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Analysis of a Transportation System With Correlated Network Intersections: A Case Study for a Central Urban City With High Seasonal Fluctuation Trends

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ABSTRACT Intelligent transportation systems (ITSs) providing efficient road-transportation strategies have recently become a very active research area. Efficient transportation of visitors to/from highly congested sites is one of the most important challenges addressed by ITS. A transportation-system analysis is presented here and is applied on an urban city ring road network that encompasses a major attraction site characterized by correlated network-intersections and large vehicle-pedestrian movement conflicts. The presented model analysis first examines the influences exerted by network-correlations at intersection-points, and second, presents case-study evacuation scenarios examined under varying circumstances and flow-requirements within each segment of the modeled network. The significance of this paper is clearly evident in emergency/evacuation scenarios or in design considerations in which the influence of correlated network-intersections must be known beforehand. As a main contribution, a mathematical model was developed with simulations evaluating the current system using real-life data as statistical input to our model. Results had demonstrated the counter-propagation effect between adjacent intersections along the ring road of an urban congested city. Furthermore, the study modeled and investigated two emergency-evacuation scenarios within chosen segments at road network sites entering and exiting the central area in order to demonstrate how efficient evacuation can be conducted during an emergency scenario. It is expected that the results of this model can also be extended and applied for evacuation analyses for other sites with similar practical conditions or in other congested cities in which correlated intersections have a significant presence that must be included in the real-life analysis of a transportation system.

INDEX TERMS Transportation systems, correlated network intersections, traffic simulations, traffic planning, emergency evacuation analysis, traffic flows, congested networks.

I. INTRODUCTION

The traffic in the central area of Madinah in Saudi Arabia has radically increased in the last few years, which has resulted with a consequent increase in city traffic. The central area of Madinah, shown in Fig. 1, is encircled by the first ring road (King Faisal Rd.), and occupies around 2.16 km^2. The area is accessed by 10 major roads which feed into the ring road. This area is very crowded, particularly during peak visiting seasons. The statistics provided by the Saudi Central Department of Statistics and Information shows the number of visitors during the last 20 years has increased by approximately 70% [1]. Thus, more traffic flows on the road network during peak seasons as compared with other time of the year. It is also noticed that the population of Madinah has increased significantly in the last decade to over one million, and it is projected that the population could increase by 50% by 2025 years due to the city economic growth (Saudi Central Department of Statistics and Information, 2013) [1].

The central area has multi-story underground car park that accommodates around 5000 cars, in addition to over

FIGURE 1. Central Area of Madinah (Enclosed by the First Ring Rd.) (Google Maps, 2016) [2].

200 hotels. The central area can accommodate around 1 million people at normal times, which can reach around 2 million at peak-times [1]. Moreover, according to [5], the first ring road carries 20,000 vehicles/hour and is crossed by 140,000 pedestrians/hour at peak-times.

The traffic in the central area of Madinah has become a major concern for authorities, particularly during peak seasons where heavy crowds form on a daily basis, exceeding the capacity of the surrounding road network. Typically, visitor-crowds compete with vehicle-traffic in a space and movement conflict problem. This study aims to model the traffic-flow around the central area of Madinah under such circumstances and provides recommendations for traffic evacuation and road-infrastructure designers based on our findings. A summary of objectives/motivations that inspired this paper are as follows:

- To present a review of the related literature of some existing transportation systems used worldwide and their possible consideration and limitations for application in the road network of central Madinah.
- To demonstrate a promising technique for incorporating a traffic-sensitive transportation system for the Madinah road network surrounding the central area that addresses the phenomenal-affect of dynamic traffic patterns and their influence and trends elsewhere within the road network, as found between adjacent network-nodes.
- To provide a model for computing traffic control-decisions (e.g. based on delay and queue-occupancy metrics) in accordance with varying circumstances within each segment of the road network to efficiently counter emergency cases or evacuation requirements.
- To provide recommendations for transportation-planning and efficient evacuation-control strategies.
- To enhance the overall safety and flow of vehicle traffic surrounding the central area through monitoring and control of the traffic-state within the Madinah central road network.
- To reduce the traffic delays encountered upon entry and exit to/from the central area and surrounding areas.
- To provide an efficient means for evacuating traffic from and around the central region in case of emergencies.

The remainder of this paper is organized as follows. Section II presents a literature review of the related work while section III provides the physical context and system description. Section IV presents the Methodology used in this paper. Section V describes the mathematical model used to represent the central Madinah region being studied while section VI provides the data analysis and simulation results, including results of the proposed traffic/transportation model and analysis of the correlations between network-intersections. Section VII describes two case-study evacuation scenarios and their implications studied in this paper. Finally, the conclusions and recommendations of this work are presented in section VIII.

II. RELATED WORK

Many factors influence the evacuation of people or vehicles. These could be general conditions (e.g. arranged events) such as religious gatherings, festivals, sports events (racing, football, soccer ... etc) and emergency conditions such as flooding, earthquakes, volcano, fire, nuclear power leaks, terrorist attacks ... etc [3]. Therefore, according to whether the situation is normal or emergency, the evacuation process can be managed and planned. Thus, the traffic congestion in the central area of Madinah has provided the recognition, the importance and need to investigate new processes in order to help manage and plan the traffic during peak times. It has been noticed that the traffic in the central area of Madinah has increased in the last decade with the increase in population and number of visitors. The evacuation plan from the central area is an issue that needs to be addressed seriously due to the fact that congestion has become severe and is more problematic to address in the case of an evacuation. Nowadays, the use of technology has eased the emergency response to situations related to traffic, flooding, hazardous materials .... etc. The goal of this work is to propose and implement a priority based traffic management system for the traffic-network in the central area of Madinah.

To the best knowledge of the authors, the only work that is closely related to traffic problem in Madinah is the work by Alginahi, et. al which presents an assessment of traffic flow on the first ring road., located around the central area of Madinah without considering evacuation scenarios. In this work, a model for the traffic distribution along the roads intersecting with the first ring road was built based on optimization. The optimization model was formulated as a minimization problem of the difference between the measured number of vehicles and the sum of portions of vehicles from all entrances of the first ring road. that move out from each road. The simulation results show good agreement with the corresponding measurement data of vehicles at the first ring road [4]. In addition, the literature work by Abdelgawad *et al.* [5], was found to deal with the issue of evaluating pedestrian-vehicle conflicts in crowded crossing areas. The study in [5] presented a micro-simulation modeling framework to deal with this issue.

The framework is used to assess large-scale pedestrian–vehicle conflicts in the first ring road. which carries 20 000 vehicles/hour and crossed by 140 000 pedestrians/hour after a major congregational event. The quantitative and visual results of the simulation exhibits serious conflicts between pedestrians and vehicles, resulting in considerable delays for pedestrians crossing the road (9 minutes average delay) and slow traffic conditions (average speed <10 km/hour).

Another work related to Pilgrim Movements is the work of Tayan, [6], which proposes a model for optimizing the flow of pilgrims between holy sites during Hajj using traffic congestion control [6]. The study investigated access control and a fairness protocol for Makkah's road network between the Holy sites during the significant annual event of Hajj. The proposed traffic congestion-awareness protocol provided a fair mechanism of controlling road access and preventing node starvation, whilst limiting the delay in the network.

The work by Tayan *et al.* [7] proposed a model for optimizing people/vehicle movements in largely-crowded areas for the Hajj event. A case study between Mina and Arafat was described in terms of developed mathematical and micro-simulation computer models. Both models were based on queuing and networking concepts with an underlying road network infrastructure used from which raw data is gathered from the environment and fed into the model to compute traffic-based control decisions. The analytical results of the proposed model shows that bottlenecks during the Hajj season can be efficiently managed resulting in improved travel times, congestion-levels, throughput, and overall enhancement to the transportation capacity under the constraints of Hajj traffic. The model was simulated and validated with key improvements being demonstrated in terms of delay and throughput when compared to other existing approaches.

Traffic flows under evacuation conditions differ from those of normal conditions. Hence, this is important in modeling evacuations since most of the performance of macro-level simulations is based on the relationship of demand to capacity, i.e., flow rate variation [8]. Thus, the Florida Department of Transportation recently recommended the use of Maximum Sustainable Evacuation Traffic Flow Rates (MSETFR) for evacuation traffic simulation modeling in the Florida Keys. This evacuation flow phenomena was further explained by Dixit *et al.* [9].

The research in the area of evacuation for vehicles or crowd during emergency or extraordinary situations is a topic that has been investigated by many researchers, with many models and systems being proposed for different scenarios and case studies. Moreover, congestion as a result of evacuations has attracted attention to develop strategies which could help save lives and reduce evacuation times. Abdelgawad and Abdulhai [10] list contra-flow operations, modified traffic control, route guidance, and staged evacuation as popular strategies. The work of Ayfadopoulou *et al.* [11] proposed a dynamic traffic assignment model based on evacuation planning for the central business district of Thessaloniki in Greece to assess the evacuation process assuming the occurrence of an incident in the area. From the simulation results, it was noted that the evacuees reach their destination faster with no deployment of Variable Message Signs (VMS) or contra-flow operations, as well as observing that overall network performance had degraded when no planning was considered. In addition, evacuees closer to contra-flow lanes had reached their destinations faster than those located in different zones. Finally, this work proposed a further study in order to identify the required spatial and temporal allocations of a measure depending on the area of the incident [11].

In [12], a non-equilibrium vehicle evacuation model at a small area under Planned Special Events (PSE) was set up. The model and its algorithm were applied to the 2008 Olympic football games in the Tianjin sports center, and compared with the data obtained by the Tianjin traffic administration bureau. In the model, the Logit multi-route selection method and dial traffic flow assignment algorithms were applied. The work in [13] presented a new framework for managing congestion during emergency evacuations. The algorithm allows a long link of the network to be used as a buffer to keep the traffic flow moving in. Concurrently, a detour trigger time was estimated to keep the traffic undersaturated in the buffer zone and minimize the total travel time. The integration algorithm provided an efficient mathematical solution for travel time cost calculations. A case study was presented to demonstrate the efficacy of the traffic demand buffering strategy developed in this research for managing the evacuation flow. The work in [14] provided a robust optimization approach for evacuation transportation planning under uncertainty. This model showed the importance of robustness by focusing on the infeasibility cost, in addition it showed that a robust solution had improved both feasibility and quality compared to a nominal solution. Therefore, it is suggested that more realistic demand scenarios with higher probabilities of occurrence should be incorporated into the analysis.

The review of traffic simulation models conducted by Pel et al. provided a direction for the current trends in modeling evacuation travel behavior [15]. Due to the evacuation participation and choices of departure times, the authors had argued in favor of the simultaneous approach to dynamic evacuation demand predication by using the Binary Logit Model. For the destination choices the authors suggested further improvements on current models, while preference was given for the hybrid route choice models for evacuation route choices since they enable both instructed routes and en-route switches [15].

A number of more recent works in the ITS literature were also found that investigate the problem of evacuation control or traffic management in general. Table 1 summarizes some of the more recent and notable works found in the IEEE Intelligent Transportation Systems (ITS) journal as well as their key features, limitations and opportunities for further enhancements.

More recently, a number of mobile crowd sensing (MCS) based approaches have emerged in the literature as a means

TABLE 1. Summary of key features and limitations of related articles in IEEE-ITS.

No.	Research Group/Literature Citation	Application Domain	Key Features/Benefits	Limitations of Work
1	Huang et al. "Design of Traffic Safety Control Systems for Emergency Vehicle Preemption Using Timed Petri Nets" [16]	Traffic Safety Control	Timed Petri nets (TPNs) are used to model pre-emption of emergency vehicle system. This work proposes a new emergency vehicle pre-emption policy, by controlling the phase of traffic light alterations.	The model needs to be extended for further applications. Complex road networks and temporal features needs to be developed based on newer versions of TPNs.
2	S. d. Oh, Y. j. Kim and J. s. Hong, "Urban Traffic Flow Prediction System Using a Multifactor Pattern Recognition Model" [17]	Urban Traffic Flow Prediction	A multifactor pattern recognition model was developed by combining a Gaussian mixture model (GMM) clustering method with Artificial Neural Networks (ANNs) to forecast traffic flow. The model uses ITS detectors as well as geographical and environmental information to provide accurate future predication. It also performs adaptive forecasting for traffic congestion caused by construction or weather.	Does not forecast traffic flow for congestion caused by accidents and buildings.
3	Zhu et al. "Computational Traffic Experiments Based on Artificial Transportation Systems: An Application of ACP Approach" [18]	Modeling and analysing transportation systems.	Two aspects of computational traffic experiments based on artificial transportation systems ATSs, were analyzed; the growing ATSs from bottom up agent-based technologies and modeling environment impacts. The following computational experiments were carried out" constructing activity plans for each individual, generating travel demand based on activity, and modeling the impacts of adverse weather.	The experiments were limited to a specific ATS, i.e., Jinan-ATS. More experiments with different scenarios need to be carried out.
4	Zhen et al."Disaster Relief Facility Network Design in Metropolises" [19]	Disaster Relief Facility Network	The problem is concerned with strategic planning for disaster relief facility network planning in metropolises. The aim is to constitute a humanitarian logistic network for effective response and relief services such as: location of emergency shelters, supply and medical centers.... etc.	The current model does not consider the dynamic changes of population distribution against time. Additionally, the radius of shelters and connecting costs between shelters and supply centers may be deterministic but depended on the spatial patterns of the traffic situations.
5	Lopez-Garcia et al. "A Hybrid Method for Short-Term Traffic Congestion Forecasting Using Genetic Algorithms and Cross Entropy" [20]	Short-Term Traffic Congestion Forecasting	Short time traffic congestion predication is achieved using a proposed hybridization method called GACE: which uses genetic algorithm (GA) and cross-entropy (CE). This is a method of optimizing the elements of a hierarchy of fuzzy-rule-based systems (FRBSs). The hybridization of the two methods proved to be more powerful in congestion predication than when used individually.	More investigation is needed to generalize this method to different problems. The population size may be an obstacle since it varies depending on the problem addressed.
6	Wunderlich et al. "A novel signal-scheduling algorithm with quality-of-service provisioning for an isolated intersection." [21]	Traffic Signal Control (Intersection)	A maximal weight matching algorithm is used to minimize the queue size at each approach in an intersection.	The algorithm becomes unstable if the aggregate traffic flows exceeds a third of the physical capacity of the approach used. The approach needs to use a real ASC/3 control box in order to make decisions about phase changes, which in turn will help to test the system before it can be used physically at an intersection.
7	Papamichail et al. "Balancing of queues or waiting times on metered dual-branch on-ramps" [22]	Balancing of queues or waiting time, Traffic control problems	Implementation of two different cycle times for metered dual-branch on-ramps measures the estimated waiting times at (queues).	More scenarios need to be carried out under different conditions such as weather, … etc., in order to generalize this method to different problems.

TABLE 1. ***(Continued)*** **Summary of key features and limitations of related articles in IEEE-ITS.**

8	Chen et al. "A review of the applications of agent technology in traffic and transportation systems" [23]	A review work on agent-based technology in traffic and transportation systems.	This work provides a review of agent-based technology applications used in traffic and transportation systems. The agent-based applications were divided into 5 categories: traffic control and management system architecture and platform, roadway, transportation, air traffic, railway transportation, and multi-agent traffic modeling and simulation	The review recommends the integration of new technologies in order to enhance the flexibility of systems and the ability to deal with uncertainty in dynamic environments.
9	Kim et al."City Vehicle Routing Problem (City VRP): A Review" [24]	A review of the City Vehicle Routing Problem (VRP)	The objective of the city VPR research focused on how the available research had contributed to the stakeholders (shippers, carriers, residents and administrators) in city logistics. This includes their interests in modeling and problem solving.	The results of the study identified the following challenges: need to place greater emphasis and study on four core characteristics (traffic regulation, noise pollution, fast response, and ITS) of City VRP, development efficient methods, more research that focus on the interests of stakeholders, and the need fornew City VRP benchmark data sets or problems.
10	List et al., "A Modular Colored Stochastic Petri Net for Modeling and Analysis of Signalized Intersections" [25]	Modeling and Analysis of Signalized Traffic Intersections	Colored Stochastic Petri-Nets were used for modeling and controlling an urban network of signalized intersections. The proposed model achieved modularity and reduced complexity. The model was demonstrated using four different signal-control strategies.	Modeling complex interactions or large networks in detail is difficult using petri-nets. The use of petri-nets alone is not self-learning or adaptive and needs to be integrated with optimization algorithms.
11	Kong et al., "UTN-Model-Based Traffic Flow Prediction for Parallel-Transportation Management Systems" [26]	Parallel Transportation Management Systems	A traffic-flow prediction method for signal-controlled urban traffic-networks (UTNs) with signalized junctions was developed based on a macroscopic UTN model. Speed-density models were employed to obtain accurate approximations of vehicle delays.	The prediction model requires several known parameters as input variables, which is difficult to obtain. Therefore, the model needs to be tested on real-world urban-road networks.
12	Wu et al., "Distributed Mutual Exclusion Algorithms for Intersection Traffic Control "[27]	Traffic Intersection Signal-Control	A distributed-computing approach was described based on the classic mutual-exclusion problem. This approach removed the need for optimization and had outperformed a benchmark study based on the adaptive traffic-light based approach. Their approach does not require deployment of any traffic-light facilities or intersection controllers, making it practical for various kinds of intersections.	The approach needs to be extended for reducing message costs, handling networked intersections, handling exceptional actions, and to allow extension of the for Vehicle Mutual Exclusion for Intersections (VMEI) problem to a general version of different applications.
13	Tettamanti et al., "Robust Control for Urban Road Traffic Networks"[28]	Traffic Control Strategies	A traffic-control approach was proposed to minimize the weighed link queue lengths within an urban network area assuming worst-possible cost degradation by demand and queue uncertainties. The proposed algorithm was capable of optimally splitting green-signal times under the influence of traffic-flow ambiguities as well as state and signal constraints.	The centralized traffic control method requires significant work to be adapted for modeling large-scale urban traffic networks, even if parts of the network are to be modeled with uncertainties. Moreover, the work should be extended to provide a decentralized solution for large-scale urban networks.
14	Osogami et al., "Toward simulating entire cities with behavioral models of traffic"[29]	Transportation systems with evacuation/ disaster recovery and resilience	This work provided an analysis of a transportation system under emergency conditions due to hazardous events.	More detailed experiments are required to precisely understand the advantages and disadvantages of the proposed design principle and of those of the model for route selection with the estimated personality.
15	Gangi, "Modeling Evacuation of a Transport System: Application of a Multimodal Mesoscopic Dynamic Traffic Assignment Model"[30]	Transportation systems with vehicles-evacuation during emergencies	This work provided an enhancement to a previous study of a mesoscopic DTA model, and included the addition of multimodal systems modelling. Such models could be eventually used to support and verify the effectiveness of existing evacuation plans without the need for expensive drills.	Further investigations are needed for the travel-time functions under different operating conditions and an evaluation of the adherence to the formulated evacuation plans

TABLE 2. A qualitative comparison between traffic congestion schemes.

No.	Approach	Application Domain	Road Network Coverage	Feasibility and Practical Deployment Considerations
1	Signal-scheduling algorithm with quality-of-service provision [21]	Traffic Signal Control	Low (monitoring and analysis had focused on isolated intersections and generalizations for other intersections).	Less practical approach since it only considers isolated intersections and is only stable for limited traffic flows.
2	Stochastic Petri Nets [25]	Traffic Signal Control	Medium (models road infrastructure as a network)	Complex when modeling large networks.
3	Distributed Mutual Exclusion Algorithms [27]	Traffic Intersection Control	Medium (traffic is controlled by coordination between vehicles).	Further work is required to reduce message costs in dense traffic conditions as well as handling networked intersections.
4	Mobile crowd sensing for Internet of Vehicles [31]	Traffic predication	High (infra structure consists of smartphones and vehicle sensors network-wide)	A promising approach; however, requires further investigation on a number of practical issues.
5	Sparse mobile crowd sensing [34]	Traffic monitoring	High (infrastructure consists of smartphones and vehicle sensors network-wide)	Difficult to implement in real life since many practical issues are yet to be resolved efficiently.
6	Proposed method: Case study on correlated network intersections	Transportation system monitoring and analysis	Medium (monitoring included correlations between network intersections)	This approach was implemented in real life with low cost; however, involves an error probability in data acquisition and use of hardware sensory equipment.

to alleviate the traffic congestion problem and address traffic fluctuation trends. In contrast to costly traditional approaches, MCS approaches employ a dynamic approach to improve the transportation efficiency. Essentially, MCS technologies based on the use of sensory devices, such as participant smartphones and sensor-equipped vehicles used for traffic data-acquisition, with sensed data being forwarded onto a central-server/cloud for analysis before informed traffic-decisions are made and related onto traffic-authorities/drivers.

In [31], Wan *et al.* proposed an MCS approach for traffic prediction in the context of cloud-assisted Internet-of-Vehicles (IoV). The proposed approach presented new algorithms for real-time prediction of travel times to provide dynamic driver route choices for congestion avoidance. However, it was noted in [31] that the work conducted on MCS was pre-mature, with important issues yet to be resolved, including: incentive schemes for user-participation and participant privacy issues. Wan *et al.* [32] provided a brief review of the promising use of Vehicular Cyber-Physical System (VCPS) and Mobile Cloud Computing (MCC) for ITS. They proposed an architecture for Integrating VCPS and MCC.

The authors concluded that the cloud supported VCPS is a promising area of research in the future. On the other hand, another review paper presented by Guo *et al.* [33] stated that the data quality of MCSC is low, suffering from issues such as built in sensor performance and the trustworthiness of user contributed data. The study concluded with the following limitations:

- Sensing object leaves fragmented, incomplete data in three spaces (cyber, physical and social spaces).
- Ethical factors, (inventiveness and user privacy) should be the fundamental building blocks of MCSC.
- MCSC should be designed keeping in mind the multi-disciplinary knowledge required (social science, cognitive science, economics, computing science, and so on).

The work by Wang *et al.* [34] presented the main challenges associated with sparse MCS, and proposed a general framework that addresses some of those research challenges. The proposed scheme considers the spatio-temporal correlations between city segments, and only assigns a small portion of the target area with sensory acquisition tasks, while inferring the data related to the unsensed regions using data-quality and sensing-cost as the main performance metrics of interest. However, the study had also pointed out on a number of research challenges, which remain unsolved and for which the development of required solutions is considered as a nontrivial problem [34]. Some critical research challenges in general MCS traffic applications were identified to include: high sensing costs when good coverage is required, participant incentives, smartphone energy consumption, network bandwidth consumption, smartphone sensor errors, malicious participants and forged sensory data, privacy protection mechanisms and sensing-cost variations between different city locations. Additionally, other research challenges specific to the proposed framework in [34] were identified to include: unavailable participants at assigned locations, missing data inference, optimal task allocation and data-quality assessment.

On a similar note, [35] presented a detailed study of the challenges in real-time MCS for public transportation and provided a comprehensive classification of the key challenges involved. Some of the main challenges had included concerns relating to: device hardware, network coverage, costs incurred, data availability and quality, trust, motivation and usability [35]. The study concluded by emphasizing the need for further investigation in the open research areas before MCS technology can be effectively deployed in real-life public-transport applications. Similarly, other related studies [31], [33], [34] had also raised their concerns about the prematurity of MCS technology when considered for practical applications such as public transportation. Therefore, further investigations are required to study these limitations and their effect in the application of transportation systems. Table 2 provides a qualitative comparison of common and relevant approaches including MCS, considered for traffic congestion.

In general, the literature presents studies on many traffic road network models to address many issues related to traffic research such as noise pollution, air pollution, accidents, traffic predication and management, signage, and surveillance. Clearly, more work investigating emergency/evacuation scenarios under varying conditions is required, in addition to the fact that very few efforts had even considered studying the real-life influences of correlated intersection-nodes on overall traffic-flows. Henceforth, the focus of this work is classified as twofold. First, this paper studies the traffic evacuation scenarios for vehicles in the central area of an urban city under particular evacuation scenarios, and secondly, to investigate how efficient evacuation can be achieved in a road network in which major network intersections/nodes are correlated and exert an influence on adjacent nodes.

III. SYSTEM DESCRIPTION

In order to achieve the objectives of this study, the area enclosed by the first ring road for the central area of Madinah was targeted in order to survey the number of vehicles using the first ring road during the most busy times of the day. The number of vehicles entering and exiting the first ring road from different directions was counted at 40 specific points. The area was divided into four sections, as shown in Fig. 1, in order to effectively manage the data collection statistics used in this work. Figs. 2 – 5 detail the four different areas (Sections A – D) from Fig. 1 with traffic-flows (TFs) shown using arrows. The statistics/data-collection was conducted over four days during peak-season. More details will be presented in the methodology section.

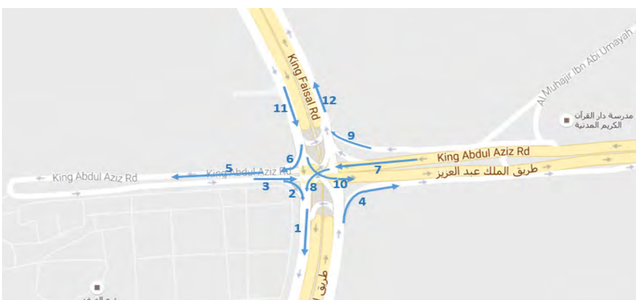

FIGURE 2. Section-A of the RoI.

An objective of this work was to model the flow of vehicles in the central area of Madinah enclosed by the first ring road.

FIGURE 3. Section-B of the RoI.

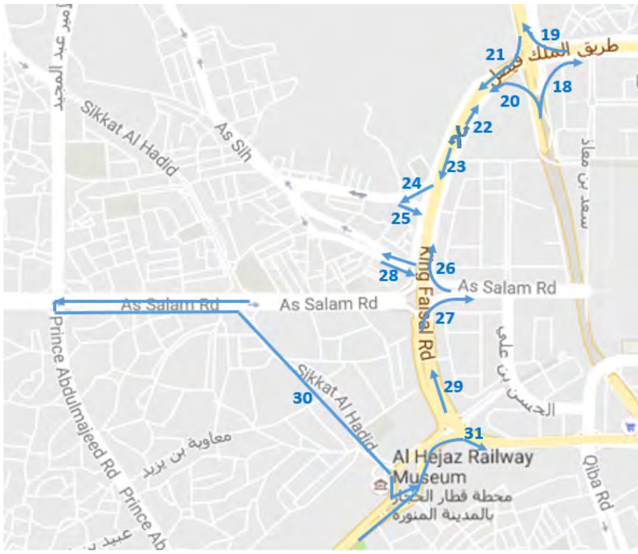

FIGURE 4. Section-C of the RoI.

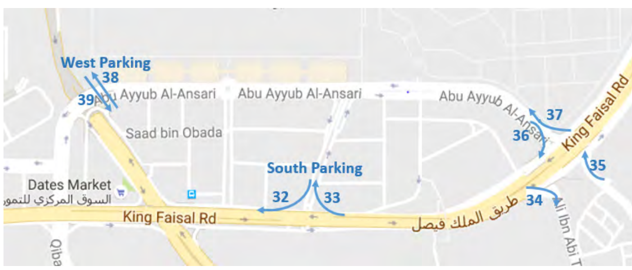

FIGURE 5. Section-D of the RoI.

Thereafter, a mathematical model and discrete-event simulations were employed for analyzing several factors, including: the transportation system using real-life on-site data as input to the model, the present influence of correlations that exist between network-intersections, and finally, two possible evacuation case-study scenarios.

IV. METHODOLOGY

The methodology used in this study comprises of four phases of progress that include: planning and investigation, statistical on-site data-collection, road network modeling and analysis of the affect of intersection-node correlations at various road-segments, and finally, presenting case-study evacuation-scenarios.

Initially, the planning and investigation phase had involved identifying various evacuation scenarios and locations from around the central area as well as those entry and exit-points from the central area. Thereafter, the location of influential traffic-points and roads representing ingress and egress traffic into/from the first ring road were identified and noted as collection-points required for statistical data-gathering. Those traffic-points were typically representative of all the major/minor roads from the main central area moving outward towards the first ring road (since roads would be congested during any emergency case in the central area), as well as the major roads from non-central areas that merge or intersect with the first ring road for all traffic moving towards the central attraction area (this external traffic is necessary for consideration since it affects the movement of traffic to and from the central area).

Next, following identification of the critical traffic monitoring points, a number of students were deployed on-site for the statistical data-collection phase, which had involved a total of 40 students being situated at 40 different traffic monitoring points for manual data-collection. Future work on this theme would ideally utilize automated data-collection hardware, which was not available for deployment at the 40 traffic-points required at the time of this study. Hence, manual data-collection was conducted for a total of 5 days using digital-counters with the data being archived for future use within our model. The recorded data provided an indication of potential significant intersection-correlations and emerging emergency-evacuation scenarios to be addressed, which would consequently require adaptive traffic-management decisions being made by any consequent intelligence software/model developed.

A notable contribution in this study involved the development of a mathematical model to evaluate the road network traffic surrounding the central area, including the ingress/egress points and the affects of correlated intersections that lie along the ring road. For model development, the mathematical model was then employed for analyzing the current transportation system under evacuation scenarios using real-life on-site data gathered from the previous phase as input to the developed model. Furthermore, the model had considered the effect of traffic from other external areas on the central-area traffic as found in the observation of a propagation ripple-effect of traffic arising due to other surrounding roads or traffic arriving from nearby congested areas. The conceptual effect of nearby traffic on other roads was found to have a real influence on particular roads which would be required in the case of an evacuation in the central area. This finding was then used to develop a particularly interesting case-study of an evacuation scenario from the central area to investigate how nearby traffic may cause disruptions of the evacuation-roads and how this may be avoided.

Finally, this study presents a detailed analysis of the results when the real-life data from the data-collection phase is applied as input to our traffic-network model and discusses the case-study that examines real-life evacuation scenarios. The effect of correlations between adjacent intersections was presented. A number of technical observations/recommendations and scope for future enhancements following the analysis of the results follows in the Conclusions section.

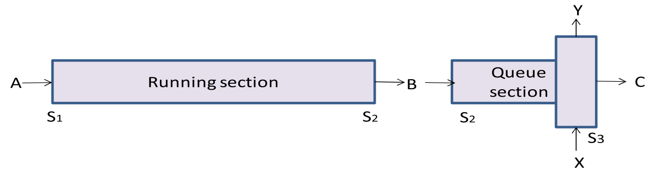

FIGURE 6. Alink in the node/intersection of the traffic network.

V. MATHEMATICAL MODEL DESCRIPTION FOR THE MADINAH CENTRAL ROAD NETWORK

In this section, a macroscopic model is developed for urban traffic-network evaluation. The model consists of a discrete-event dynamic system that describes the relationship between ingoing/ingress and outgoing/egress traffic as well as the influence of adjacent network intersections. First, a link within the network is split into two parts, namely, a running section and a queue section as shown in Fig. 6. It can be observed from Fig. 6, that a traffic-propagation affect exists along the intersections of the ring road since the output 'C' from one intersection follows on to become the input 'A' at another intersection further down the link/road. This propagation-effect must be considered when investigating evacuation of particular segments along the road – e.g. evacuation preparation at a particular segment cannot be treated independently of other parts/intersections along the ring road due to the dependency between those interlinked roads.

Now, the length of the section, average speed of the vehicles, and vehicle density in the running section are denoted by L_r, v_r, and p_r, respectively. The same quantities are represented in the queue section with subscript q. The notations A and $B$are used to imply inflow/ingress and outflow/egress of the vehicles in the running section. B and C denote the inflow and outflow on the queue section. Observe that at the end of queue section, two additional flows, X and Y indicate the flow of the vehicles through the intersection/crossroad. X implies the cumulative vehicles that join inflow C, and Y is the cumulative vehicles that divert from B. We denote the sampling interval time by h (measurements of all inflows and outflows) with the set of sampling time steps $\{0, h, 2h, \ldots, nh\}$. The time steps correspond with the set of iteration steps $\{0, 1, 2, \ldots, n\}$. The total sampling time is $T := nh$. The subscript k with the inflow/outflow implies the associated quantity at the k-th sampling interval (e.g. the k-th iteration step).

The outflow of the vehicles at the next iteration $(k + 1)$ on the running section can be expressed by equation (1):

$$B_{k+1} = B_k + \frac{A_{k+1} - A_k}{h}\left(h - \frac{L_r}{v_r}\right) \tag{1}$$

Note that the term $\left(\frac{L_r}{v_r}\right)$ calculates the average time required for the vehicles to travel from S_1 to S_2. Therefore, vehicles coming from S_1 at $k+1$ and k are linearly interpolated to find the additional number of vehicles for the time period $\left(h - \frac{L_r}{v_r}\right)$. These additional vehicles are added to the current number of outgoing vehicles, B_k.

The outflow of the vehicles at the next iteration $(k+1)$ on the queue section can be expressed by equation (2):

$$C_{k+1} = C_k + \frac{B_{k+1} - B_k}{h}\left(h - \frac{L_q}{v_q}\right) + \mathrm{X}_k - \mathrm{Y}_k \tag{2}$$

Equation (2) requires the current and next iteration of B_k, (B_{k+1}) as computed in (1). Observe that the equation takes into account the inflow X and the outflow Y at the intersection/crossroad. Note that v_r in (1) can be considered as a standard value as it represents the average velocity in free space, i.e., on the running section. v_r was considered as 10m/s. The velocity on the queue section is given by equation (3):

$$v_q = v_r\left[1 - \left(\frac{p_r}{p_q}\right)^a\right]^b \tag{3}$$

Where a, b are two suitable constants. We assumed that $a = 3$ and $b = 2$. $p_q := 1/l$; where l is the average length of the vehicles.

The length of the whole section $L := L_\mathrm{r} + L_\mathrm{q}$ is known from measurement.We calculate that $L_\mathrm{q} := z/p_q = lz$, where z is the number of vehicles in the queue section. Now, z is updated as shown in equation (4):

$$z_{k+1} = z_k + \max\left\{h\left(B_k - C_k - X_k + Y_k\right), 0\right\} \tag{4}$$

VI. DATA ANALYSIS AND SIMULATION RESULTS

The number of vehicles over 5 minute intervals from 3:00pm to 9:00pm was collected at 40 directed locations on the first ring road over 5 days. The most useful data was further considered as those values obtained between 5:30pm to 8:30pm, in order to ensure data consistency (over the 5 days) and reduce the missing values/points using the Regression estimation technique.

Madinah's first ring road is divided into 4 regions in this study, namely; Area-A, Area-B, Area-C and Area-D, in which 40 directed locations were situated on or along the first ring road to measure the intensity of traffic ingress, egress and continuing traffic (e.g. the traffic continuing movement along the ring road itself).

The major intersections on these regions of the ring road are shown in Fig. 7, and comprise of 6-major intersections being modeled. Details of each crossroad and their traffic-flow identifiers are presented in Fig. 8 (a) – (f), with vehicle movement directions illustrated using distinctive numbers. It is noted that the diagrams in Fig. 8 represent traffic-flows for the statistics obtained and not the road network itself.

For the purposes of simulations and in order to provide a more complete analysis, a number of additional traffic-flows (TFs) labeled 41 through to 55 were considered as aggregates of exiting traffic flows (AGTFs) from which manual recordings were taken. Those additional aggregate traffic-flows are defined in Table 3.

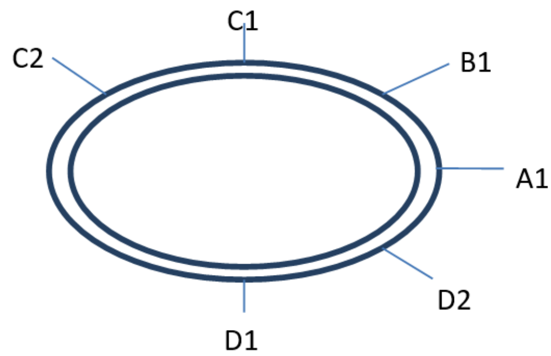

FIGURE 7. Overview of the six crossroads being studied on the first ring road.

A. DATA ANALYSIS AND SIMULATIONS DURING PEAK-SEASON

Figs. 9-14 presents a selection of results pertaining to the data analysis and simulations using the developed model and onsite data obtained, where only a sample of results for crossroads over those days with exceptionally high traffic-flows are presented. In these figures, the number of vehicles passing over the time-axis is plotted. The time index is considered to represent the 36 time-points corresponding to those time points between 5:30pm to 8:30pm at 5 minute intervals. It can be observed that the left-side graph in each figure from Figs. 9-14 displays the number of vehicles which passes along the ring road (Figs. 9(a) - 14(a)), while the right-side graph shows values for traffic intersecting with the ring road (Figs. 9(b) - 14(b)). In these figures, the sample results are plotted sequentially for all six intersections being modeled.

It can be noted from Fig. 9 plotted for Crossroad-A1, that the number of vehicles passing locations Int-44 and Int-45 are much higher than those passing Int-5 and Int-43. Clearly Int-45 is the busiest location. On the other hand, Int-1 and Int-46 are busier than Int-11 and Int-12. Int-11 is the least busy location. The observed trends at Crossroad-A1 (for directed locations) were found to be similar for each of the three days in which results were taken.

For Crossroad-B1, it can be observed from Fig. 10 that Int-16 is the location through which most vehicles pass along the ring road. However, across the ring road, Int-13, Int-14 and Int-55 were less busy, with Int-11 and Int-12 behaving almost similar.

Results from for Crossroad-C1 (Fig. 11) demonstrates that Int-54 is the least busy point along the ring road, with Int-21 becoming the busiest road crossing the ring road. Regarding the Crossroad-C2 for which results are plotted in Fig. 12, it can be seen that Int-24 and Int-40 receives the least number of vehicles along the ring road. The trend in the number of vehicles at other locations was unpredictable as it was found to vary between days.

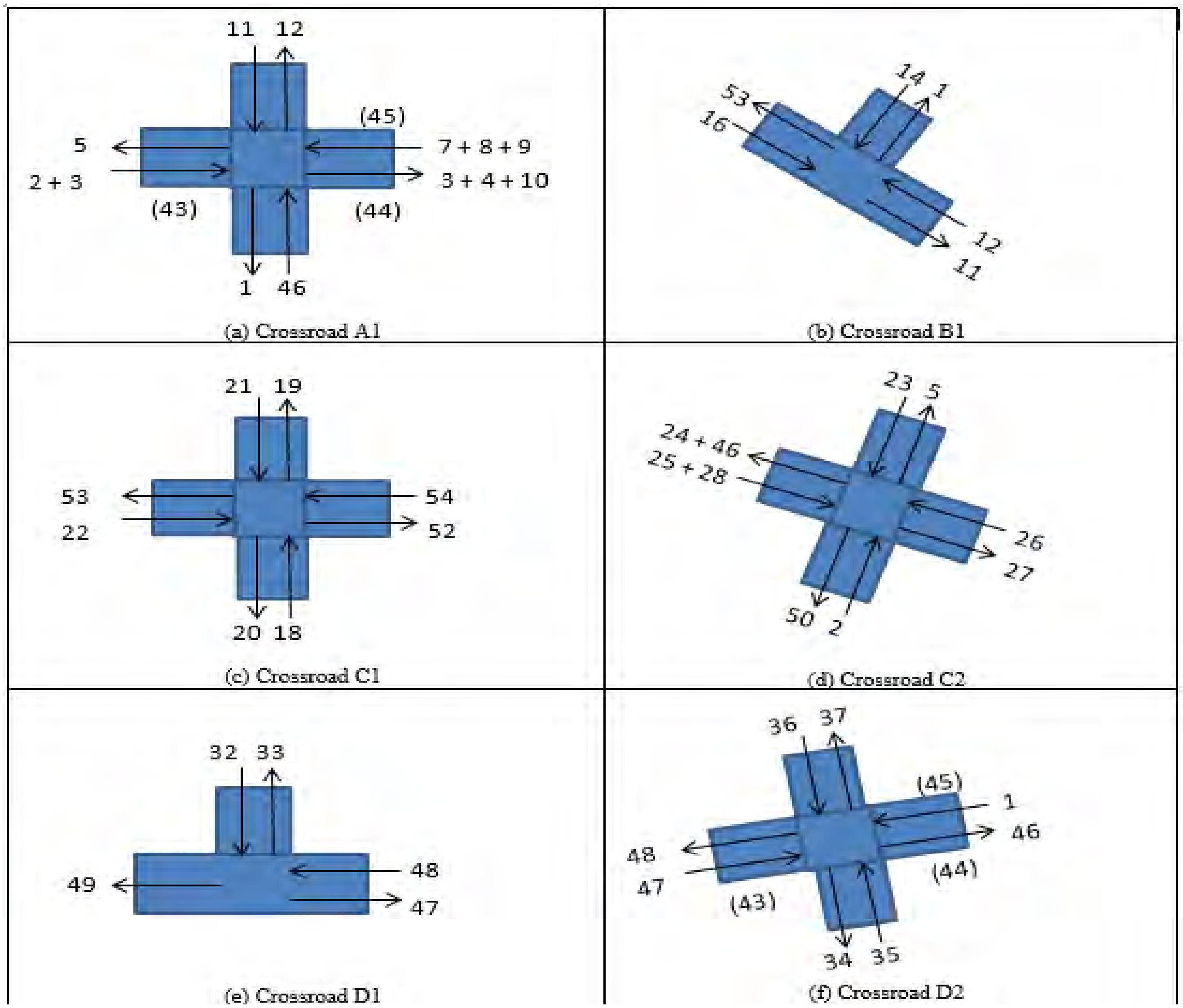

FIGURE 8. Different crossroads at the first ring road and their traffic-flow direction indicators.

TABLE 3. Definitions of aggregate traffic flows derived from known traffic-flows.

Aggregate Traffic Flows (AGTF)	Composite Traffic Flows (TFs)
43	2+3
44	3+4+10
45	7+8+9
46	47-34+35
47	50+30+31
48	1-37+36
49	48-33+32
50	23-24+25-40+28
51	29-27
52	22-20+18
53	54-19+21
54	55+17-E1* (*E1represents an estimate ofthe number of vehicles exiting at King Fahd Rd.)
55	12-13+14

Fig. 13 relating to Crossroad-D1, observed traffic statistics at Int-32 and Int-33 random and variable during the days considered. Traffic volume trends at Int-48 remained between the levels found at Int-47 and 49. Fig. 14 corresponding to Crossroad-D2, observed traffic statistics at Int-35 as variable between the days considered. However, traffic at Int-34 is

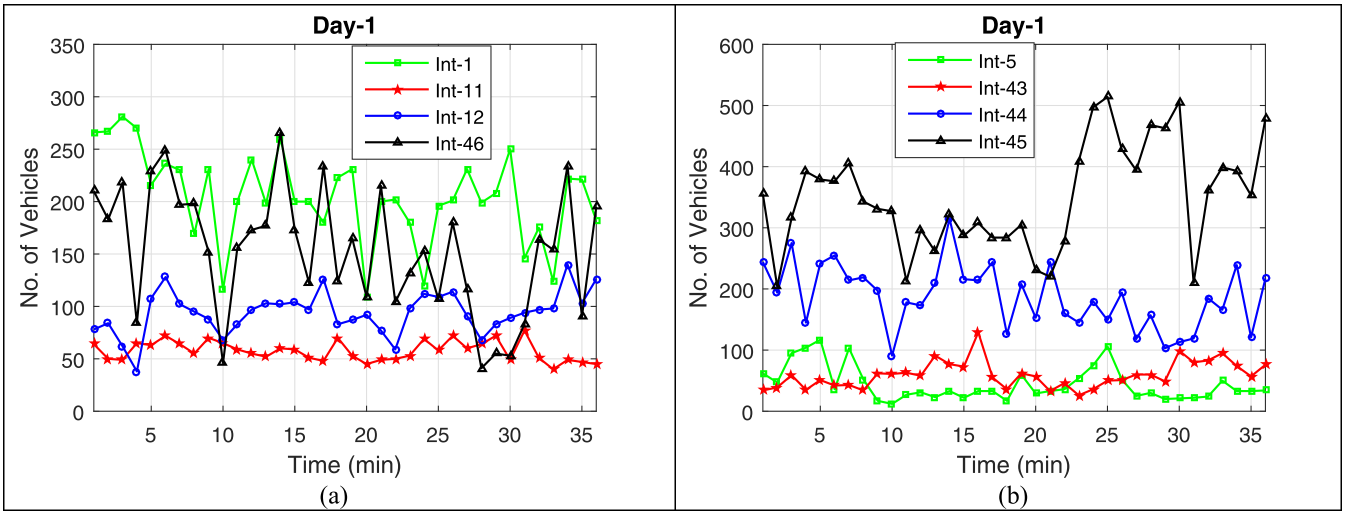

FIGURE 9. Number of vehicles vs time at Crossroad-A1 (sample taken from day 1). (a) Vehicles along the ring road. (b) Vehicles intersecting the ring road.

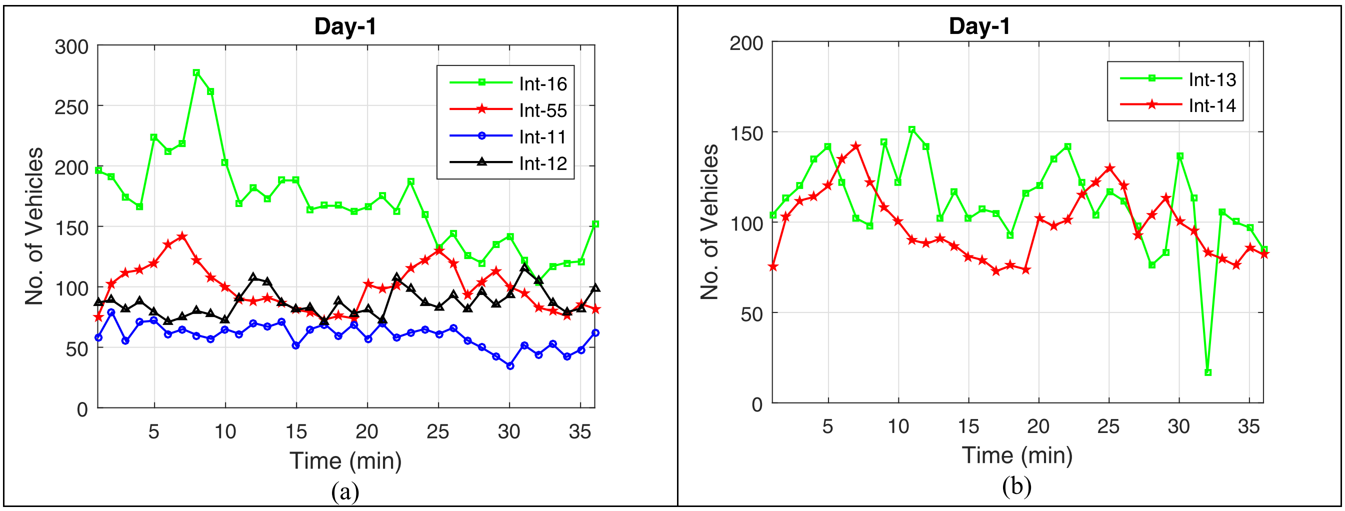

FIGURE 10. Number of vehicles vs time at Crossroad-B1 (sample taken from day 1). (a) Vehicles along the ring road. (b) Vehicles intersecting the ring road.

higher than Int-36 and Int-37, which mostly remains between the range of 0-50. The traffic volume passing at Int-1, Int-46 and Int-48 were found to be unpredictable.

B. ANALYSIS OF CORRELATIONS BETWEEN NETWORK INTERSECTIONS

The following results demonstrate the correlation and consequent influence between the network intersections. Figs. 15-16 shows the simulation results for a period of ten minutes for 6 sections annotated in Fig. 7: A1-B1, B1-C1, C1-C2, C2-D1, D1-D2.

In simulations from Figs. 15-16, the maximum vehicle velocity was considered as 60 km/h, with a random number of vehicles being considered at ingress and egress points. Thereafter, the corresponding number of vehicles flowing at each entrance is computed. With the current density of vehicles, the velocity is estimated, and thus, the travel time of vehicles to reach the end of the section is determined. This information is required to update the number of vehicles at the end of the section in the future time frame. In Figs. 15-16, the time lag between the vehicles at ingress and arriving at the egress are computed. This time lag increases with the length of the section. For example, Section C2-D1 is the longest section, and hence, the time lag is the largest for this section. It is observed that the time lag is not constant for a particular section since the estimated velocity plays a role other than the length of the section itself. Furthermore, the velocity increases with the lower density of the vehicles. In other words, if more vehicles are on the road, then vehicles maintain a slower speed. Consequently, the time lag increases. Once the number of vehicles at egress points is calculated, the estimate is used to calculate the number of vehicles at the start of next section considering the ingress and egress points of the next section at the crossroad. Thereafter,

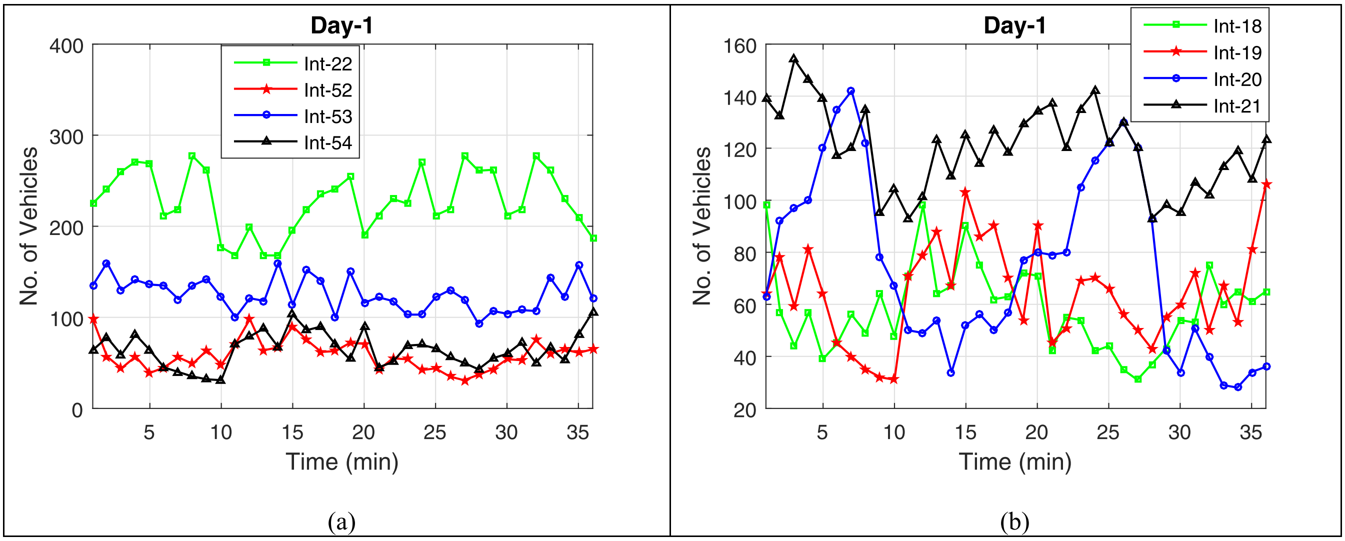

FIGURE 11. Number of vehicles vs time at Crossroad-C1 (sample taken from day 1). (a) Vehicles along the ring road. (b) Vehicles intersecting the ring road.

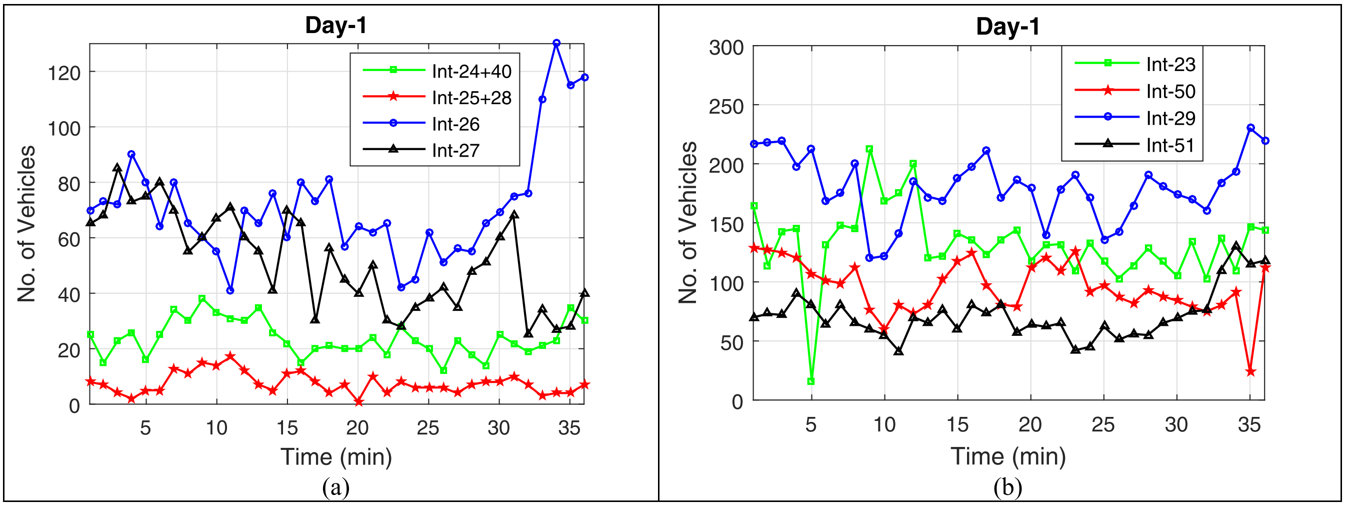

FIGURE 12. Number of vehicles vs time at Crossroad-C2 (sample taken from day 1). (a) Vehicles along the ring road. (b) Vehicles intersecting the ring road.

the simulation for the next section follows in a similar manner. It can be observed that the number of vehicles at the egress point for each section does not match with the number of vehicles at the beginning of the next section. This is explained due to other incoming and outgoing traffic at the crossroad which, of course, are not similar.

VII. CASE STUDIES OF TRAFFIC EVACUATION SCENARIOS

A. CASE STUDY 1 – EVACUATION FROM EASTERN SIDE OF THE CENTRAL DISTRICT

One particularly interesting evacuation scenario to examine could be when traffic has to be evacuated from one/multiple sides of the central area (North, East, South or West sides) at any particular time. This would largely involve traffic emerging from the parking slots as well as other traffic stationed or moving between buildings and within the boundaries of the first ring road. The case where any particular sector should be evacuated can easily be represented on the model diagram as in the example of the evacuation of the Eastern-side (Section-A in Fig. 2), in which the intersections that push traffic onto intersection-A1 (e.g. B1 and D1) would consequently divert their traffic onto other roads away from the evacuation area (using intelligently-controlled traffic signals or road-traffic police) and therefore also moving further traffic away from the most critical-intersection (e.g. intersection-A1) used for evacuating the Eastern sector of the central district. A similar scenario applies for the North, West and South, with some notable limitations in road capacity between the Western and Southern sectors since fewer major intersections are available to serve the huge emergence of evacuated traffic (e.g. only minor roads are available for clearing evacuation traffic from the West and South-West sides of the central parking areas).

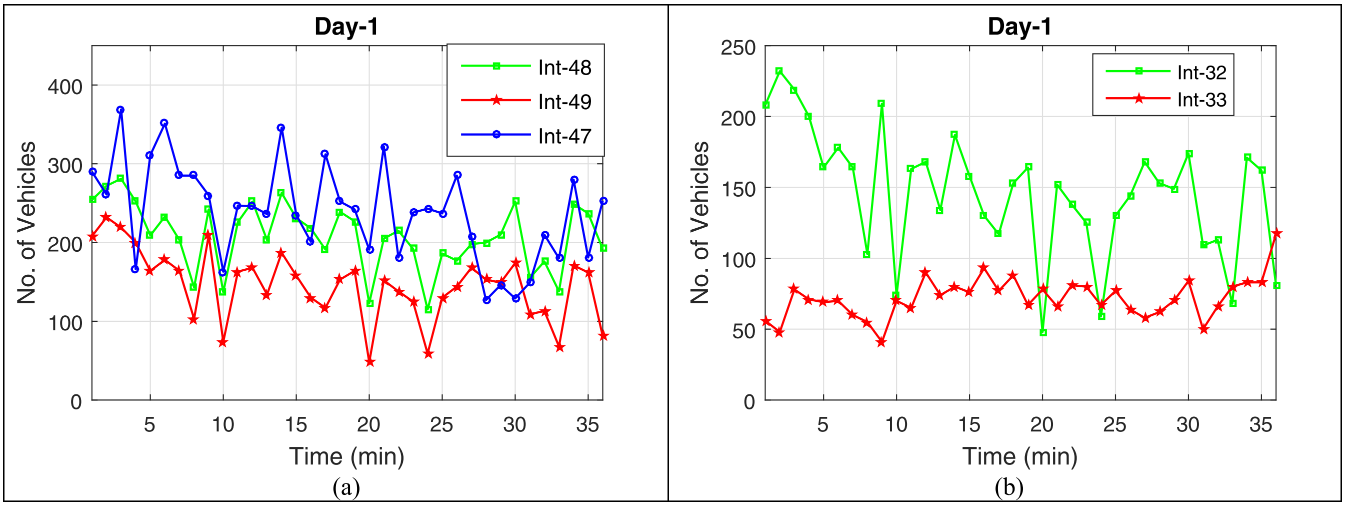

FIGURE 13. Number of vehicles versus time at Crossroad-D1 (sample taken from day 1). (a) Vehicles along the ring road. (b) Vehicles intersecting the ring road.

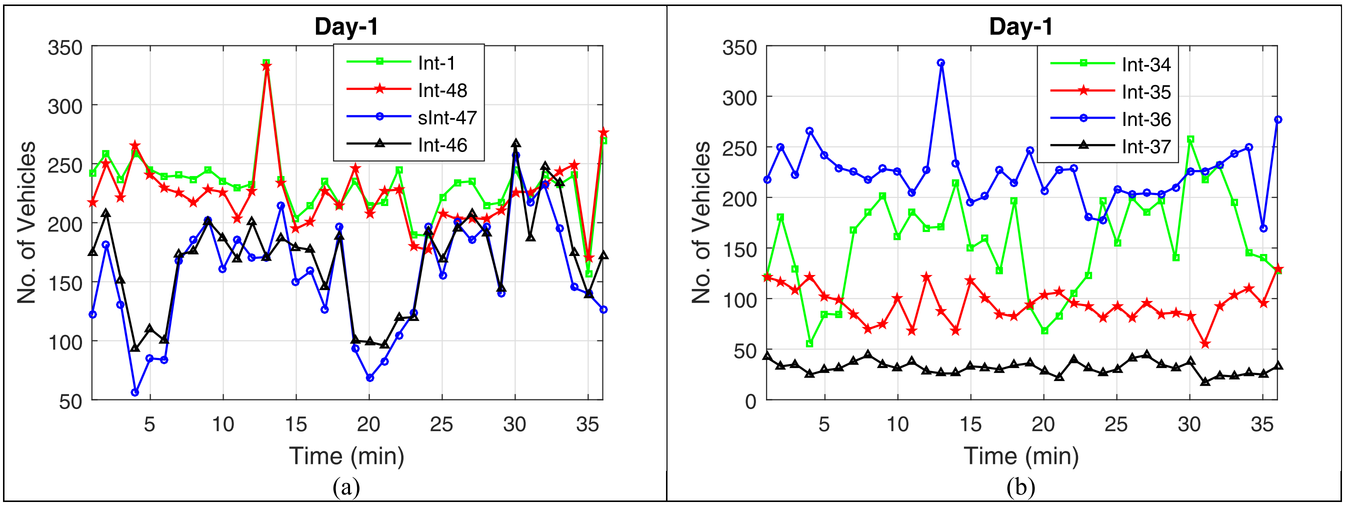

FIGURE 14. Number of vehicles vs time at Crossroad-D2 (sample taken from day 1). (a) Vehicles along the ring road. (b) Vehicles intersecting the ring road.

B. CASE STUDY 2 – EVACUATION FROM FIRST RING ROAD IMMEDIATELY SURROUNDING THE CENTRAL DISTRICT

Traffic evacuation from the first ring road describes another essential scenario for modeling an emergency situation. Traffic evacuation can be performed using the following approach. First, all the vehicles around the ring road that are moving towards the central area should be diverted to outer regions of the central area by traffic signals, signage, traffic police commands or road blocks. Hence, all vehicles along the ring road shall only move out of the ring road through the nearest intersections moving outwards from the central area as shown in Fig. 17.

In Fig. 17, it can be observed that six intersections (A_1, B_1, C_1, C_2, D_1, D_2) are considered through which evacuation will take place for traffic moving outwards from the central area, i.e., the vehicles flowing on the ring road will escape hazards/traffic blockage and further danger by using those intersections to move away from the central area. It can be observed from Fig. 17, that if the outgoing links of the intersections are free, then it takes little time to evacuate traffic on the ring road itself. Next, suppose that all the links between two crossroads are fully occupied with vehicles. Taking into account the longest link which is between D_1 and C_2 (whose length is approximately 600 meters), with the average velocity 10m/s, then we can calculate that the evacuation time is 60 seconds (600/10) i.e., 1 minute. The evacuation time for other links will be less than 1 minute as the distances between any two other consecutive intersections are shorter.

C. DISCUSSION OF RESULTS

The contributions of this paper can be classified as follows. First, the study has introduced the emerging concept of a transportation-system involving correlated-intersections

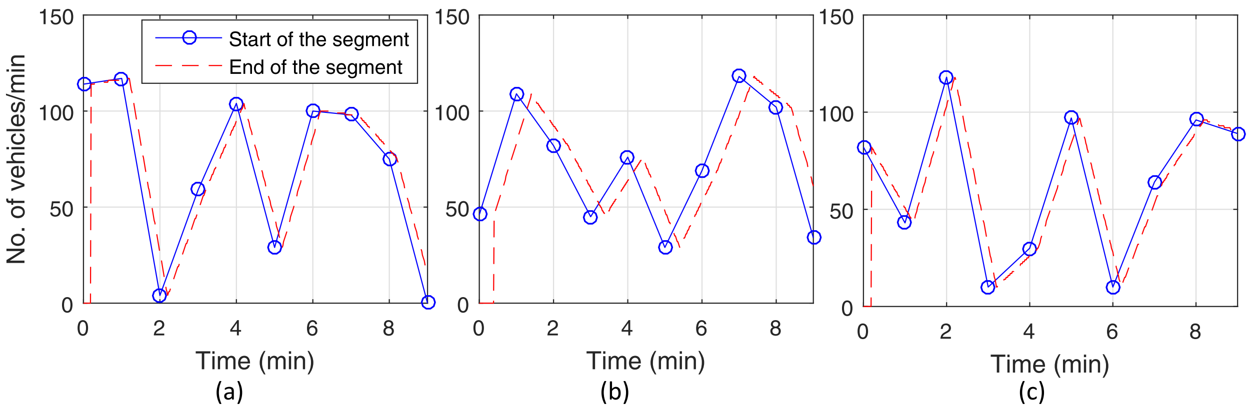

FIGURE 15. Simulation results: number of vehicles flow over simulation time. (a) Section A1-B1. (b) Section B1-C1. (c) Section C1-C2.

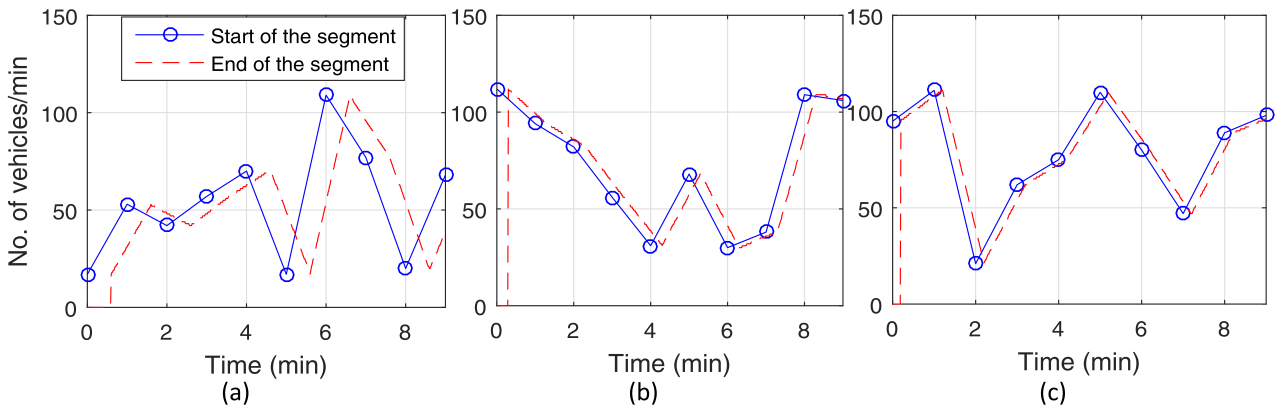

FIGURE 16. Simulation results: number of vehicles flow over simulation time. (a) Section C2-D1. (b) Section D1-D2. (c) Section D2-A1.

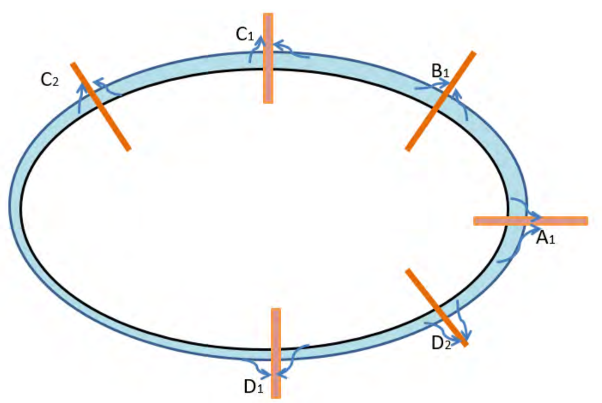

FIGURE 17. Different intersections at different regions of the ring road as evacuation terminals.

between network nodes/intersections in the congested attraction and central area of Madinah, with the capability of analyzing site-evacuation at any segment in the road network. Notably, the major intersections on the first ring road had affected traffic to/from other adjacent intersections on the ring road which meant that during an evacuation other influential/nearby intersections must also be considered and controlled to ensure optimal evacuation can be achieved. Another key objective in this study was to address the requirement of efficient and swift emergency-evacuation for traffic movements before and after peak congestion–times at the central district in Madinah. Third, the study had analyzed the current transportation system through model-development using mathematical modeling techniques with real-life data used as input to the model with an analysis of the influences exerted by adjacently correlated intersections. Next, emergency-evacuation case-studies using chosen segments within surrounding areas of the central area were investigated in order to illustrate how evacuation can be conducted following deployment of the modeled system.

A summary of the recommendations can now be drawn up as a result of this study:

1. The deployment of an ITS for the central Madinah road network area is a primary recommendation; this typically comprises of three main components: onsite data-gathering sensory equipment, data-processing and computation of optimum traffic decisions based on real-time data, and, feeding of such traffic-control decisions

made through to the existing traffic signals or traffic-police for effective and real-time onsite monitoring and control. The recommended transportation system has been demonstrated to provide a highly effective replacement to the current non-optimal open-loop traffic-light system (non-intelligent system) currently being used at some intersections and elsewhere.

2. The interaction between vehicles and pedestrians should be carefully revised. Blocking-objects and other impedances on the roads should also be revised to avoid limiting vehicular-traffic capacity on those roads and to increase safety of pedestrians. This is particularly important during peak-times and emergencies, whereby vehicles must utilize maximum road-capacity to minimize evacuation times. Therefore, all necessary precautions should be taken to ensure that no bottlenecks on the road network are presented by pedestrians or other objects along the road (which result with a limiting-factor on the evacuation-times experienced).
3. Pedestrian crossings along the central/critical roads can be more stringently controlled using clear and enforced stop-and-go signs for pedestrians and vehicles so as to prevent pedestrians moving/flowing across busy central roads in a random, unexpected and uncontrolled manner. This is expected to further reduce queues and delays along such links.
4. A congestion-charge can be applied on the busiest roads of the central Madinah region during the peak periods to deter a large portion of traffic. It is expected that many classes of traffic would consider other roads or means by charging vehicles a known fare in advance (e.g. the presence of taxis and free-riding drivers, or drivers' dropping-of-people would be reduced on such roads). A similar policy is already in-place and made effective for the busiest roads of central London and other European cities since a number of years.
5. More effective use of static and digital signage should be employed in the central Madinah region. Normal (static-signs) can increase awareness under normal circumstances and traffic-levels, while digital-signage could be effective for instructing pedestrians based on circumstances further ahead.
6. The Madinah traffic-authorities should establish/collaborate with a team of experts/academics from the Traffic-Engineering community to continuously monitor and re-evaluate the central Madinah road network conditions, in terms of evaluating efficient road-utilization, capacity, emerging-constraints, re-design recommendations and traffic-forecasting and analysis in-light of those many other related studies and trials of transportation systems already witnessed in Europe, the USA and other selected countries.
7. The local authorities should consider the above findings and recommendations carefully in the new design of the central area and the new central ring road following the decision of the Saudi government to start with a new expansion project in the central and surrounding areas.
8. The use of multi-language SMSs will increase the efficiency of the evacuation, and will decrease confusion and worry of pedestrians and drivers.

VIII. CONCLUSIONS

In conclusion, the dynamics of the central Madinah road network and surrounding environment was shown to present a much-needed solution for optimal traffic movement (e.g. under normal traffic conditions) as well as efficient evacuation-control (e.g. with acceptable delays required at peak-times and high-congestion levels). In this study, a mathematical model of the current transportation-system was presented that had considered the impact of an important but ignored phenomena in the relevant-literature and recent transportation-systems currently deployed; the phenomena here relates to that of the inter-relation and traffic-dependency of vehicles at various points in the ring road or road network (e.g. the traffic propagation-effects that had resulted with correlated adjacent intersections) that had resulted with further traffic delays which cannot normally be predicted in previous transportation-models found. Significantly, the model presented here computes the expected-delays and queue-occupancies at nodes/intersections whilst considering the propagation-effect of traffic further down and along the link (e.g. on the ring road). Hence, a real modeling requirement of the ring road leading in and out of the central Madinah region was addressed here. Once the important modeling requirements were addressed in this study, it is possible to extend/adapt the given model to other related traffic-scenarios being investigated.

Due to the limitations of manual data-collection techniques used and limited human-resources available, this study had only considered a total of 40 points for onsite live data-monitoring. The traffic-data obtained was then statistically analyzed to give a picture of the traffic-behavioral patterns and trends. Thereafter, the data was processed as input into the model in order to derive the expected delay and queue-occupancies for any given traffic-scenario. A simulation for the mathematical model was then developed using Matlab to generate the expected delays and queue-link vehicle occupancies at any required intersection under analysis. The model could therefore be applied to provide a realistic traffic-forecast when investigating different evacuation-scenarios. This study provided a discussion of two particularly interesting case-study evacuation scenarios, which could easily be modeled if sufficient data-collection resources are made available for use. Finally, a detailed sum-up of recommendations had outlined some of the key points for improvements which were observed as a result of this study.

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REFERENCES

[1] (Oct. 2013). *Saudi Central Department of Statistics and Information*. [Online]. Available: http://www.cdsi.gov.sa/english/
[2] *Google*, accessed in Oct. 2016. [Online]. Available: https://maps.google.com
[3] G. Haddow, J. Bullock, and D. P. Coppola, *Introduction to Emergency Management*. London, U.K.: Butterworth, 2013.
[4] M. N. Kabir, Y. M. Alginahi, and A. I. Mohamed, "Modeling and simulation of a proposed traffic flow model: Case study, first ring road in downtown Madinah," *Int. J. Softw. Eng. Comput. Syst. (IJSECS)*, vol. 2, pp. 89–107, Feb. 2016.
[5] H. Abdelgawad, A. Shalaby, B. Abdulhai, and A. Gutub, "Microscopic modeling of large-scale pedestrian-vehicle conflicts in the city of Madinah, Saudi Arabia," *J. Adv. Transp.*, vol. 48, no. 6, pp. 507–525, Oct. 2014.
[6] O. Tayan, "A proposed model for optimizing the flow of pilgrims between holy sites during Hajj using traffic congestion control," *Int. J. Eng. Technol. IJET-IJENS*, vol. 10, no. 2, pp.52–59, Apr. 2010.
[7] O. Tayan, A. M. Al BinAli, and M. N. Kabir, "Analytical and computer modelling of transportation systems for traffic bottleneck resolution: A Hajj case study," *Arabian J. Sci. Eng. (Springer Sci. Bus. Media BV)*, vol. 39, no. 10, pp. 7013–7037, Oct. 2014.
[8] B. Wolshon and B. McArdle, "Temporospatial analysis of Hurricane Katrina regional evacuation traffic patterns," *J. Infrastruct. Syst.*, vol. 15, no. 1, pp. 12–20, 2009.
[9] V. Dixit, T. Montz, and B. Wolshon, "Validation techniques for region-level microscopic mass evacuation traffic simulations," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2229, pp. 66–74, Sep. 2011.
[10] H. Abdelgawad and B. Abdulhai, "Emergency evacuation planning as a network design problem: A critical review," *Transp. Lett.*, vol. 1, no. 1, pp. 41–58, 2009.
[11] G. Ayfadopoulou, I. Stamos, E. Mitsakis, and J. M. S. Grau, "Dynamic traffic assignment based evacuation planning for CBD areas," *Proc.-Soc. Behavioral Sci.*, vol. 48, pp. 1078–1087, Jan. 2012.
[12] T. Cheng, M. Li, Q. Wang, and Z. Ma, "The non-equilibrium vehicle evacuation model of regional traffic under planned special events and its application to the 2008 olympic games," in *Proc. IEEE Int. Conf. Manage. Service Sci. (MASS)*, vol. 9. Sep. 2009, pp. 1–4.
[13] J. Duanmu, M. Chowdhury, K. Taaffe, and C. Jordan, "Buffering in evacuation management for optimal traffic demand distribution," *Transp. Res. E, Logistics Transp. Rev.*, vol. 48, no. 3, pp. 684–700, 2012.
[14] T. Yao, S. R. Mandala, and B. Do Chung, "Evacuation transportation planning under uncertainty: A robust optimization approach," *Netw. Spatial Econ.*, vol. 9, no. 2, pp. 171–189, 2009.
[15] A. J. Pel, M. C. Bliemer, and S. P. Hoogendoorn, "A review on travel behaviour modelling in dynamic traffic simulation models for evacuations," *Transportation*, vol. 39, no. 1, pp. 97–123, 2012.
[16] Y. S. Huang, Y. S. Weng, and M. Zhou, "Design of traffic safety control systems for emergency vehicle preemption using timed petri nets," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 4, pp. 2113–2120, Aug. 2015.
[17] S. D. Oh, Y. J. Kim, and J. S. Hong, "Urban traffic flow prediction system using a multifactor pattern recognition model," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 5, pp. 2744–2755, Oct. 2015.
[18] F. Zhu, D. Wen, and S. Chen, "Computational traffic experiments based on artificial transportation systems: An application of ACP approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 189–198, Mar. 2013.
[19] L. Zhen, K. Wang, and H. C. Liu, "Disaster relief facility network design in metropolises," *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 45, no. 5, pp. 751–761, May 2015.
[20] P. Lopez-Garcia, E. Onieva, E. Osaba, A. D. Masegosa, and A. Perallos, "A hybrid method for short-term traffic congestion forecasting using genetic algorithms and cross entropy," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 2, pp. 557–569, Feb. 2016.
[21] R. Wunderlich, C. Liu, I. Elhanany, and T. UrbanikII, "A novel signal-scheduling algorithm with quality-of-service provisioning for an isolated intersection," *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 3, pp. 536–547, Sep. 2008.
[22] I. Papamichail and M. Papageorgiou, "Balancing of queues or waiting times on metered dual-branch on-ramps," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 2, pp. 438–452, Jun. 2011.
[23] B. Chen and H. H. Cheng, "A review of the applications of agent technology in traffic and transportation systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 2, pp. 485–497, Jun. 2010.
[24] G. Kim, Y. S. Ong, C. K. Heng, P. S. Tan, and N. A. Zhang, "City vehicle routing problem (City VRP): A review," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 4, pp. 1654–1666, Aug. 2015.
[25] G. F. List and M. Mashayekhi, "A modular colored stochastic Petri net for modeling and analysis of signalized intersections," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 3, pp. 701–713, Mar. 2016.
[26] Q. J. Kong, Y. Xu, S. Lin, D. Wen, F. Zhu, and Y. Liu, "UTN-model-based traffic flow prediction for parallel-transportation management systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 3, pp. 1541–1547, Sep. 2013.
[27] W. Wu, J. Zhang, A. Luo, and J. Cao, "Distributed mutual exclusion algorithms for intersection traffic control," *IEEE Trans. Parallel Distrib. Syst.*, vol. 26, no. 1, pp. 1541–1547, Jan. 2015.
[28] T. Tettamanti, T. Luspay, B. Kulcsár, T. Péni, and I. Varga, "Robust control for urban road traffic networks," *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 1, pp. 385–339, Feb. 2014.
[29] T. Osogami, T. Imamichi, H. Mizuta, T. Suzumura, and T. Ide, "Toward simulating entire cities with behavioral models of traffic," *IBM J. Res. Develop.*, vol. 57, no. 5, pp. 6-1–6-10, Sep./Oct. 2013.
[30] M. Di Gangi, "Modeling evacuation of a transport system: Application of a multimodal mesoscopic dynamic traffic assignment model," *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 4, pp. 6-1–6-10, Dec. 2011.
[31] J. Wan, J. Liu, Z. Shao, A. V. Vasilakos, M. Imran, and K. Zhou, "Mobile crowd sensing for traffic prediction in Internet of vehicles," *Sensors*, vol. 16, no. 1, p. 88, Jan. 2016.
[32] J. Wan, D. Zhang, Y. Sun, K. Lin, C. Zou, and H. Cai, "VCMIA: A novel architecture for integrating vehicular cyber-physical systems and mobile cloud computing," *Mobile Netw. Appl.*, vol. 19, no. 2, pp. 153–160, 2014.
[33] B. Guo *et al.*, "Mobile crowd sensing and computing: The review of an emerging human-powered sensing paradigm," *ACM Comput. Surv.*, vol. 48, no. 1, pp. 7-1–7-31, Aug. 2015.
[34] L. Wang, D. Zhang, Y. Wang, C. Chen, X. Han, and A. M'hamed, "Sparse mobile crowdsensing: Challenges and opportunities," *IEEE Commun. Mag.*, vol. 54, no. 7, pp. 161–167, Jul. 2016.
[35] N. Nandan, A. Pursche, and X. Zhe, "Challenges in crowdsourcing real-time information for public transportation," in *Proc. IEEE 15th Int. Conf. Mobile Data Manage.*, vol. 2, Jul. 2014, pp. 67–72.

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