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Microscopic modeling of large-scale pedestrian–vehicle conflicts in the city of Madinah, Saudi Arabia

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SUMMARY

This paper presents a micro-simulation modeling framework for evaluating pedestrian–vehicle conflicts in crowded crossing areas. The framework adopts a simulation approach that models vehicles and pedestrians at the microscopic level while satisfying two sets of constraints: (1) flow constraints and (2) non-collision constraints. Pedestrians move across two-directional cells as opposed to one-dimensional lanes as in the case of vehicles; therefore, extra caution is considered when modeling the shared space between vehicles and pedestrians. The framework is used to assess large-scale pedestrian–vehicle conflicts in a highly congested ring road in the City of Madinah that carries 20 000 vehicles/hour and crossed by 140 000 pedestrians/hour after a major congregational prayer. 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). The model is then used to evaluate the following three mitigating strategies: (1) pedestrian-only phase; (2) grade separation; and (3) pedestrian mall. A matrix of operational measures of effectiveness for network-wide performance (e.g., average travel time, average speed) and for pedestrian-specific performance (e.g., mean speed, mean density, mean delay, mean moving time) is used to assess the effectiveness of the proposed strategies.

KEY WORDS: pedestrian–vehicle conflicts; crowd management; pedestrian micro-simulation; strategies for pedestrian crossings

1. INTRODUCTION

In public places and events that attract large crowds, such as sport events and religious gatherings, conflicts between pedestrian and vehicular movements are inevitable, leading to delays and unsafe conditions and, in extreme cases, chaos and panic. This is of major concern to those responsible for the planning and operation of large public places and major events. Our objective therefore is to model the space shared by vehicular traffic and pedestrian movements during these crowded events in order to provide an analytical base for investigating the operational and safety issues resulting from conflicts between pedestrians and vehicles. Fundamentally, modeling and analysis are the *sine qua non* for the effective planning and operation of the facilities where such conflicts may occur. Modeling pedestrian movements has been extensively investigated in the literature. Two major streams are found: (1) empirical approach, which primarily relies on static models to capture the behavior of pedestrian movements through magnetic

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force, social force, and cellular automata (CA) models; and (2) simulation approach, which endeavors to capture the interaction behavior of pedestrians considering the heterogeneity associated with pedestrian flow.

Okazaki adopted the concept of magnetic force to emulate how pedestrians avoid obstacles while moving in urban areas [1]. Following Okazaki, Gipps and Marksjo [2] introduced the basis for pedestrians' CA models. Helbing and Molnar built a social force model that considers kinetic theory of traffic flow [3], which provided an extensive body of contributions in pedestrian modeling. Models developed by Blue and Adler [4] produced acceptable fundamental flow patterns for unidirectional and bi-directional pedestrian flows. Dijkstra *et al.* [5] then developed a multi-agent CA system to model the movement of pedestrians in two-dimensional space. Abdelghany *et al.* used a micro-simulation CA platform to evaluate the performance of large-scale crowded pedestrian facilities during emergency evacuation [6]. Their framework was used to capture exit gate choice, path choice, frequency of updating path, and the evacuees' tolerance to congestion. Blue and Adler introduced a CA technique to represent pedestrian movements [7]. Still simulated the crowd as an emergent phenomenon using simulated annealing and mobile CA [8]. Fang and Wang conducted a study on pedestrian–vehicle collisions using vehicle–pedestrian conflict and crash models for pedestrians crossing one lane of traffic [9]. Ishaque and Noland [10] have recently investigated the simulation of pedestrian movements and interaction with vehicles. Ishaque and Noland [11] primarily focused on studying how travel/walk time of vehicles/pedestrian vary with the introduction of new traffic signals policies. They also estimated the exposure of pedestrian to vehicle emissions in a shared urban environment.

Although the aforementioned models contributed significantly to the state-of-the-art of pedestrian micro-simulation modeling, the applicability and complexity of these models vary greatly with respect to the model size and its geometry complexity. These methods are not readily amendable to modeling the urban street environment including the conflict between pedestrians and vehicles in a limited shared space while capturing their dynamic interaction/friction, especially in highly congested urban areas.

Achieving a realistic representation of the conflicts between pedestrians and vehicles during special events and large crowds accentuates the need for a modeling framework that captures adequately the interaction between pedestrians and vehicles. Although regional planning models are widely utilized for transport network analysis, they are generally inadequate if operational details are of interest. Microscopic modeling offers abundant opportunities to achieve this goal by capturing the dynamic and stochastic behavior of individual vehicle and pedestrian movements within a system of transportation facilities. While microscopic modeling of vehicular traffic is essential to evaluate the performance of the roadway network, modeling pedestrian movements has become an indispensable matter when considering urban space design. Because of the different physical and operational characteristics of vehicular and pedestrian movements, it has become essential to consider modeling approaches that can handle and evaluate both movements in tandem. Urban analysis framework (UAF), an integrated framework for urban analysis within the Paramics environment [12], offers many opportunities to model the pedestrian–vehicle interaction in highly dense urban settings.

The simultaneous modeling of pedestrians and vehicles at the microscopic level requires a comprehensive set of data especially when it comes to real-world transportation problems in congested areas, the subject of our study. Extreme conditions in large-scale events and pedestrian crowds might further complicate the matter, putting more pressure on the data collection and model calibration efforts. To mitigate this issue, special effort is devoted to provide the model with a set of comprehensive data sources to calibrate the micro-simulation model such that it reflects a range of situations that might be encountered under real-world conditions. This framework is applied to evaluate the performance of the First Ring Road (RR) in the Central Area in Madinah, Saudi Arabia. The case study is concerned with modeling the conflict behavior between pedestrians and vehicles right after the Friday Prayer where 140 000 worshipers exit the Prophets' mosque and cross the RR at 13 locations while conflicting with 20 000 vehicles traveling in the RR. The framework presented in this paper provides the tools to quantitatively assess the operational performance of the urban traffic network for "what if" scenarios including the base case model and three proposed mitigation strategies. The current framework however does not produce safety-specific surrogate measures. Safety surrogate measures can be estimated through the interaction of microscopic simulation models and Surrogate Safety Assessment Models [13] as recently investigated by Ariza A. [14]. However, this elaborative research effort considers only the interaction between vehicles

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without any pedestrian component. Such models could be extended to include pedestrian–vehicle interaction to capture safety-specific measures, which is still on-going research.

2. MICROSCOPIC MODELING FRAMEWORK

2.1. Overall modeling framework

The overall modeling framework, shown in Figure 1, consists of two phases. In Phase 1, the traffic model was developed and calibrated to reflect existing traffic conditions. An origin–destination (OD) estimation procedure was then designed to estimate the vehicular demand. In Phase 2, the interaction between pedestrians and traffic was configured and coded at a great level of detail using UAF. Following the integration of traffic and pedestrians in detail, extra calibration effort was exercised to resolve issues that arose in the model development. Finally, multiple model runs were undertaken to provide simulation results and compute a matrix of measures of effectiveness (MOEs). More details on the methodology and implementation of the framework are presented next.

2.2. Input requirements

Microscopic modeling requires a comprehensive set of data for the development and the calibration stages. Digital representation of the transportation network, number of lanes, roadway and intersection geometry, speed limits, unsignalized intersections, signalized intersections, turning restrictions, turning movements, pedestrian characteristics, and pedestrian behavior at crossings are few examples of data that were acquired to properly model the traffic operations in the area subject to study.

2.3. Phase 1: Traffic model development

The development of a micro-simulation model includes several steps, namely the determination of modeling scope, collection of input data, coding of the network, calibration, and validation of the simulation model. The model of this study was developed using Paramics© and UAF© [12], a suite of high performance software tools for the microscopic simulation of realistic traffic and pedestrians

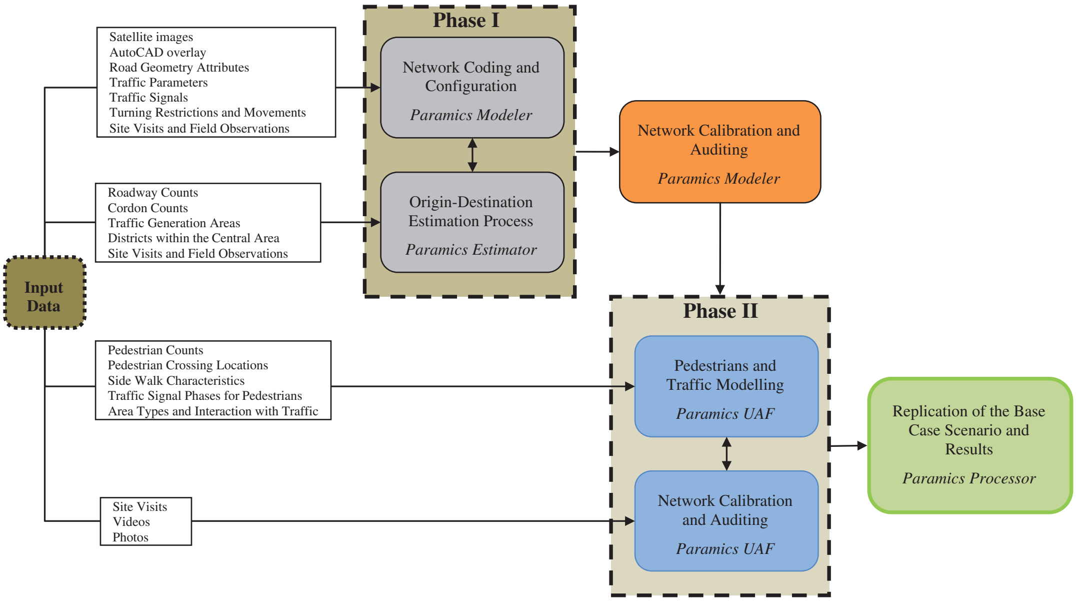

Figure 1. Overall modeling framework.

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networks. Each vehicle in the simulation is moved through the network of transportation facilities on a split-second basis according to the physical characteristics of the vehicle (length, maximum acceleration rate, etc.), the fundamental rules of motion (e.g., acceleration times time equals velocity, velocity times time equals distance), and rules of driver behavior (car following rules, lane changing rules, route choice rules, etc.).

2.3.1. Estimation of traffic demand. In order to employ any traffic simulation model, an OD matrix that describes the trip patterns is required. In very general terms, OD estimation is a collection of methods that estimate an OD matrix from a set of traffic counts and (optionally) a historical OD matrix. Although simple and straightforward to define, it is a complex and computationally very demanding multivariable optimization problem.

The problem can be stated as follows:

> Find an OD Matrix that **minimizes** the "**distance/error**" of **trip values** in the **generated matrix** from the corresponding values in the **historical matrix**, while simultaneously **minimizing** the "**distance/error**" of the **simulated traffic counts** in the model from the observed counts in real life.

In order to properly estimate an OD matrix, the following elements are integrated in one platform:

(1) Input data (road and cordon counts, an optional historical OD matrix).
(2) Model of the environment (traffic network representation).
(3) Optimization logic (minimum distance between modeled and observed counts).
(4) Method of traffic assignment (dynamic stochastic traffic assignment).
(5) Convergence criterion (e.g., no. of iterations).

2.4. Phase 2: Pedestrian model development and integration with traffic model

Pedestrian modeling typically requires more details compared with traffic modeling because of the fact that pedestrians move across two-dimensional cells as opposed to one-dimensional lanes as in the case of vehicles. Each cell in the urban space should be modeled for pedestrians to navigate through the network. Each *agent* (i) has a unique position (x_i,y_i) inside a predefined *region R* within the entire simulation environment. This *region* can be a generation region or simply a predefined area for pedestrian movement. Each *agent* navigates through the network on a set of paths (P_i) while satisfying two sets of constraints: (1) flow constrains and (2) non-collision constraints. The flow constraint assures the flow of agents according to a pedestrian speed distribution and the allowed space for agents to use. The non-collision constraint assures that agents cannot occupy each other's position at the same time. It is assumed that *agents* are rational decision makers in that they will choose the set of paths that would maximize their utility (U_i). U_i is a function of path length, path total time, and effort while navigating through the network. It is noteworthy that this utility is dynamically changing within the course of simulation allowing for capturing the effect of congestion in crowded networks.

The following sections highlight the main elements of modeling agents using the UAF environment.

2.4.1. Regions

At each intersection or crosswalk, pedestrians pass through specific regions that can take on the following forms: demand, waypoints, and data collection. Demand regions are the generating points for agents to be released onto the network with a customizable temporal profile. Waypoints are pin points to help the agent decide its path depending on the surrounding conditions of obstacles, conflicts, comfort, congestion, and so on. Data collection is a region defined to collect and assess performance measures of specific interest. Finally, demand and waypoints are linked using connectors that are directional paths between regions to control the agents' routes.

2.4.2. Space type and compliance

Space type specifies the level of interaction between agents and vehicles. Three main space types can be defined: agent only, shared space, and vehicle aware. In agent only, agents can move freely such as

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designated sidewalks. In shared space, on the other hand, a potential conflict might occur between vehicles and pedestrians such as traffic signal crossings and the unsignalized cross walks at mid-blocks (where jaywalking is common). Therefore, certain level of aggression/courtesy should be defined in such space type. Finally, In vehicle aware spaces, vehicles and pedestrians are aware of each other's presence, speed, direction, and so on.

To properly model the compliance of agents while interacting with vehicles and road crossings, a blocking functionality is used to block agents from interacting with vehicular traffic in some instances. The compliance level specifies how many agents ignore the state of blocking, which is of great benefit to model pedestrians disobedient to traffic regulation and to assess various enforcement options, such as physical barrier, tunnel, and overpass. The main features/elements utilized while configuring the urban space of pedestrians are illustrated in Figure 2.

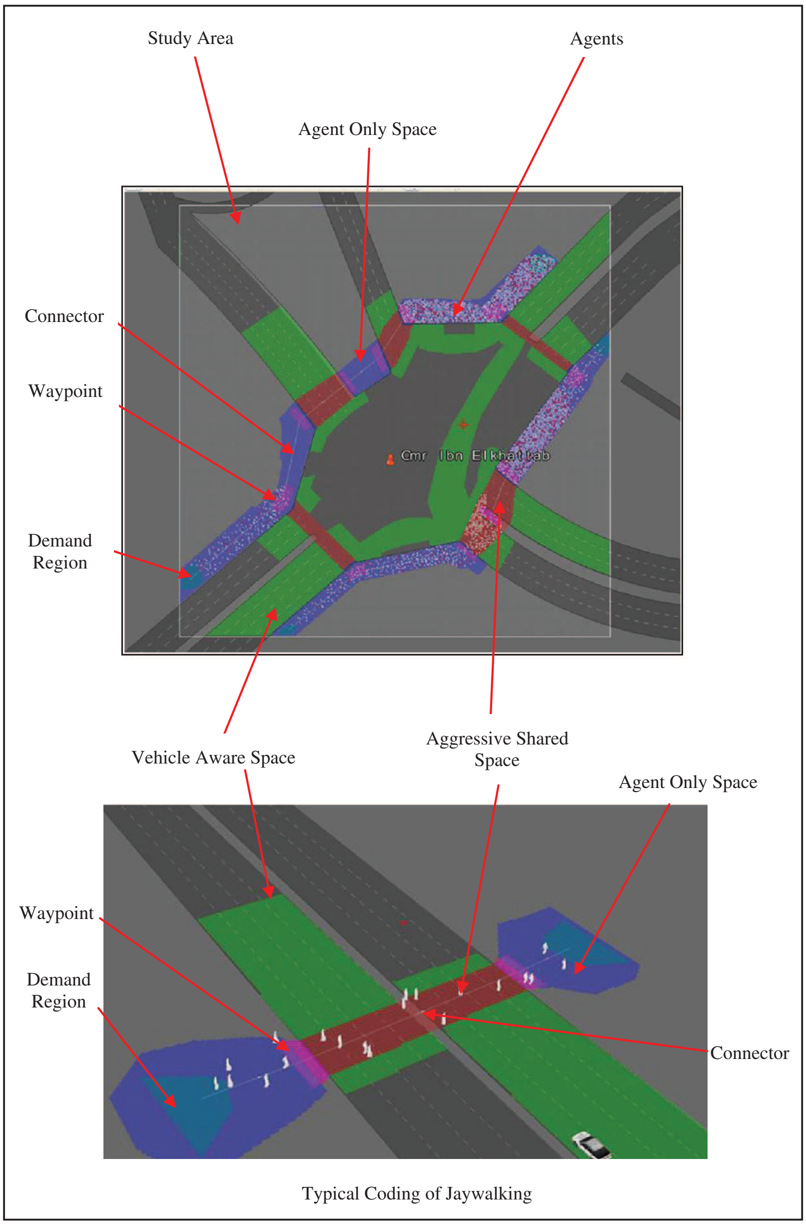

Figure 2. Agent network structure.

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3. MODEL APPLICATION

3.1. Background and study area

This framework is applied to evaluate the performance of the First RR in the Central Area in Madinah, Saudi Arabia (Figure 3). Madinah holds a distinguished place in the hearts of Muslims as it is the second holy city for Muslims to visit and is the burial place of Prophet Mohamed (PBUH). Madinah hosts Al-Masjid Al-Nabawai (the Prophet's Mosque), which attracts nearly 1.5 M visitors during the Hajj season

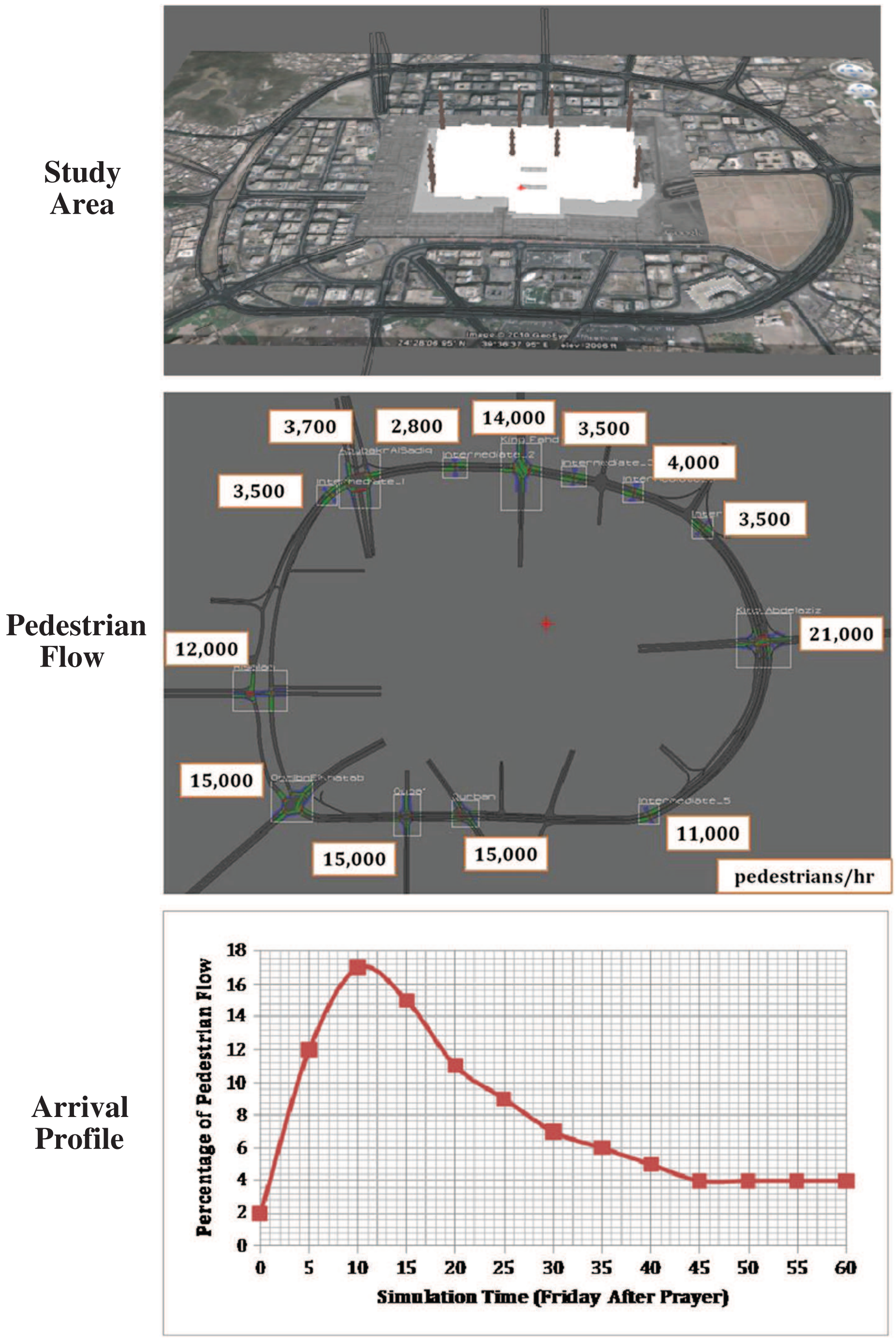

Figure 3. Study area, hourly pedestrian flow, and pedestrian arrival profile.

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and about 3 M visitors during the month of Ramadan, in addition to the city residents that are estimated at 1 M according to the 2006 Census. With the number of pilgrims and visitors to Madinah expected to double over the next 50 years, the Central Area and its existing infrastructure cannot cope with such surge in the number of inhabitants and visitors. This growth pattern will intensify the pressure on the existing transportation system in Madinah. The RR has seven signalized intersections and one pedestrian control light and few unsignalized crosswalks where jaywalking is common. These locations are either marked pedestrian crossing areas (but generally ignored by drivers) or completely jaywalking locations through which pedestrians destine to the prophet's mosque entrances. The municipalities in Madinah were aware of these locations and therefore conducted pedestrian counts at these locations as shown in Figure 3. This behavior was proactively modeled as observed and according to the observed counts. Jaywalking is coded by defining the following spaces: vehicle aware space, shared space, and agent-only space with the addition of a compliance area to prevent vehicles from blocking the pedestrian flow. A snapshot of jaywalking crossing is shown in Figure 2. The RR perimeter is around 5.32 km and covers an area of 1.9-km width (EW) × 1.3-km length (NS). The average distance between adjacent intersections is 760 m. In peak periods, specifically after Friday congregational prayer, the number of pedestrians crossing the RR can exceed 25 000 pedestrians/hour at some locations.

3.2. Supply modeling

3.2.1. Traffic signals

Currently, there are eight traffic signals operating and maintained by the Traffic Authority of the Police and Safety Department. Traffic signals are mostly pre-timed (except for some changes during peak prayer times) and not coordinated to reflect any green wave between adjacent intersections. Police personnel may adjust the timing on the basis of field observations and not on any rigorous optimization methodologies.

3.2.2. Network coding and configuration

The development of a micro-simulation network can be summarized into the following list of general tasks although details vary on the basis of the micro-simulation software and the quality of the provided data:

(1) Overlay a map that is used as a reference for network coding to match reality.
(2) Define roadway types/categories, which have common characteristics such as number of lanes, design speed, and lane width.
(3) Define vehicle composition and its characteristics such as vehicle length, width, acceleration/deceleration rates, and maximum or desired speeds.
(4) Define pedestrian physical characteristics such as height, width, breadth, speed distribution, and compliance rate.
(5) Build up the network by coding intersections (nodes) as well as roadway segments. Refine the intersection geometry to ensure realistic vehicle turns.
(6) Define the traffic signal control logic for all signalized intersections, including information such as signal type and signal phasing.
(7) Define zones and vehicle generation areas such as parking garages and define the appropriate segments for releasing and attracting demand from these zones.
(8) Input the dynamic (time-dependent) OD matrices. Each OD matrix is specific to a period (10 minutes in this study) and vehicle type, and a profile is defined to further control vehicle release within a period.
(9) Define places that generate pedestrian demand and model the agents by defining a set of guidelines for their movement such as release rate, the walking environment and space, the friction with traffic, and the interaction with traffic signals.

3.3. Demand modeling

Four site visits were conducted to collect the required data for the model development. The acquired data include satellite images, road geometry attributes, traffic signal timings, turning restrictions and

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movements, roadway counts, cordon counts, and traffic generation areas. In Madinah, the travel pattern is unique, varying considerably on an hourly, daily, and monthly basis. Therefore, a thorough assessment for the study period was conducted. The 1 hour following Friday Noon Prayer was considered the base case for this study. This decision was based on the desire to have a consistent set of pedestrian and vehicular data and to reflect the worst case scenario of a typical Friday day crossings.

3.3.1. Vehicular demand

According to the collected traffic counts along the RR sections as well as the radial roads leading to the Central Area, the evening period was found the peak period on a typical day [15]. Additional traffic counts were collected during the month of Ramadan, the Friday prayer, and the season of Hajj at selected intersections to estimate the traffic volumes during these peak periods. Expansion factors were then extracted on the basis of the field survey data to reflect the 2010 conditions. Then, an extensive iterative process was undertaken using *Paramics Estimator* [16] to estimate the seeded OD matrix. This iterative process can be best described by the flow chart illustrated in Figure 4. It is noteworthy that traffic patterns within Paramics are updated according to a dynamic feedback mechanism, which captures the change in route choice with the variation in trip travel times.

3.3.2. Origin–destination estimation results

GEH is a statistical formula that measures the percent error with respect to the mean value of the observed (Y_{obs}) and simulated counts (Y_{sim}) for individual link (i) at peak period T as shown in Equation (1).

$$GEH = \sqrt{\frac{2(Y_{\text{obs}}(i, peak_T) - Y_{\text{sim}}(i, peak\_T))^2}{Y_{\text{obs}}(i, peak_T) + Y_{\text{sim}}(i, peak\_T)}} \tag{1}$$

The estimated roadway counts resulting from the final OD estimation method exhibit close correspondence to the observed counts with an average GEH of 4% and 10% absolute difference (Table I). The output of the OD estimation process resulted in almost 20 000 vehicles fed into the simulation model. It is noteworthy that the vehicular flow is found to be considerably high right after the Friday prayer given the mandatory congregation prayer. The following factors could attribute to such high traffic volume:

- The study area (2 km × 1.3 km) is relatively small, and therefore, intra-trips can be generated in a few minutes and access the RR.
- Significant parking violations are observed on the periphery of the RR during the prayer time; most of those parking violators typically rush after the prayer to start moving their cars.
- Right after the prayer, significant shopping activities are taking place. Also, tourism groups tend to quickly mobilize to visit other surrounding holy places.
- Considerable instantaneous traffic volume is generated from the Mosque’s underground parking right after the prayer.

The RR simulation model characteristics are presented in Table II.

3.3.3. Pedestrian demand

Field counts were conducted over two 15-minute intervals to estimate the hourly pedestrian flow crossing the RR at selected locations as shown in Figure 3 [17]. However, it is to be noted that these counts do not necessarily represent all pedestrians crossing the RR. Therefore, pedestrian counts at other locations where jaywalking is common are approximated on the basis of observation and similarity to the existing counts.

The temporal profile of pedestrians is unique because of the sudden flow of worshipers right after the prayer. It is found that pedestrian flow can be approximated as follows: (1) sudden peak in pedestrian flows within 10 minutes of completion of the Noon prayer; (2) a fairly stable peak flow

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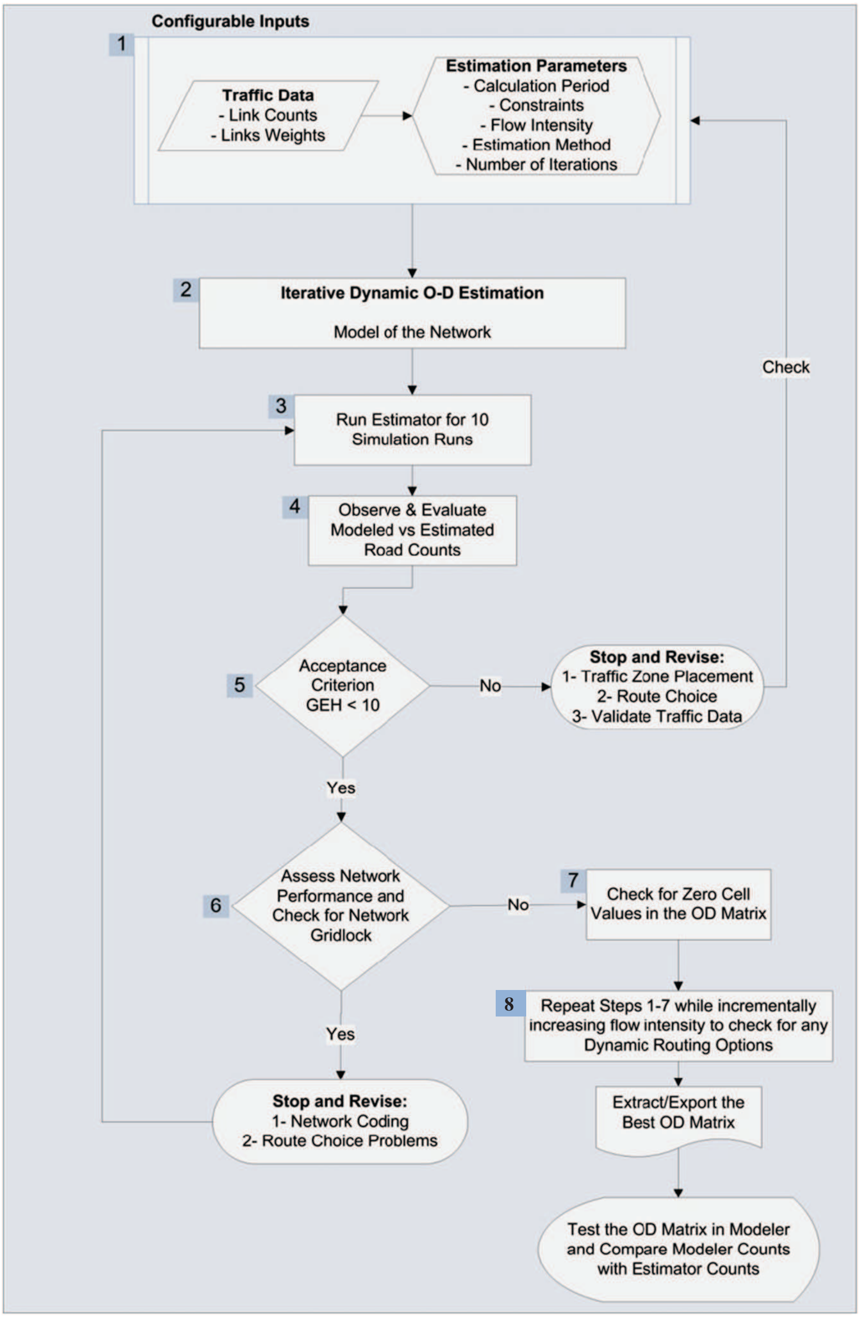

Figure 4. Iterative dynamic OD estimation using paramics estimator.

for a 15-minute period; and (3) a gradual decrease in demand to approximately 75% of the peak demand for the third and fourth 15-minute count period (Figure 3).

3.3.4. Operation with traffic signals

Because vehicular traffic signals allow movements in all direction (right turn, through, left turn, U turn), it is expected that this type of operation will cause serious conflict between pedestrian and right-turn and left-turn movements. This conflict was found more vivid in case of high turning movements and high pedestrian flows. A snapshot at Omr Ibn Elkhatab intersection is depicted in Table I to illustrate how the model captures such conflict behavior.

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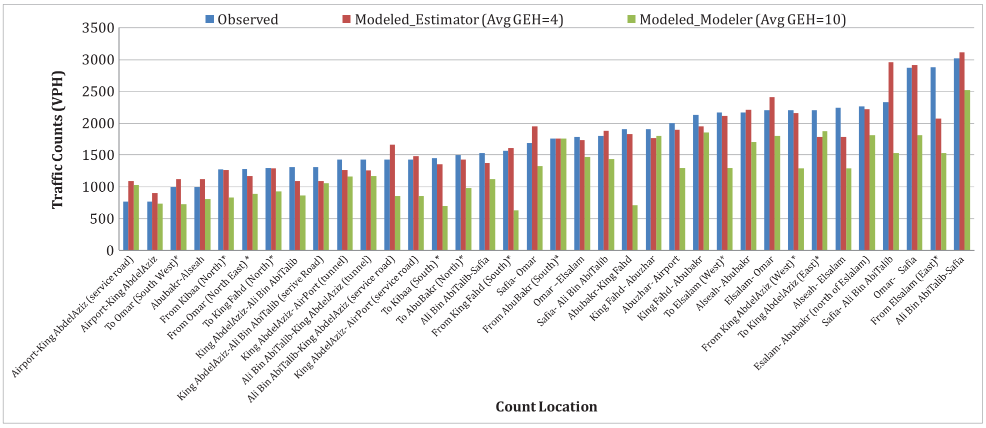
Table I. Modeling calibration process and results.

Parameter category	Parameter	Description	Default values and acceptable range*	Calibrated values
Core Paramics parameters	Headway (seconds)	The global mean target headway between a vehicle and a following vehicle.	0.6–2.2 (default = 1.0)	1
	Reaction time (seconds)	The lag in time between a change in speed of the preceding vehicle and the following vehicle reaction to that change.	0.3–1.9 (default = 1.0)	1
	Timesteps per second	Number of timesteps, previous to the current timestep, that all vehicles record.	1–9 (default = 3)	2
Traffic assignment parameters	Feedback interval (minutes)	Sets the period at which link times are updated into the routing calculation.	2–10 (default 5)	5
	Familiarity (%)	Percentage of drivers aware of dynamically updated cost to destination each feedback interval.	—	60
	Perturbation (%)	Models perception error or variation in perceiving true travel costs	—	5

Observed versus modeled counts



Capturing conflict between vehicles and pedestrians

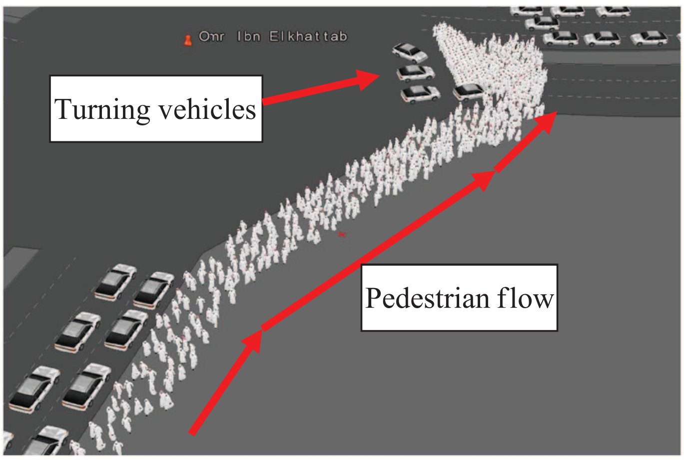


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Table II. Simulation model characteristics.

Area covered (km^2)	1.9 km × 1.3 km = 2.5
Perimeter (km)	5.5
No. of nodes	198
No. of links	244
No. of zones	26
Length of roads (km)	35
No. of signalized intersections	8

3.3.5. Agent physical and operational characteristics

The maximum pedestrian speed is chosen to be slightly above normal to mimic the observed rushing behavior crossing the RR. In UAF, the average speed of pedestrians followed a normal distribution with a maximum speed of 1.3 m/second. In addition, field observations revealed some variations in speeds because of the diverse demographic mix of pedestrians (elderly, women, kids, etc.). The height, breadth, and width were chosen as the default in UAF.

Therefore, the following characteristics were defined to model the agent movements in detail [12]:

- Agent speed: Agent speed follows a normal distribution with a maximum value of 1.3 m/second and a standard deviation of 0.25 m/second.
- Agent width: 0.51 m.
- Agent breadth: 0.32 m.
- Agent height: 1.8 m.

3.4. MODEL CALIBRATION

Coding the network and performing the OD estimation were followed by the calibration process, which ensures that the model parameters reflect local traffic conditions. Outputs used in the calibration process can be at the disaggregated level such as detailed vehicle's trajectories or at the aggregate level such as the traffic counts and average trip travel times. The following sections detail the calibration process.

3.4.1. Geometric refinement and calibration

During the initial stage of network coding, extra care is taken to properly build the network based on the overlays and the data provided. However, once the demand is generated by the OD estimation process and assigned to the network, further model refinement was required. Considerable improvements were achieved through geometric refinement and calibration that include the following: node/link, curb and stop lines, next lanes, signposting, traffic signal, traffic zones, and travel demand.

3.4.2. Calibration of network-wide parameters

Several system-wide micro-simulation parameters were calibrated using a factorial design experiment procedure (high–low combination of parameters). These parameters include the following: headway (seconds), reaction time (seconds), time steps per second, feedback interval (minutes), familiarity (%), and perturbation (%). Table I shows a detailed description of each parameter, the default values defined by Quadstone Paramics [18] and Park and Qi [19], and the calibrated values for each parameter. Repetitions of the model were conducted for each combination of parameters, and the results were assessed on the basis of the GEH. The most significant parameters were found to be the *time steps per second* and the *dynamic feedback* assignment.

To generate travel times necessary for traffic assignment, a half-hour warm-up period was specified in the simulation model, as it is not realistic to start the Friday Peak simulation hour with an empty network. Then, a demand profile was applied to this half-hour, so that the 100% demand level was reached gradually.

It is worth noting that while conducting the OD estimation process in *Paramics Estimator*, a dynamic traffic assignment was running in the background to capture the congestion effect on the resultant traffic

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flow values. Also, the flow intensity had to be incrementally increased from iteration to another to capture any dynamic routing options as shown in step 8 in Figure 4.

It is noteworthy that the OD matrix resulting from the OD estimation process had to be reassigned using the *Paramics Modeler* to capture any congestion pattern and reflect its effect on the modeled counts. The results of this comparison are shown in Table I.

The modeled counts obtained by the *Paramics Modeler* were found generally less than the ones obtained by the *Paramics Estimator*. A possible explanation for the inconsistency between the *Estimator* and *Modeler* counts is the fact that *Estimator* considers only a fraction of the flows while estimating the road counts (i.e., flow per 20 minutes interval) and then scales up these values to reflect the 1-hour traffic counts. In congested networks, this method might underestimate the congestion effect on modeled counts, and therefore, *Modeler* plausibly produces less flow compared to *Estimator*.

3.4.3. Calibration of pedestrian–vehicle shared space

After the network development and traffic calibration is complete, the inclusion of pedestrian demand and shared space adds more complexity to the calibration process. Although videos were collected for calibrating the speeds and variations of speeds, it was not used to capture the pedestrians' violations. However, two types of interactions between pedestrians and vehicles can be modeled in the shared space: aggressive and courtesy.

- Aggressive: agents and vehicles will try with equal effort to move forward avoiding each other, similar to an opposed right turn with traffic sneaking through crossing pedestrians.
- Courtesy: vehicles will avoid entering the shared space until all agents are outside their field of view, similar to a mid-block unsignalised pedestrian crossing.

From the aforementioned definitions, field observations, and input from the stakeholders, it was found that the aggressive behavior in the shared space mimics better the interaction between vehicles and pedestrians and therefore could, to some extent, capture pedestrian violations.

Therefore, a rigorous process of network refinement and calibration was undertaken, ranging from small improvements at individual crossing points to adjustments of entire intersections. The calibration process covers four major categories of issues as follows:

(1) Coding shared space.
- Ensure appropriate coding of aggressive shared space at crossings.
- Ensure that vehicle aware/shared space meet properly at crossing edges.
- Remove unnecessary agent-only space.

(2) Connectors/waypoints/agent navigation.
- Ensure that agents use the best path when moving from region to region.
- Split single waypoints into more than one waypoint to ensure smooth flow of agents.

(3) Vehicle aware space.
- Ensure correct vehicle aware length and sight distance parameters.
- Ensure vehicle aware space exists on exit side of crossing.

(4) Blocking regions.
- Ensure blocking region covers shared space.
- Improve blocking region design to avoid agents "stuck" in blocking regions.
- Define compliance rates at blocking regions.

4. RESULTS AND ANALYSIS

Because of the stochastic nature of the simulation model and underlying processes, each micro-simulation run can be regarded as a random experiment, that is, a random day in real life. Therefore, for proper comparative analyses, 10 simulations were completed for the base case network. The final results, averaged over the multiple runs, are reported. When comparing different strategies, a representative run (median run) is then chosen.

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Table III. Base case performance measures.

Network-wide performance measures				
	Total travel time (hours)	Average travel time/ vehicle (minutes)	Average speed (km/hour)	Average number of vehicles
Min.	67.7	49.4	6.3	9698
Avg.	71.8	59.8	6.4	10 034
Max.	74.2	68.6	6.5	10 246
St. Dev.	2.2	5.3	0.1	203

Pedestrian-only performance measures								
	Mean speed (m/second)	Mean density (a/m/m)	Mean delay (seconds)	Mean time in network (seconds)	Mean stop time (seconds)	Mean moving time (seconds)	Mean distance traveled (m)	Mean no. of agents
Min.	0.47	1.73	318.7	366.8	277.9	70.3	70.2	6060
Avg.	0.60	1.97	464.2	509.9	423.5	86.4	81.0	7122
Max.	0.70	2.20	804.3	845.1	759.1	124.5	101.3	8253
St. dev.	0.08	0.16	156.6	153.9	159.7	18.0	9.5	803

4.1. Network-level simulation results

Table III shows network-level results for pedestrians and vehicular traffic (including their interaction) and pedestrian agents only. Overall, the average speed of traffic was found around 6.5 km/hour, which was expected because of the severe congestion and the rushing behavior of pedestrians right after the Friday prayer. On average, across the 1-hour simulation, it was found that the number of vehicles remaining in the network is around 10 000 vehicles. The standard deviation depicts the model stability across various traffic conditions/days in the real life. The model shows reasonable stability (around 3%) across different performance measures.

For pedestrians, the average speed was found around 0.6 m/second, which matches our expectation because almost half of the time agents were found stopping at the traffic lights. On average, pedestrians were delayed around 8 minutes because of the traffic lights' operations and the conflicts with vehicles. On average, across the 1-hour simulation, it was found that the current number of pedestrians remaining in the network is around 7500 agents. The mean stop (waiting) time was found to be five times as agents moving time, which reflects high congestion levels and pedestrian friction with vehicles. In terms of model stability, the model exhibits more variation—compared to vehicles—when considering pedestrian-only measures.

4.2. Pedestrian-specific simulation results

This section sheds more light on the pedestrian-specific performance measures at the network level and at the intersection level. As part of the calibration analysis, it is interesting to show the collective behavior of individual agents in the form of fundamental diagrams of pedestrian flow. Figure 5 depicts a linear relationship between speed and density, which corresponds to Fruin's model of pedestrian flow [20]. Figure 5 also illustrates the speed versus flow relationship. It is clear that the network is operating at the congested side of the speed-flow diagram.

As discussed earlier, the maximum observed speed was found to be 1.3 m/second. At very low density levels (e.g., 1 agent/m^2), the modeled speed is found to be around 1.2 m/second. On average, the density was found to be 2 agent/m^2, with an average modeled speed of 0.6 m/second. From observing the crossing time of pedestrians after the Friday prayer, it was found that pedestrians spent almost double the crossing time they would spend without interaction with vehicles (i.e., 0.65 m/second), which closely corresponds to the average agent modeled speed of 0.6 m/second (Table III).

5. STRATEGIES FOR PEDESTRIAN CROSSING TREATMENT

This section introduces alternative strategies for pedestrian crossing treatment along the RR. It is noteworthy that these strategies are meant to demonstrate the ability of the modeling framework to help assess alternative mitigating treatments rather than providing a comprehensive set of solutions.

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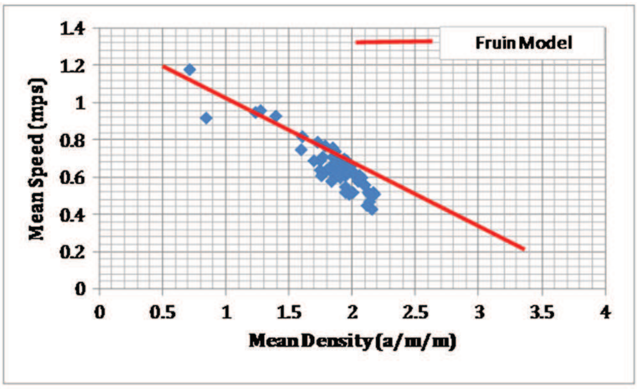
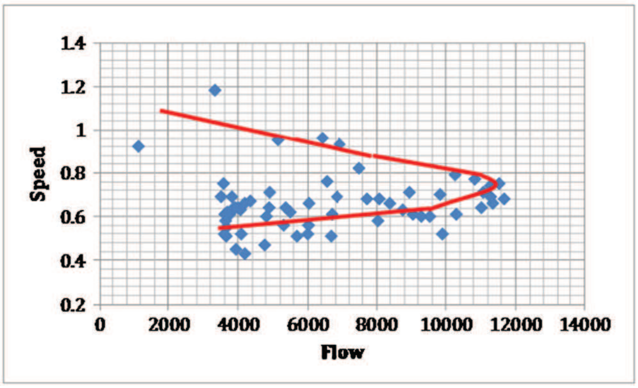


Speed vs Density



Speed vs Flow

Figure 5. Fundamental diagrams of pedestrian flow.

Pedestrian crossings can be categorized as controlled crossings (e.g., signalized intersection, stop sign control) or uncontrolled crossings (e.g., mid-block crossings). In general, a pedestrian-friendly crossing should be as follows: (1) compact (e.g., include refuge islands, minimal turning radii); (2) visible (with clear marking and proper sight distance for vehicles); (3) useful (for candidate pedestrian locations, for meeting the pedestrian desire lines); and (4) safe (decide on controlling versus uncontrolling the crossing) [21,22].

In the following sections, we discuss the proposed strategies and provide a quantitative analysis of each strategy based on the microscopic simulation testing.

5.1. Strategy 1—Pedestrian-only phase: scrambled intersection

As previously described, a substantial number of pedestrians cross the RR during peak seasons reaching 25 000 pedestrians/hour at some locations. In such crowded crossings, special consideration to pedestrian movements is required to minimize the conflict between pedestrian and traffic.

Pedestrian "scrambled" intersections are the ones controlled by traffic signals that provide an additional "pedestrian-only" phase while permitting simultaneous crossings in all directions. Typically, the diagonal directions are permitted in the scrambled intersections, but in the case of modeling the RR, we restrict the pedestrian movement to the perpendicular direction to the traffic for the following two reasons: (1) pedestrian flow is unidirectional (i.e., pedestrian cross the RR after the Friday prayer in the outbound direction) and pedestrians are less likely to diagonally cross the street given that their destination is the same, and (2) wide intersection area (exceeding 90 m in some locations) will result in long diagonal crossing length and walking time, which is unlikely to happen and might jeopardize the efficiency of the proposed strategy.

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The terms “pedestrian only” and “scrambled” are interchangeably used in this paper. The intersections are redesigned to add a pedestrian phase (60 seconds) that starts at the end/start of each cycle while vehicular traffic in all directions is stopped, and when the vehicular phases are activated, pedestrian crossings are still active to maximize pedestrian flow. Figure 6 depicts the redesign of King Fahd road as a pedestrian-only phase intersection.

5.2. Strategy 2—Grade separation: pedestrian tunnel

Grade separation of pedestrians and vehicles is typically considered where the number of pedestrian–vehicle conflicts is high, thus increasing the probability of incidents. The guidelines listed by Turner and Carlson [23] were the base for considering a pedestrian tunnel as one of the strategies to be evaluated as a mitigation to eliminate pedestrian–vehicles along the RR (Figure 6).

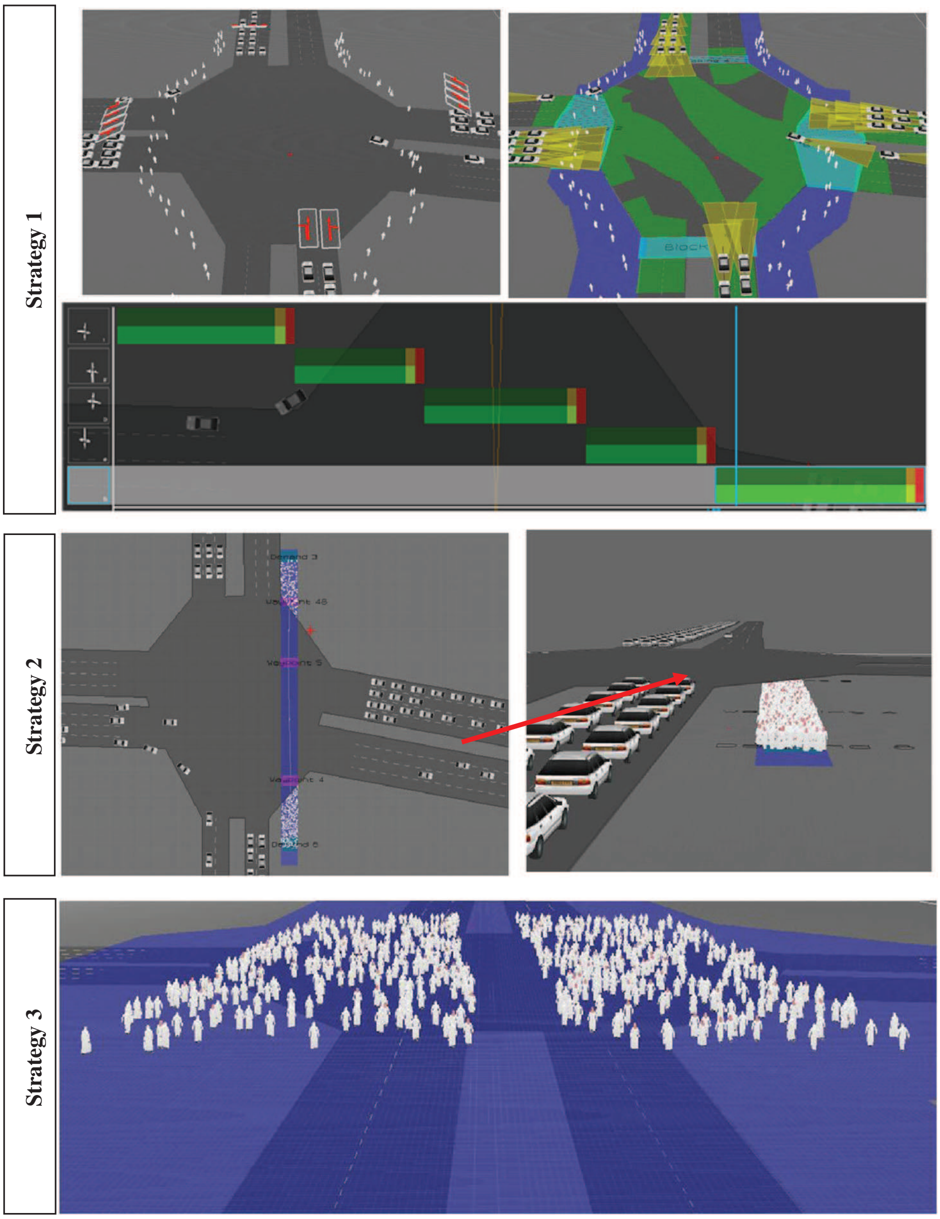

Figure 6. Example of proposed strategies at King Fahd Road.

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Pedestrian tunnels are designed to provide an effective method for pedestrian crossings. Because many pedestrians (and especially visitors and the elderly) are less amenable to enter a tunnel with a depressed profile, it is generally desirable to design a tunnel with a nearly level profile to provide complete vision from portal to portal. The following design elements are recommended for pedestrian tunnels [24]:

- The minimum overhead clearance is 3 m.
- The minimum width is 3.5–4 m.
- These should have adequate right of way to accommodate accessible ramp approaches, elevators, escalators, and so on.
- These should be adequately designed to satisfy the minimum accessibility and circulation path requirements (maximum 5% slope). See Exhibit 1510–27 in [24] for details.
- The minimum width is designed to maintain Level of Service D (LOS D).

In the Central Area and in the vicinity of the Prophet's Mosque, a platooning behavior is observed throughout the pedestrian stream. Therefore, the LOS thresholds for platooning in transportation facilities proposed by Rouphail *et al.* [25] are used as the base design criterion for the tunnel width at each crossing. This study considers LOS D as the primary design criterion and the pedestrian flow as the primary MOE, that is, maintain at least LOS D for the proposed tunnel width with a maximum permissible flow rate of 75 pedestrians/minutes/m.

5.3. Strategy 3—Pedestrian mall

This strategy involves banning all vehicular traffic from using the RR during the peak periods such as Friday after Noon prayer, Hajj, and Omrah seasons. This strategy therefore creates a pedestrian-friendly environment (Figure 6).

The pedestrian mall is designed as follows: (1) to allow pedestrian to use the entire road space as a pedestrian-friendly space with no interaction with traffic; (2) to ban traffic from using the RR after the Friday prayer; and (3) to respect the existing infrastructures (tunnels and bridges across the RR). Although we recognize the importance of considering the routing options for Strategy 3 outside the Central Area and the divergence of traffic elsewhere, the study area was constrained by the scope of the project as well as the computational constraints. In addition the surrounding areas at the periphery of the RR have amble room for transit facilities and/or parking lots for vehicles accessing the Central Area, not to mention the high sensitivity of the Central Area compared with the outer area.

5.4. Scenario comparison

This section presents a comparison between the three proposed strategies and the base case model. Each scenario (strategy or base case model) is represented by one run (median run) of the simulation model out of the 10 executed simulation runs. Table IV shows a matrix of MOEs for the proposed strategies and the base case model for vehicular traffic and pedestrian only. For each measure, the relative performance to the base case is indicated between parentheses. For example, Strategy 1 exhibits 16% savings on the average speed compared with the base case scenario.

The analysis of the proposed strategies leads to the following conclusions:

- Strategy 1 resulted in increasing the travel time of vehicles by 8% while improving the moving time of pedestrians by only 2%.
- Strategy 2 resulted in a significant decrease in the travel time of vehicles by 66% and moving time of pedestrians by 87%.
- Strategy 3 obviously resulted in a profound effect on the performance of pedestrians (negligible delay and free flow speed) while banning the traffic from using the RR after the Friday prayer.

Figure 7(a) depicts the effect of each strategy on the number of agents remaining in the network. It is shown that the scrambled strategy has a minor effect on the flow of pedestrians compared with the base case model, while the tunnel and pedestrian mall strategies exhibits profound effect. The mean number of agents in the model is an important measure as it reflects the pedestrian throughput, which is paramount should an emergency scenario be considered that warrants the evacuation of the Central Area.

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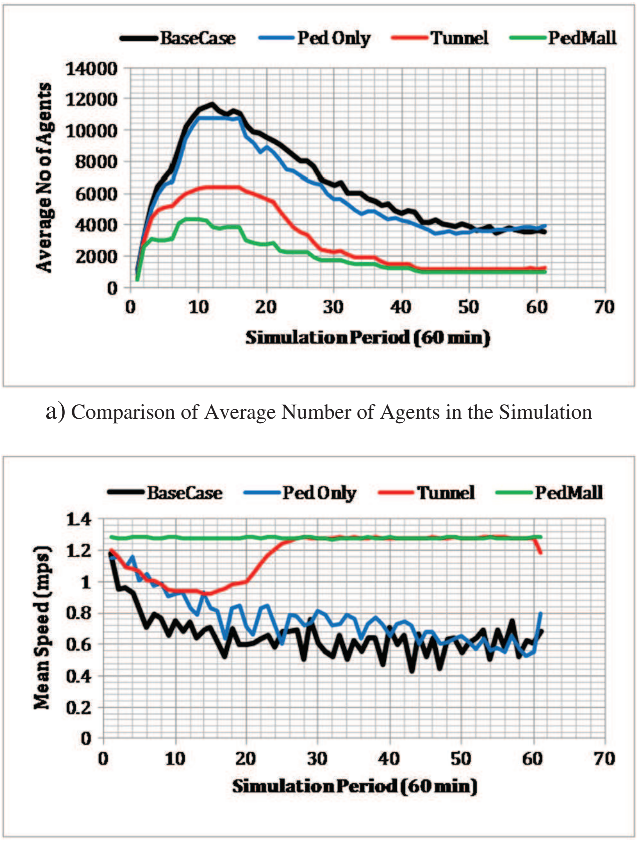
Table IV. Measures of performance of proposed strategies.

Network-wide performance measures				
	Base case	Strategy 1—pedestrian-only phase	Strategy 2—tunnel	Strategy 3—pedestrian mall
Total travel time (hours)	74	74 (0%)	66 (−11%)	—
Average Travel Time (minutes)	60	65 (8%)	20 (−66%)	—
Average Speed (km/hour)	6	5 (−16%)	10 (66%)	—
Pedestrian-only performance measures				
	Base case	Strategy 1—pedestrian only phase	Strategy 2—tunnel	Strategy 3—pedestrian mall
Mean speed (m/second)	0.69	0.79 (15%)	1.19 (72%)	1.28 (85%)
Mean density (a/m/m)	1.78	1.57 (−11%)	1.03 (−42%)	0.31(−82%)
Mean delay (seconds)	355.73	348.17 (−2%)	11.62 (−96%)	0.00 (—%)
Mean time in network (seconds)	403.48	398.43 (−2%)	50.05 (−87%)	35.97 (−91%)
Mean stop time (seconds)	329.57	311.77 (−6%)	3.74 (−99%)	0.00 (—%)
Mean moving time (seconds)	73.91	86.66 (17%)	46.32 (−37%)	35.97 (−51%)
Mean distance traveled (m)	78.93	84.30 (7%)	55.98 (−30)	45.62 (−42%)
Mean no. of agents	6158	5653 (−8%)	2920 (−52%)	1956 (−68%)



a) Comparison of Average Number of Agents in the Simulation

b) Comparison of Average Speed

Figure 7. Comparison of base case versus proposed strategies.

It is found that pedestrians in the scrambled strategy and the base case scenario encounter similar delay. With the introduction of the pedestrian tunnel and the pedestrian mall, pedestrians encounter minimal delay and move freely as depicted in Figure 7(b). For the tunnel strategy, it is interesting to show the effect of the

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confined tunnel space on the speed of pedestrians within the first 20 minutes of the simulation. The reason of this drop in pedestrian speed is twofold: (1) limited tunnel width that satisfies LOS D, which implies that pedestrians will encounter friction and exert some effort crossing the tunnel (as opposed to LOS A, for instance), and (2) the peak arrival flow pattern within the first 20 minutes of the simulation (Figure 3).

6. SUMMARY AND CONCLUSIONS

This paper presents a significant contribution in two areas:

1 The development of a new modeling framework that captures the interaction between pedestrians and vehicles at the microscopic level.
2 The application of the framework to a large-scale pedestrian–vehicle conflict in a highly congested urban area, namely the Central Area of Madinah, Saudi Arabia, at the time following a major congregational prayer.

The presented framework adopts a micro-simulation assignment approach that was implemented through two phases: Phase 1 involved modeling and calibrating traffic operations, whereas Phase 2 involved coding the pedestrian network structure while capturing the interaction/conflict between pedestrians and vehicles. It is important to note that the two phases are interrelated and several feedback mechanisms were used to reflect the effect of any change in the parameters of a certain phase on the other. Once the base case model was developed and calibrated, multiple simulation runs were conducted and the operational MOEs were reported.

The examination of the base case model results and visualization of the micro-simulation runs confirmed the serious conflict between pedestrians and vehicles in Madinah. This conflict has resulted in considerable delays to pedestrians crossing the RR (9 minutes average delay) and also to congested and slow vehicular traffic conditions (average speed <10 km/hour). Because of the high crossing volumes and limited walkway capacity, pedestrian density and speed deteriorate to poor levels.

A set of plausible strategies were then proposed to mitigate the conflicts between pedestrians and traffic in Madinah. Three models (in addition to the base case model) were developed to reflect each of the proposed strategies: (1) pedestrian-only phase; (2) grade-separation (tunnel); and (3) pedestrian mall. A set of MOEs was reported for each strategy and analyzed at a great level of detail.

The analysis of the proposed strategies revealed that Strategy 1 slightly improved pedestrians moving time on the expense of vehicular travel time. Strategy 2 is the most favorable option as it resulted in substantial savings for vehicular traffic and pedestrians, and more importantly, it complements the endeavors of the Development Commission of Madinah. Strategy 3, on the other hand, can be viewed as a long-term solution that would require the integration of public transit and parking strategies to/from the Central Area.

The authors believe that the techniques developed in this research could be improved in future phases in the following directions:

- Validation of microscopic traffic simulation could be refined by (1) using travel time information for vehicular traffic and (2) observing pedestrian behavioral characteristics and video recording their movements in platoons.
- Better handling the path choice of pedestrians and its effect on routing behavior could explain better the conflict between vehicles and pedestrians.
- Calibrating the model for actual pedestrian violations and vehicle conflicts is an important research direction. Such effort requires the following: (1) a comprehensive pedestrian survey to capture the detailed interaction between pedestrian and vehicles and (2) a microscopic simulation tools that can produce conflict safety surrogate measures.

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