able to estimate the values of control delay at priority junctions, precisely. Then, an ANN and several mathematical formulas of control delay for operational assessment of several categories of priority junctions are developed. Next, in order to validate models, observed control delays from a new priority junction with same geometry and period of data collection were utilized and compared with outputs of proposed formulas. Additionally, the needed data sets associated with each proposed models are substituted into the relationship and applications of the models are shown throughout several graphs.

1.5 Significance of the study

This study investigates and introduces a methodology for field evaluation of control delay at priority junctions with three categories including four lanes major/four lanes minor, four lanes major/two lanes minor, and also two lanes major/two lanes minor road. Additionally, since the control delay formulated is dependent on data gathered with diverse traffic flow and geometric features in Malaysia, it is expected that the new approach would be useful in contributing to the Malaysian practice associated to the operational performance evaluation of priority junctions.

By comparing the observation data set and performance of the models, it is discovered that the ANN can estimate traffic control delays incurred on minor road vehicles and also right-turning manoeuvre from major road at priority junctions more precisely. Therefore, results from this research would present a basis to substantiate the usage of method for calculating control delay which has been arguable for a long time and consequently provides a contribution in that respect.

1.6 Thesis structure

This thesis is arranged in seven Chapters and each one reporting a specific aspect of the whole research. Chapter 1 explains the background of the research, statement of the problem, objectives of the research, scope of research, and also significance of the research.

Chapter 2 consists of discussions on earlier works associated with estimation of traffic delays, critical gap, and follow-up time at priority junction. The Chapter discusses the existing problem concerning approaches utilized in calculating traffic delays, their weaknesses, strengths, and suggestions on the way forward in advancing the existing practice.

Chapter 3 describes the methodology of research that consists of research approach and procedure activities. This Chapter consists of 5 main Sections including artificial neural network, conflicting flow, priority of streams, control delay, critical gap, and follow-up time.

Chapter 4 first identifies the priority junctions at suburban area. Then, data gathering at eight priority junctions are explained. In addition, a complete description about traffic characteristic at priority junction, as well as data analysis for estimation of traffic composition, critical gap, follow-up time, and control delay is provided. Lastly, a comparative analysis among U.S. Highway Capacity Manual (HCM), Malaysia Highway Capacity Manual (MHCM), and observed control delays is performed. The data and information gathered in this Section are used to develop new mathematical models from ANN's model for estimation of control delay at priority junctions.

Chapter 5 gives the details of the procedure for model development using ANN. In addition, nine mathematical models (i.e. three models for each category of priority junction based on different movements), in which flow rates were taken into consideration in terms of vehicle per hour (veh/h) and nine mathematical models based on Passenger Car Unit (PCU) are developed. Furthermore, some validations and verifications are performed to show the precision of the models.

Chapter 6 provides the application of the models developed. In this matter, several observed data sets from junctions with diverse traffic flow conditions and compositions are used. Then, the need data sets associated with each model are substituted into the relationship and application of the models were shown throughout several graphs.

Chapter 7 outlines the essential conclusions drawn from this research and suggestions for further investigation.

REFERENCES

AASHTO (2001). American association of state highway and transportation officials (AASHTO). *Washington, DC,* 10.

ABOU-HENAIDY, M., TEPLY, S. & HUNT, J. D. (1994). Gap acceptance investigations in Canada. *In:* Proceedings of the second international symposium on highway capacity, volume 1, 1994 of Conference.

ADEBISI, O. & SAMA, G. (1989). Influence of Stopped Delay on Driver Gap Acceptance Behavior. *Journal of Transportation Engineering,* 115**,** 305-315.

AKCELIK, R. & BESLEY, M. (1998). *SIDRA 5 User Guide,* Vermont South, Australia, ARRB Transport Research Ltd.

AKCELIK, R., CHRISTENSEN, B. & CHUNG, E. (1998a). A comparison of three delay models for sign-controlled intersections. *In:* Third International Symposium on Highway Capacity, 1998a of Conference., 35-56.

AKCELIK, R. & TROUTBECK, R. (1991). Implementation of the Australian roundabout analysis method in SIDRA. *In:* International Symposium On Highway Capacity, 1991 of Conference.

AL-OMARI, B. & BENEKOHAL, R. F. (1999). Hybrid delay models for unsaturated two-way stop controlled intersections. *Journal of Transportation Engineering-Asce,* 125**,** 291-296.

ALEXANDER, J., BARHAM, P. & BLACK, I. (2002). Factors influencing the probability of an incident at a junction: results from an interactive driving simulator. *Accident Analysis & Prevention,* 34**,** 779-792.

ASHALATHA, R. & CHANDRA, S. (2011a). Critical gap through clearing behavior of drivers at unsignalised intersections. *KSCE Journal of Civil Engineering,* 15**,** 1427-1434.

ASHALATHA, R. & CHANDRA, S. (2011b). Service delay analysis at TWSC intersections through simulation. *KSCE Journal of Civil Engineering,* 15**,** 413-425.

ASHTON, W. D. (1971). Gap-acceptance problems at a traffic intersection. *Applied Statistics***,** 130-138.

ASHWORTH, R. (1968). A note on the selection of gap acceptance criteria for traffic simulation studies. *Transportation Research,* 2**,** 171-175.

ASHWORTH, R. (1970). The analysis and interpretation of gap acceptance data. *Transportation Science,* 4**,** 270-280.

ASHWORTH, R. (1976). A Video Tape Recording System For Traffic Data Collection and Analysis. *Traffic engineering & control,* 17.

ASHWORTH, R. & BOTTOM, C. (1977). Some observations of driver gap-acceptance behaviour at a priority intersection. *Traffic Engineering and Control,* 18**,** 569-571.

BEALE, M., HAGAN, M. & DEMUTH, H. (2015). *Neural Network Toolbox-User's Guide (Vol. R2015b)*, MATLAB.

BLUMENFELD, D. & WEISS, G. (1979). Effects of gap acceptance criteria on merging delay and capacity at an uncontrolled junction. *Traffic Engineering and Control,* 20**,** 16-20.

BRILON, W. (1988). Recent developments in calculation methods for unsignalized intersections in West Germany. *Intersections without Traffic Signals.* Springer.

BRILON, W. (1995). Delays at oversaturated unsignalized intersections based on reserve capacities. *Transportation research record***,** 1-8.

BRILON, W. (2007a). Time dependent delay at unsignalized intersections. *In:* Proceedings of 17th International Symposium on Transportation and Traffic Theory (ISTTT17), London, 2007a of Conference.

BRILON, W. (2007b). Time dependent delay at unsignalized intersections. *In:* Transportation and Traffic Theory 2007. Papers Selected for Presentation at ISTTT17, 2007b of Conference.

BRILON, W. (2008). Delay at Unsignalized Intersections. *Transportation Research Record***,** 98-108.

BRILON, W. (2015). Average Delay at Unsignalized Intersections for Periods with Variable Traffic Demand. *Transportation Research Record: Journal of the Transportation Research Board*, 57-65.

BRILON, W. & GROßMANN, M. (1991). The new German guideline for capacity of unsignalized intersections. *Intersections without Traffic Signals II.* Springer.

BRILON, W., KOENIG, R. & TROUTBECK, R. J. (1999). Useful estimation procedures for critical gaps. *Transportation Research Part A: Policy and Practice,* 33**,** 161-186.

BRILON, W., TROUTBECK, R. & TRACZ, M. (1997). Review of international practices used to evaluate unsignalized intersections. *Transportation Research Circular*.

CALIENDO, C. (2014). Delay Time Model at Unsignalized Intersections. *Journal of transportation engineering,* 140**,** 04014042.

CATCHPOLE, E. & PLANK, A. (1986). The capacity of a priority intersection. *Transportation Research Part B: Methodological,* 20**,** 441-456.

CHANDRA, S., AGRAWAL, A. & RAJAMMA, A. (2009). Microscopic analysis of service delay at uncontrolled intersections in mixed traffic conditions. *Journal of transportation engineering,* 135**,** 323-329.

CHODUR, J. (2005). Capacity models and parameters for unsignalized urban intersections in Poland. *Journal of transportation engineering,* 131**,** 924-930.

CHUNG, E. C. (1993). *Modelling single-lane roundabout performance*, Monash University.

COOPER, D., SMITH, W. & BROADIE, V. (1976). Traffic studies at t-junctions. (1) the effect of approach speed on merging gap acceptance. *Traffic engineering & control,* 17.

COOPER, D., STORR, P. & WENNELL, J. (1977). Traffic studies at T-junctions. 4. The effect of speed on gap acceptance and conflict rate. *Traffic engineering & control,* 18.

COOPER, D. & WENNELL, J. (1978). Models of gap acceptance by queues at intersections. *Transportation Engineering,* 19.

COWAN, R. J. (1975). Useful headway models. *Transportation Research,* 9**,** 371-375.

CVITANIĆ, D., BREŠKI, D. & VIDAK, B. (2012). Review, testing and validation of capacity and delay models at unsignalized intersections. *PROMET-Traffic&Transportation,* 19**,** 71-82.

DAGANZO, C. & SCHOENFELD, L. (1978). *CHOMP user's manual*, Institute of Transportation Studies, University of California Berkeley.

DAGANZO, C. F. (1981). Estimation of gap acceptance parameters within and across the population from direct roadside observation. *Transportation Research Part B: Methodological,* 15**,** 1-15.

DAGANZO, C. F., BOUTHELIER, F. & SHEFFI, Y. (1977). Multinomial probit and qualitative choice: A computationally efficient algorithm. *Transportation Science,* 11**,** 338-358.

DAVIS, G. & SWENSON, T. (2004). Field study of gap acceptance by left-turning drivers. *Transportation Research Record: Journal of the Transportation Research Board***,** 71-75.

DELUCIA, P. R., BLECKLEY, M. K., MEYER, L. E. & BUSH, J. M. (2003). Judgments about collision in younger and older drivers. *Transportation Research Part F: Traffic Psychology and Behaviour,* 6**,** 63-80.

DEMUTH, H. B., BEALE, M. H., DE JESS, O. & HAGAN, M. T. (2014). *Neural network design*, Martin Hagan.

DEVARASETTY, P., ZHANG, Y. & FITZPATRICK, K. (2012). Differentiating between Left-Turn Gap and Lag Acceptance at Unsignalized Intersections as a Function of the Site Characteristics. *Journal of Transportation Engineering,* 138**,** 580-588.

EBERHART, R. C. (2014). *Neural network PC tools: a practical guide*, Academic Press.

ENGELBRECHT, A. P. (2007). *Computational intelligence: an introduction*, John Wiley & Sons.

FITZPATRICK, K. (1991). *Gaps accepted at stop-controlled intersections*.

GUO, R.-J., WANG, X.-J. & WANG, W.-X. (2014). Estimation of critical gap based on Raff's definition. *Computational intelligence and neuroscience,* 2014**,** 16.

GUO, R. & LIN, B. (2011). Gap Acceptance at Priority-Controlled Intersections. *Journal of Transportation Engineering,* 137**,** 269-276.

HAGAN, M. T., DEMUTH, H. B. & BEALE, M. H. (1996). Neural network design, PWS Pub. *Co., Boston,* 3632.

HAGRING, O. (1996). The use of the Cowan M3 distribution for modelling roundabout flow. *Traffic engineering & control,* 37**,** 328-332.

HAGRING, O. (2000). Estimation of critical gaps in two major streams. *Transportation Research Part B: Methodological,* 34**,** 293-313.

HANSSON, A. & BERGH, T. (1988). A new Swedish capacity manual CAPCAL 2. *In:* AUSTRALIAN ROAD RESEARCH BOARD PROCEEDINGS, 1988 of Conference.

HARDERS, J. (1968). The capacity of unsignalized urban intersections. *Schriftenreihe Strassenbau und Strassenverkehrstechnik,* 76**,** 1968.

HARDERS, J. (1976). Critical gaps and move up thes as the basis of capacity caiculations for rural roads. *Strassenban und Strassenverherstechni,* Heft 216, Federal Republic of German.

HARWOOD, D., MASON JR, J. & BRYDIA, R. (2000). Sight distance for stop-controlled intersections based on gap acceptance. *Transportation Research Record: Journal of the Transportation Research Board***,** 32-41.

HAWKES, A. (1966). Delay at Traffic Intersections. *Journal of the Royal Statistical Society. Series B (Methodological),* 28**,** 202-212.

HAYKIN, S. S. (2001). *Neural networks: a comprehensive foundation*, Tsinghua University Press.

HEIDEMANN, D. (1991). Queue length and waiting-time distributions at priority intersections. *Transportation Research Part B: Methodological,* 25**,** 163-174.

HEWITT, R. (1983). Measuring critical gap. *Transportation Science,* 17**,** 87-109.

HEWITT, R. (1985). A comparison between some methods of measuring critical gap. *Traffic engineering & control,* 26**,** 13-22.

HOTHERSALL, D. & SALTER, R. (1981). The effect of major road headway distribution on capacity and vehicular delays at priority junctions. *In:* Institution of Civil Engineers, Proceedings, Pt2, 1981 of Conference.

IVEY, D. L., LEHTIPUU, E. K. & BUTTON, J. (1975). Rainfall invisibility--the view from behind the wheel. *Journal of safety research,* 7**,** 156-169.

KARLAFTIS, M. G. & VLAHOGIANNI, E. I. (2011). Statistical methods versus neural networks in transportation research: Differences, similarities and some insights. *Transportation Research Part C: Emerging Technologies,* 19**,** 387-399.

KAYSI, I. & ALAM, G. (2000). Driver Behavior and Traffic Stream Interactions at Unsignalized Intersections. *Journal of Transportation Engineering,* 126**,** 498-505.

KAYSI, I. A. & ABBANY, A. S. (2007). Modeling aggressive driver behavior at unsignalized intersections. *Accident Analysis & Prevention,* 39**,** 671-678.

KHATTAK, A. & JOVANIS, P. (1990). Capacity and delay estimation for priority unsignalized intersections: Conceptual and empirical issues. *Transportation research record,* 1287**,** 129-137.

KIMBER, R. & HOLLIS, E. (1978). Peak-period traffic delays at road junctions and other bottlenecks. *Traffic engineering & control,* 19.

KIMBER, R., SUMMERSGILL, I. & BURROW, I. (1986). Delay processes at unsignalised junctions: the interrelation between geometric and queueing delay. *Transportation Research Part B: Methodological,* 20**,** 457-476.

KOIVISTO, N. (1999). *Valo-ohjaamattomien tasoliittymien liikennevirta ja liikenteen simulointi [Traffic flowof unsignalized at-grade intersections and traffic simulation].* Master's thesis, Helsinki University of Technology.

KRÖSE, B., KROSE, B., VAN DER SMAGT, P. & SMAGT, P. (1993). An introduction to neural networks.

KUMAR, P., NIGAM, S. & KUMAR, N. (2014). Vehicular traffic noise modeling using artificial neural network approach. *Transportation Research Part C: Emerging Technologies,* 40**,** 111-122.

Author (1991). *Traffic Data Input Program (TDIP)*, University of Idaho.

KYTE, MICHAEL, TIAN ZONGZHONG, ZAKIR MIR, ZIA HAMEEDMANSOOR, WAYNE KITTELSON, MARK VANDEHEY, BRUCE ROBINSON, WERNER BRILON, L., BONDZIO, N. W. & TROUTBECK, A. R. (1996). *Capacity and Level of Service at Unsignalized Intersections*, NCHRP.

KYTE, M., CLEMOW, C., MAHFOOD, N., LALL, B. K. & KHISTY, C. J. (1991). *Capacity and delay characteristics of two-way stop-controlled intersections.*

LABERGE, J. C., CREASER, J. I., RAKAUSKAS, M. E. & WARD, N. J. (2006). Design of an intersection decision support (IDS) interface to reduce crashes at rural stop-controlled intersections. *Transportation Research Part C: Emerging Technologies,* 14**,** 39-56.

LU, J. J. & LALL, B. K. (1995). Empirical analysis of traffic characteristics at two-way stop-controlled intersections in Alaska. *Transportation Research Record*, 49-56.

MA, D.-F., MA, X.-L., JIN, S., SUN, F. & WANG, D.-H. (2013). Estimation of major stream delays with a limited priority merge. *Canadian Journal of Civil Engineering,* 40, 1227-1233.

MA, D.-F., WANG, D., BIE, Y.-M. & TAO, P. (2011). Critical traffic volume of traffic signal warrant at unsignalized intersections. *In:* Transportation Research Board 90th Annual Meeting, 2011 of Conference.

MADANAT, S., CASSIDY, M. & WANG, M. (1994). Probabilistic Delay Model at Stop-Controlled Intersection. *Journal of Transportation Engineering,* 120, 21-36.

MAHDI, T. (1991). *The effect of overtaking provision on the operation characteristics of single carriageway roads.* Cardiff University.

MAY, A. D. (1990). *Traffic flow fundamentals*, Prentice-Hall, Upper Saddle River, NJ.

MCGOWEN, P. & STANLEY, L. (2012). Alternative Methodology for Determining Gap Acceptance for Two-Way Stop-Controlled Intersections. *Journal of Transportation Engineering,* 138, 495-501.

MHCM (2011). Highway Planning Unit. *Ministry of Work Malaysia*.

MILLER, A. J. (1971). Nine estimators of gap-acceptance parameters. *Publication of: Traffic Flow and Transportation*.

MILLER, A. J. (1974). A note on the analysis of gap-acceptance in traffic. *Applied Statistics*, 66-73.

MORSE, P. M. (1958). *Queues, inventories and maintenance*, Wiley New York.

MORSE, P. M. (1976). *queues-inventories and mentenance*, John Wiley & Sons, revised version (first edition 1958).

NEWELL, C. (1982). *Applications of queueing theory,* London.

NEWELL, C. (2013). *Applications of queueing theory*, Springer Science & Business Media.

OXLEY, J., FILDES, B., CORBEN, B. & LANGFORD, J. (2006). Intersection design for older drivers. *Transportation Research Part F: Traffic Psychology and Behaviour,* 9, 335-346.

PANT, P. & BALAKRISHNAN, P. (1994). Neural Network for Gap Acceptance at Stop-Controlled Intersections. *Journal of Transportation Engineering,* 120**,** 432-446.

POLLATSCHEK, M. A., POLUS, A. & LIVNEH, M. (2002). A decision model for gap acceptance and capacity at intersections. *Transportation Research Part B: Methodological,* 36**,** 649-663.

PUAN, O. C. (1999). A simulation study of speed and capacity of rural single carriageway roads. *Division of Civil Engineering, Cardiff School of Engineering, University of Wales Cardiff*.

PUAN, O. C. (2004). Drivers car following headway on single carriageway roads. *Malaysian Journal of Civil Engineering (MJCE),* 16**,** 15-27.

RAFF, M. S. (1950). A volume warrant for urban stop signs.

RAHMAN, A. & LOWNES, N. E. (2012). Analysis of rainfall impacts on platooned vehicle spacing and speed. *Transportation Research Part F: Traffic Psychology and Behaviour,* 15**,** 395-403.

SADEK, A. W., SPRING, G., SMITH, B.L., (2003). toward more effective transportation applications of computational intelligence paradigms. *Transportation research record***,** 57-63.

SANGOLE, J. P., PATIL, G. R. & PATARE, P. S. (2011). Modelling gap acceptance behavior of two-wheelers at uncontrolled intersection using neuro-fuzzy. *Procedia-Social and Behavioral Sciences,* 20**,** 927-941.

SHAHPAR, A. H., AASHTIANI, H. Z. & FAGHRI, A. (2011). Development of a delay model for unsignalized intersections applicable to traffic assignment. *Transportation Planning and Technology,* 34**,** 497-507.

SHARIFF, M., PUAN, O. C. & MASHROS, N. (2016). REVIEW OF TRAFFIC DATA COLLECTION METHODS FOR DRIVERS'CAR-FOLLOWING BEHAVIOUR UNDER VARIOUS WEATHER CONDITIONS. *Jurnal Teknologi,* 78**,** 37-47.

SIMPSON, S. & MATTHIAS, J. (2000). Validation of left-turn delay at two-way stop-controlled intersections. *Transportation Research Record: Journal of the Transportation Research Board***,** 181-188.

SINHA, K. (1971). SECTION GAP ACCEPTANCE PHENOMENON AT STOP-CONTROLLED INTERSECTIONS. *Traffic Engineering, Inst Traffic Engr*.

SOLBERG, P. & OPPENLANDER, J. (1966). Lag and gap acceptances at stop-controlled intersections.

SPECHT, D. F. (1991). A general regression neural network. *Neural Networks, IEEE Transactions on,* 2**,** 568-576.

SPEK, A., WIERINGA, P. A. & JANSSEN, W. (2006). Intersection approach speed and accident probability. *Transportation Research Part F: Traffic Psychology and Behaviour,* 9**,** 155-171.

SULLIVAN, D. & TROUTBECK, R. (1994). The use of Cowan's M3 headway distribution for modelling urban traffic flow. *Traffic engineering & control,* 35**,** 445-450.

TAKÁCS, L. (1959). Introduction to the Theory of Queues.

TANNER, J. (1962). A Theoretical Analysis of Delays at an Uncontrolled Intersection. *Biometrika,* 49**,** 163-170.

TAPIO, R. (2004). Capacity and Level of Service at Finnish Unsignalized Intersections.

TARABIA, A. (2000). Transient analysis of m/m/1/n queue-an alternative approach. *淡江理工學刊,* 3**,** 263-266.

TIAN, Z., VANDEHEY, M., ROBINSON, B. W., KITTELSON, W., KYTE, M., TROUTBECK, R., BRILON, W. & WU, N. (1999). Implementing the maximum likelihood methodology to measure a driver's critical gap. *Transportation Research Part A: Policy and Practice,* 33**,** 187-197.

TIAN ZONGZHONG, M. K. A. J. C. (1997). Field Measurements of Capacity and Delay at Unsignalized Intersections. *ITE JOURNALC***,** 22-26.

TIAN, Z. Z., TROUTBECK, R., KYTE, M., BRILON, W., VANDEHEY, M., KITTELSON, W. & ROBINSON, B. (2000). A further investigation on critical gap and follow-up time. *In:* Proceedings of the 4th International Symposium on Highway Capacity, Maui/Hawaii, Transportation Research Circular E-C018, 2000 of Conference., 409-421.

TRB (1985). *Highway Capacity Manual,* Washington D.C., Transportation Research Board (TRB), National Research Council.

TRB (1994). *Highway Capacity Manual,* Washington D.C., Transportation Research Board (TRB), National Research Council.

TRB (2000). *Highway Capacity Manual,* Washington D.C., Transportation Research Board (TRB), National Research Council.

TRB (2010). *Highway Capacity Manual,* Washington D.C., Transportation Research Board (TRB), National Research Council.

TROUTBECK (1986). Average delay at an unsignalized intersection with two major streams each having a dichotomized headway distribution. *Transportation Science,* 20**,** 272-286.

TROUTBECK (1989). *Evaluating the Performance of a Roundabout*.

TROUTBECK, R. (1992). *Estimating the critical acceptance gap from traffic movements*, Physical Infrastructure Centre, Queensland University of Technology.

TROUTBECK, R. & BLOGG, M. (1998). Queueing at congested intersections. *Transportation Research Record: Journal of the Transportation Research Board***,** 124-131.

TROUTBECK, R. & BRILON, W. (1997). Unsignalized intersection theory. *Traffic Flow Theory, TRB*.

TUPPER, S., KNODLER JR, M. A., FITZPATRICK, C. & HURWITZ, D. S. (2013). Estimating critical gap—a comparison of methodologies using a robust, real-world data set. *In:* 92nd Annual Meeting of the Transportation Research Board, Washington, DC, 2013 of Conference.

VASCONCELOS, L., SECO, Á. & SILVA, A. B. (2013). Comparison of procedures to estimate critical headways at roundabouts. *Promet–Traffic&Transportation,* 25**,** 43-53.

VELAN, S. & VAN AERDE, M. (1996). Gap acceptance and approach capacity at unsignalized intersections. *ITE Journal,* 66**,** 40-45.

VELAN, S. M. (1998). *Gap acceptance of permissive movements at signalised and unsignalised intersections.* Queen's University at Kingston.

WAGNER JR, F. A. (1966). An evaluation of fundamental driver decisions and reactions at an intersection. *Highway Research Record*.

WASSERMAN, P. D. (1993). *Advanced methods in neural computing*, John Wiley & Sons, Inc.

WEINERT, A. (2000). Estimation of Critical Gaps and Follow-Up Times at Rural Unsignalized Intersections in Germany. *In:* Proceedings of the 4th International Symposium on Highway Capacity, Maui/Hawaii, Transportation Research Circular EC018, 2000 of Conference., 397-408.

WEISS, G. H. (1969). The single lane merging problem with mixed cars and trucks. *Transportation Research,* 3**,** 195-199.

WU, N. (2006). A new model for estimating critical gap and its distribution at unsignalized intersections based on the equilibrium of probabilities. *In:* Proceeding of the 5th International Symposium on Highway Capacity and Quality of Service, 2006 of Conference.

WU, N. (2012). Estimating Distribution Function of Critical Gaps at Unsignalized Intersections Based on Equilibrium of Probabilities. *Transportation research record*.

YAN, X., RADWAN, E. & GUO, D. (2007). Effects of major-road vehicle speed and driver age and gender on left-turn gap acceptance. *Accident Analysis & Prevention,* 39**,** 843-852.

ZHOU, H., HAGEN, L., LU, J. J. & TIAN, Z. (2006). Empirical delay models for multi-lane two-way stop-controlled intersections. *Ite Journal-Institute of Transportation Engineers,* 76**,** 41-46.