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A Simulation Study of the Shuttle-Bus Pilgrim Transportation System between the Holy Sites for the 1422H *Hajj* Season

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Abstract. The shuttle-bus transportation system in the annual Islamic pilgrimage, known as *Hajj*, relies on using dedicated two-way lanes between the holy sites of Arafat and Muzdalifah, in the first segment, and between Muzdalifah and Mina in the second segment. Shuttle buses have been used successfully for the past seven years to transport one group of pilgrims consisting of more than 160,000 pilgrims out of a total of more than two million pilgrims. The Saudi Ministry of *Hajj* would like to revise the current experience gained from this project and evaluate any constraints or shortcomings associated with it. In this paper, a description of the shuttle bus transportation system that existed in the 2002 *Hajj* season is given. Next, a simulation model is designed for this system and translated into a simulation program using the Arena simulation system. This simulation model is used to conduct a series of experiments designed with the goal of achieving a better understanding of the characteristics and limitations of the system.

Keywords: Hajj, *Al-Nafrah*, Shuttle Buses, Decision-Support Tool.

1. Introduction

Hajj is a major religious event in which more than two million individuals from all over the world gather at the same time in the *Makkah* area in the Kingdom of Saudi Arabia, each year. It is the pilgrimage duty in the *Islamic* faith required, once in a lifetime, from each physically and financially capable adult Muslim. It consists of a set of rituals to be performed in order at specific times and in specific locations in the *Makkah* area. The *Hajj* holy sites have religiously-fixed boundaries. *Hajj* consists of the set of ordered steps shown in Fig. 1 which illustrates pilgrim movements during the *Hajj* journey. All pilgrims must start their *Hajj* journey in *Makkah* where they perform certain rituals and prayers in the *Makkah* Holy Mosque. Later, most pilgrims move on to stay in pre-assigned camps in the area of *Mina* from the 8th day until the 9th day of the 12th *Hijri* month, *Dul Hijja*. The 9th day is known as the day of *Arafat* because, on that day, all pilgrims must move from *Mina* after sunrise to spend the whole day at the holy site of *Arafat*, also within the *Makkah* area. After sunset, all pilgrims must move together to the adjacent site of *Muzdalifah* to spend the night. After sunrise on the 10th day of the *Hijri* month *Dul Hijja*, known as the *Sacrifice Feast Day*, most pilgrims start moving back to their camps in *Mina.* Three days later they return to *Makkah* to perform their final rituals and prayers in the Holy Mosque in preparation for their final departure. The collective movement of pilgrims from *Arafat* to *Muzdalifah*, and later from *Muzdalifah* to *Mina* is called *Al-Nafrah* phase of the *Hajj* journey, which corresponds to the trip segments 4 and 5 in Fig. 1.

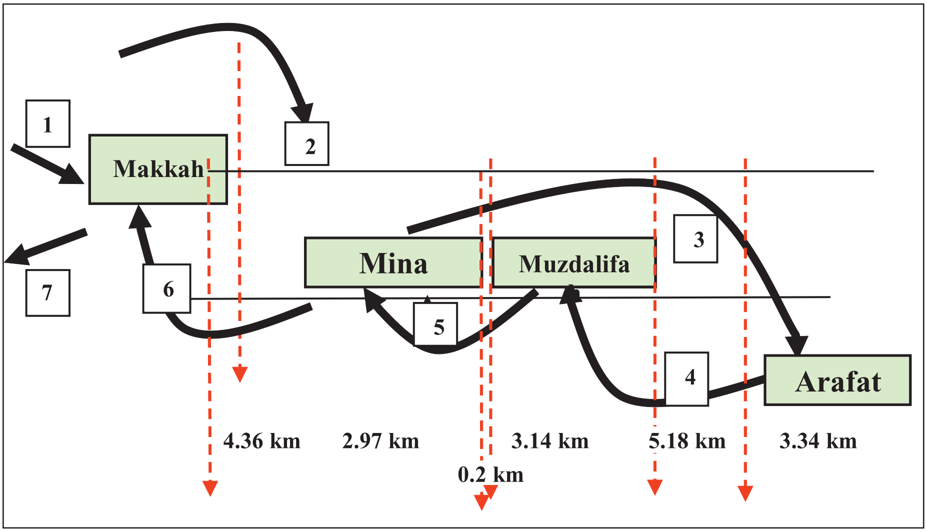

Fig. 1. Pilgrim path during the *Hajj* journey.

The holy sites of *Mina*, *Muzdalifah* and *Arafat* have fixed boundaries. They are connected with a limited number of roads. Consequently, severe traffic congestions occur each year between these sites, which result in vehicular trip times that are relatively high. Extremely congested traffic also results in great waste of fuel, higher transportation cost per passenger, higher probability of vehicle failures, and more environmental pollution.

Al-Nafrah is one of the most critical traffic trips in *Hajj* in terms of traffic congestion. During *Al-Nafrah*, all pilgrims move together after sunset using the nine available roads between *Arafat* and *Muzdalifah* in a five-kilometer trip. Most pilgrims, except for the elderly and the sick, spend the night in the open area of *Muzdalifah.* After dawn, pilgrims move together again to the *Mina* area which lies about three kilometers west of *Muzdalifah*. Due to the simultaneous movement of thousands of vehicles on limited-capacity roads, long queues of traffic build up quickly. During peak hours of *Al-Nafrah*, these queues usually span along the distance between *Arafat* and *Muzdalifah* on most roads. The average vehicle trip time between *Arafat* and *Muzdalifah* was estimated to be about 3 hours, which in urban areas under normal traffic conditions should be about 10 minutes. Ironically, the average pedestrian trip time for the same distance was estimated to be 2 hours[1].

Since these congestion problems that occur during *Al-Nafrah* in each *Hajj* season were getting worse as the number of pilgrims increased year after year, it was crucial to find effective solutions for this problem. Several studies were conducted between 1990 and 1993 to evaluate the vehicular movement during *Al-Nafrah* and measure the vehicle and pedestrian delays between *Arafat*, *Muzdalifah*, and *Mina*[2, 3]. The idea of using shuttle buses to transport pilgrims between *Arafat* and *Muzdalifah* was first proposed in 1992 in a report by the Saudi Ministry of Transportation[4]. Later, the study by Othman in 1993 appeared as a more extensive proposal of the idea[5]. This study was followed by a detailed plan prepared by the *Hajj* Research Center of Um Al-Qura University in 1996 to implement it as an experimental project[6]. In the *Hajj* season of 1996, shuttle buses were used for the first time to transport pilgrims between *Arafat* and *Muzdalifah* using exclusive bus lanes. The experiment was conducted successfully to transport pilgrims of one category of about 130,000 pilgrims from Turkey, Europe, North America, and Australia. Several road-expansion and bridge construction projects had to be carried out prior to applying the shuttle bus experiment to modify existing roads and to isolate the shuttle-bus way. Specifically, one of the roads connecting *Arafat* and *Muzdalifah* was widened, isolated, and dedicated to shuttle-bus movement between those two sites. In addition, a bus parking lot with a capacity of about 2000 buses was constructed about two-kilometers west of *Arafat* and was equipped with accommodation facilities for bus drivers. Loading and unloading stations were also constructed in proper locations in both *Arafat* and *Muzdalifah*. Later, isolated pedestrian lanes were also constructed alongside the shuttle bus road from *Muzdalifah* to *Mina*. In 1997, the shuttle-bus project was extended successfully to include the *Muzdalifah-Mina* segment of *Al-Nafrah*. The use of shuttle buses in *Al-Nafrah* for the two segments continued during *Hajj* seasons from 1998 until now.

In a recent simulation study, a simulation model was developed using Promodel for the *classical* pilgrim transportation system during *Al-Nafrah*, that is not based on shuttle buses[7]. In this system , a bus is dedicated and closely coupled to each group of pilgrims and remains with them wherever they go. This transportation system is still applied to all categories of pilgrims except those who are served by the shuttle-bus service. However, this study pertains to a completely different system that has fundamental differences from the shuttle-bus system both in structure and assumptions. In another simulation study, a simulation model using Promodel was developed for the shuttle-bus pilgrim transportation system during *Al-Nafrah*[8]. However, this study relied on field data collected in 1996 for model validation and input.

Before committing more resources for further expansion of this successful project, the Ministry of *Hajj* would like to revise the current experiences gained from this project during the past seven years, study the lessons learned, and assess the constraints and shortcomings associated with it[9, 10]. To achieve this goal, the Ministry of *Hajj* has recently initiated this computer simulation research study of the existing shuttle-bus system in *Al-Nafrah* with the objectives to: 1) understand the system characteristics and any constraints or limitations it may have; 2) use this knowledge to better prepare and plan for future operation and expansion. Computer simulation was selected as a tool for conducting this study due to the large scale and complexity of the problem. Moreover, simulation models will permit decision-makers to conduct what-if analyses on the constructed model and define and test several cases of interest before applying them in reality during the annual *Hajj* event.

In this paper, a detailed description of the shuttle bus transportation system between the holy sites during *Hajj* is given. This includes the shuttle-bus route details, the dispatching mechanism of buses from their parking lot in the form of caravans to the loading stations corresponding to their bus labels in one holy site and the unloading of buses at the unloading stations with the same label in the other holy sites. System details also include the different types of pilgrims and their special transportation requirements, and the effect of external factors like pedestrian pilgrims crossing the shuttle-bus path on the overall system performance.

Next, a conceptual model of this described system is constructed. This model is then translated into a simulation model using the *Arena* simulation tool (Research Edition), from Rockwell Software[11], which is based on the well-known simulation language SIMAN. The simulation model is verified and validated using actual performance data collected during the 2002 *Hajj* season (Hijri Year 1422 – February 2002). The final simulation model is then used to conduct a set of simulation experiments whose results are later analyzed in order to draw conclusions.

The rest of this paper is organized as follows. Section 2 provides a detailed system description. Section 3 discusses the data collection process conducted during the 2002 *Hajj* season. Section 4 describes the Arena simulation model design and implementation. Section 5 describes the model verification and validation process. Section 6 discusses the design of the conducted simulation experiments and the output results obtained. Finally, Section 7 gives conclusions.

2. System Description

The shuttle bus transportation project has been a successful attempt to find solutions to the traffic congestion problem during *Al-Nafrah*[10, 12, 13]. A two-lane road is dedicated for buses to make shuttle trips between the holy sites of *Arafat* and *Muzdalifah* beginning at sunset, and from *Muzdalifah* to *Mina* beginning at midnight. Pilgrims are grouped in *Arafat* and *Muzdalifah* in adjacent camp areas with two loading/unloading gates each. At each camp area, a busload, consisting of a maximum of 50 pilgrims, is either loaded on/unloaded from each bus using any of the two available gates at each stage of the trip.

A camp area is assigned to each of the Field Service Groups (FSGs). These are hosting agents responsible for the accommodation, transportation, and any other arrangements for pilgrims. There are a total of 38 FSGs within the *Establishment of the Pilgrims of Turkey, and Muslims of Europe, America, and Australia*[14]. This was the only establishment (among six pilgrim establishments) that was served by the shuttle-bus system during the *Hajj* seasons up to the 2002 season (staring in the 2003 *Hajj* season, the *Establishment of the Pilgrims of South East Asia* was included for the first time in the shuttle-bus system). Each FSG in this pilgrim establishment is assigned a unique identification number in the ranges from 1 to 28 and from 31 to 40. All FSG's have similar temporary camp areas in *Arafat* and *Muzdalifah*, in addition to the main living camps in *Mina*. Each bus is assigned a specific FSG number using number signs, and thereby becomes dedicated to that FSG.

Buses are initially stored in a special parking area located on the road to *Muzdalifah*, about two kilometers west of *Arafat.* Only buses at the head of each waiting lane can be dispatched to their assigned FSGs. These buses are not usually dispatched once again unless there is need for extra buses for some other FSGs.

The shuttle-bus path during *Al-Nafrah* consists of two loops: loop1 and loop2. Loop 1 connects *Arafat* and *Muzdalifah* for a seven-kilometer distance. Bus activity in loop1 starts at sunset (around 6 PM) and ends around 2 AM. Loop 2 connects *Muzdalifah* to *Mina* for two-kilometer distance. Bus activity in loop2 starts around 12 AM and ends around 8 AM. Moreover, loop1 does not terminate completely before loop2 starts. Rather, loop2 starts by dispatching buses from the bus-parking area to the *Muzdalifah* loading gates at midnight while loop1 usually ends around 2 AM after all pilgrims have been transported from *Arafat* to *Muzdalifah*. Figures 2 and 3 describe the shuttle-bus paths in loop1 and loop2, respectively. The road between *Arafat* and *Muzdalifah* passes over a steep hill of 6-8.5% steepness slope for a distance of about one kilometer just before the beginning of *Muzdalifah.* Over this distance, ascending loaded buses experience significant speed reduction to less than 10 km/hour on the average. This results in long queues of slow-moving buses attempting to pass the hill from both directions.

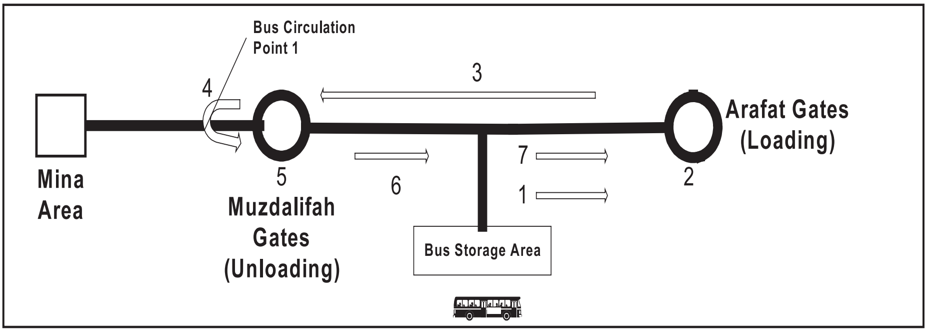

Fig. 2. Shuttle-bus path in loop 1.

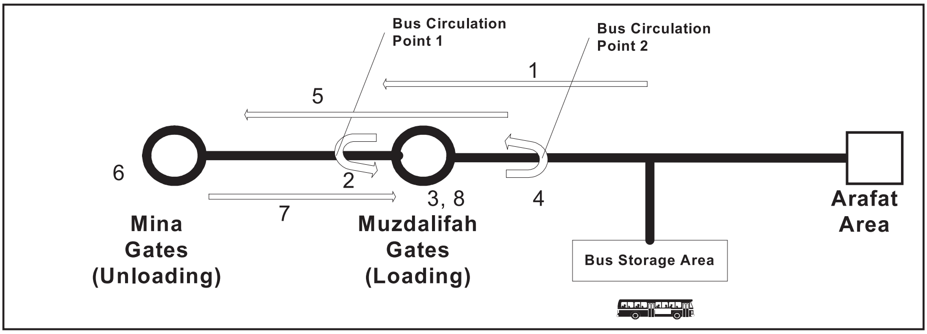

Fig. 3. Shuttle-bus path in loop 2.

In the 2002 *Hajj* season, approximately 160,000 pilgrims from the Establishment of the *Pilgrims of Turkey, and Muslims of Europe, America, and Australia* used the shuttle buses. These pilgrims were divided unequally among 38 FSGs[14]. In loop1 in the 2002 *Hajj* season, 542 buses were used to transport pilgrims from *Arafat* to *Muzdalifah*. Buses were dispatched to the FSG camp areas in

Arafat in the form of successive bus caravans with one bus for each FSG. Each bus within each caravan proceeds to its assigned FSG camp area for loading at either one of the two loading gates, depending on vacancy. Bus caravans consist of 28 buses each for Turkish pilgrims, and 10 buses each for European, American, and Australian pilgrims. The latter category of pilgrims spent the day of *Arafat* in 10 camps located on the northern side of the main *Arafat* road. A total of 15 bus caravans for this group were parked before sunset at a special location near their camps. The Turkish pilgrims were distributed on 28 FSG camp areas located both south and north of the main *Arafat* road. One caravan of buses was moved to park in front of the FSG loading gates in *Arafat* before sunset. A total of nine other bus caravans were parked on the right-hand side of the road between the bus parking area and *Arafat.* The remaining four bus caravans for Turkish pilgrims were dispatched at a rate of about one caravan every 3 minutes from the bus-parking area after all the other bus caravans dispatched earlier were loaded.

Due to the lack of adequate camping space in *Muzdalifah*, five FSGs serving Turkish pilgrims with the numbers 19-23 had their main *Mina* living camps constructed in the far east of *Mina* as an extension within the borders of *Muzdalifah.* Pilgrims belonging to these five FSGs are transported in loop1 from their *Arafat* camps directly to their Muzdalifah camps and, therefore, are not transported again in loop2 to *Mina*. These five FSG camps are called the *Zhill* camps (Arabic for shadow), because they are constructed as permanent roofed tents and not open areas like the other *Muzdalifah* FSG camp areas.

Special transportation arrangements were made in loop1 for the sick and elderly pilgrims, and for the Royal guests. About 3000 pilgrims from the former category were transported in loop1 using 60 special buses at around 1 AM from their *Arafat* locations to *Muzdalifah* where they stayed for only a few minutes and then moved directly to *Makkah* to conclude their pilgrimage rituals. Similarly, about 2000 Royal guests were transported in loop1 using 40 special buses at sunset from their *Arafat* locations to *Muzdalifah* where they stayed only until 2 AM. At that time, they were picked up again and transported directly to *Makkah* to conclude their pilgrimage rituals. In addition to shuttle buses, service and backup vehicles (*e.g.* ambulance vans, maintenance and fuel trucks, and field supervisor cars) frequently roam the shuttle-bus road between *Arafat* and *Muzdalifah* at a rate of about one vehicle every 4 minutes, generating a total of 120 two-way trips and 30 one-way trips from *Arafat* to *Muzdalifah.*

In loop2 of *Al-Nafrah*, about one eighth of pilgrims served by shuttle buses prefer to walk the three-kilometer distance from *Muzdalifah* to *Mina*. Bus caravans are dispatched, starting at midnight, from the bus-parking area to *Muzdalifah* loading gates at a rate of about one caravan every 30 minutes. However, from

3 AM on, the rate becomes about one caravan every 7 minutes. In addition, 26 buses were dispatched as early as 8 PM to pick up the religiously-excused pilgrims who wish to leave *Muzdalifah* to *Mina* early (usually the elderly and sick pilgrims).

In loop2, very large numbers of pedestrian pilgrims who walk from *Muzdalifah* to *Mina* repeatedly cross the shuttle-bus road near the *Mina* camp area in groups starting from midnight. This hinders traffic at the entrance to *Mina* and causes severe delays for shuttle buses. Due to these delays, the average bus waiting time for pilgrims in *Muzdalifah* can become very long. Therefore, in the 2002 *Hajj* season, a set of 138 backup buses were parked behind the *Muzdalifah* camps to help in transporting any remaining pilgrims from *Muzdalifah* to *Mina* after sunrise[14].

3. Data Collection

In the 2002 *Hajj* season, a team of 22 college students was depolyed among selected points in the areas of *Arafat, Muzdalifah, Mina*, and the bus parking lot. Nine fixed locations were selected for data collection in loop1 and six others were selected for loop2. In addition, four people per loop were bus-riding data collectors.

Table 1 defines the variables for which data were collected and shows the observed mean values for each variable. These mean values have been used in the simulation as mean values for the random-number generators which provide random variates representing the values of those random variable. Variables L1, L2, U1, and U2 were observed by two persons in each loop. One person observed pilgrim loading at randomly selected FSG camps and the other observed pilgrim unloading, also at randomly selected FSG camps at the other end of the loop. Variables D1 and D2 were observed by two persons per loop who rode randomly selected buses for the entire trip and recorded the observed trip time. Finally, variables F1 and F2 were observed by one person per loop who counted the number of buses passing at his fixed observation point in successive five-minute periods.

4. Model Design and Implementation

The system described in Section 2 was used to build a conceptual model that summarized the system rules, constraints and entities in an organized form to facilitate communication between domain experts and simulation analysts. The revised conceptual model is the starting point for designing and implementing the simulation model. In this section, the simulation model for the shuttle-bus transportation system in loop1 and loop2 of *Al-Nafrah* will be described using

Table 1. Field data summary.

Variable	Definition	Mean value
L1	Bus loading time for each bus in loop1	3.2 minutes
L2	Bus loading time for each bus in loop2	4.38 minutes
U1	Bus unloading time for each bus in loop1	3.07 minutes
U2	Bus unloading time for each bus in loop1	3.42 minutes
D1	Duration of the one-way trip in loop1	33.1 minutes
D2	Duration of the one-way trip in loop2	18.8 minutes
F1	Vehicular flow in bus per minute at a certain point on the path in loop1	7.4 bus/minute
F2	Vehicular flow in bus per minute at a certain point on the path in loop2	4.2 bus/minute

the *Arena* (Research Edition) simulation tool modeling concepts. The modeling methodology used is the process-view methodology using a queuing-system modeling framework.

Arena requires that two main items be specified for models that involve the simulation of transporting entities. These items are: a flow-chart-like logical model of the system and a topological map of the locations between which transporter entities move. The latter map is mainly used for animation purposes. It specifies the relative locations of all landmarks on the shuttle-bus path, including the loading-gates area at *Arafat*, the unloading and loading-gates at *Muzdalifah*, and the bus-parking area. In addition, the flow-chart model defines many details to the *Arena* simulation engine about the road network, like the exact distance between these landmarks, any road segments in which shuttle-buses (transporters) must accelerate or decelerate, the transporter speed, and any road curvatures. The maximum bus speed is assumed in this model to be fixed at 50 km per hour.

The flow-chart model of the simulated system also includes the logical steps that must be followed to simulate the system. It consists of a number of Arena modules. These are the building blocks for any Arena simulation. They are grouped based on their functionality into *panels.* For example, Arena 5.0 contains a Basic panel, an Advanced Process panel, and an Advanced Transfer panel[11]. The model logic is described by defining one or more logical paths to be taken by the model entities under different conditions. For the current model, two main types of entities are defined: pedestrian pilgrims and bus drivers. Passenger pilgrims are represented in this model by counters that are initialized with the maximum number of pilgrims that will be initially waiting for boarding in *Arafat* at the various FSG loading gates. These initial numbers are based on actual pilgrim statistics from the 2002 *Hajj* season. As pilgrims are boarded onto shuttle-buses at each gate, the number of FSG pilgrims is decremented by the bus capacity, which is fixed at 50 passengers. Bus-driver entities are represented by actual simulation entities since Arena requires that each transporter be controlled by one controlling entity. Therefore, bus-drivers are created in batches, each corresponding to one bus caravan. Successive creations of bus-driver batches are separated in time by the same time periods as the inter-dispatching time periods between successive bus caravans. These are assumed in the model to be normally distributed because they are controlled by human operators who strive to have these random times centered around an agreed upon average value. Each driver entity possesses two main attributes: *Rounds:* the number of loop rounds made by that driver, and *GIndex*: The index identifying the FSG for which this driver (and his bus) is assigned. Each driver starts by requesting a transporter (bus) entity from the queue of parked buses. Next, the bus and its driver join a caravan and move out on the road heading to its assigned FSG's loading gates. Bus breakdowns were not included in the model because a small number of them usually occur, and no precise data exists on their number or frequency.

In loop1, when a bus caravan reaches *Arafat*, each bus proceeds to its assigned FSG's loading gate. At the gate area, each bus stops at the first vacant gate of the two FSG's camp gates and picks up its capacity of pilgrims during a normally distributed time period. The bus then moves to the corresponding FSG in *Muzdalifah.* Upon arrival in *Muzdalifah*, the bus takes a U-turn and heads to the unloading area on the southern side of the road, where it stops at the first vacant gate of the two FSG's camp gates to unload pilgrims in a normally distributed time period. After the *Rounds* attribute is incremented, a check is then made whether more pilgrims are waiting at the FSG's camp in *Arafat.* If so, the bus returns to *Arafat* to take another round. If not, the bus moves back to the bus-parking area. This check is usually performed by radio-equipped supervisors in both *Arafat* and *Muzdalifah* who direct bus drivers appropriately.

Similarly, in loop2, buses in each caravan proceed to their assigned FSGs loading gates in *Muzdalifah*. At the gate area, each bus stops at the first vacant gate of the two FSG's camp gates and picks up its capacity of pilgrims during a normally distributed time period. The bus then moves to the corresponding FSG's camp in *Mina.* On the way, buses may be forced to stop for a short period of time that corresponds to the time needed for a batch of pedestrian pilgrims to cross the road at either of the two identified pedestrian-crossing points at the entrance to the *Mina* camp area. Upon arrival in *Mina*, buses stop in front of their FSGs permanent-tent living camps to unload pilgrims in a normally distributed time period. There are no labeled unloading gates in *Mina.* Rather, buses stop freely on the right-side of the road as close as possible to the living camps of their FSGs. After the *Rounds* attribute is incremented, a check is then made (by supervisors) whether more pilgrims are waiting at the FSG's camp in *Muzdalifah.* If so, the bus returns to *Muzdalifah* to take another round. If not, the bus moves back to the bus-parking area.

All types of buses in the model are represented in Arena as guided transporters. These are transporters restricted to run on fixed paths and whose operation is affected by other vehicles due to congestion. Different guided transporter types are used to represent the various types of shuttle buses and vehicles present in the model. For example, buses that transport the sick and elderly pilgrims in loop1, backup buses in loop2, buses that transport the Royal guest pilgrims, and emergency and service vehicles, are all represented in the simulation model by different types of guided transporters.

5. Model Validation

Model validation is the process of comparing the simulation model behavior with the real system behavior. The comparison of the model to reality is carried out by a variety of tests that can be either subjective or objective. Two techniques were used to validate our model[15]:

1. *Validation of Model Assumptions:* Where model assumptions can be either structural or data assumptions. Structural assumptions are related to how the system operates. On the other hand, data assumptions involve characteristics of system parameter data. In our model, structural assumptions were validated by the direct observation and comparison of the real system and the operational simulation model by system domain experts. Data assumptions include the assumed statistical characteristics of model parameters, like the average bus loading and unloading times. These data assumptions were validated by collecting data from the real system during the 2002 *Hajj* season and calculating the average values and standard deviations for these data. These same values were used to represent the averages and standard deviations of these data quantities in the simulation model.

2. *Validation of Input-output Transformations:* Which is based on comparing the output of the model to the output of the real system using the same input data set. If they approximately match, it means that the model represents the real system; otherwise the model should be revised. We simulated the same *Hajj* scenario that existed in the 2002 season and compared the real system output with the simulation model output based on four performance measures (see Table 2). The results of this performance measure comparison can be found in Table 3. It can be seen that percentage difference values between the real

system output and the simulation model output are sufficiently small to conclude that the model is a good-enough representation of the real system under the assumptions made and for the default parameters used.

Table 2. Performance measure definitions.

Performance measure variable	Definition	Units
E1	Time needed to evacuate *Arafat* from all pilgrims in loop1	hours
E2	Time needed to evacuate *Muzdalifah* from all pilgrims in loop2	hours
D1	Duration of the one-way trip in loop1	minutes
D2	Duration of the one-way trip in loop2	minutes

Table 3. Comparison of the real and simulated system performance measures.

	E1	E2	D1	D2
Real system	8.25 h	10 h	33.1 min	18.8 min
Simulation model	8 h	9.7 h	34 min	17 min
Percentage difference	–3%	–3%	3%	–9%

6. Experimental Design and Output Results

This section discusses the experimental design and the obtained simulation output results and their interpretation. We will identify a set of controllable decision variables whose effects on the defined system performance measures are to be evaluated using the developed simulation model. The performance measures that will be studied in the experiments described below are defined in Table 2 and the controllable decision variables are defined in Table 4. In addition, output data will also be collected by the simulation model for some quantities that are of interest to decision makers. These quantities are defined in Table 5. The following simulation experiments are designed to study the effect of decision variables N1 and I1 on both E1 and D1 and of N2 and I2 on both E2 and D2, while keeping all uncontrollable model parameters fixed. Each simulation experiment was repeated 3 times and the average value of the resulting performance measures was calculated.

6.1 *Loop1: Arafat – Muzdalifah*

Figure 4 illustrates the relationship between the time needed to evacuate *Arafat* from pilgrims E1 and the number of main shuttle buses used N1. It can be seen that increasing the number of shuttle buses beyond the 542 figure that was used in the 2002 *Hajj* season does not seem to help in reducing E1, as the

Table 4. Decision variable definitions.

Decision variable	Definition	Units
N1	The number of main shuttle buses used to transport pilgrims from Arafat to Muzdalifah in loop1	Buses
N2	The number of main shuttle buses used to transport pilgrims from Muzdalifah to Mina in loop2	Buses
I1	The average inter-dispatching time of shuttle bus caravans in loop1	Minutes
I2	The average inter-dispatching time of shuttle bus caravans in loop2	Minutes

Table 5. Output quantities of interest.

Output quantity	Definition	Units
R1	The average number of rounds made by the main shuttle buses in loop1	Round
R2	The average number of rounds made by the main shuttle buses in loop2	Round

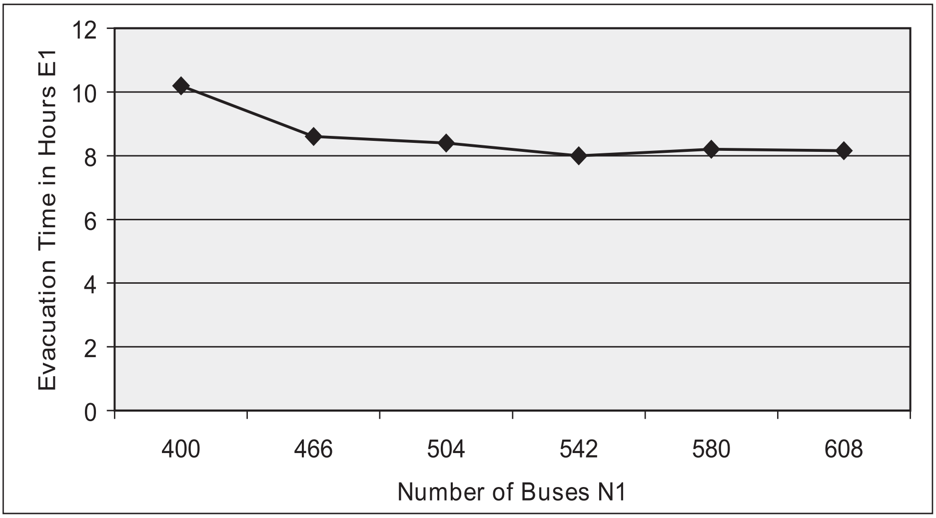

Fig. 4. The relationship between the time needed to evacuate arafat and the number of buses used in loop1.

road will be already saturated with traffic. In the meantime, reducing the number of buses below a threshold of 466 starts to be noticeably harmful to the system performance as E1 starts to increase sharply due to the great reduction in the available transportation capacity.

However, a modest reduction in the number of buses to about 500 buses can be tolerated without significantly affecting performance. Similarly, Fig. 5 shows the relationship between the average duration of the one-way trip D1 and the number of main shuttle-buses N1. This figure shows that raising the number of buses from about 400 to 608 buses leads to a steady increase in D1, since pumping more and more buses to the road will result in more traffic congestion and, therefore, longer trip times.

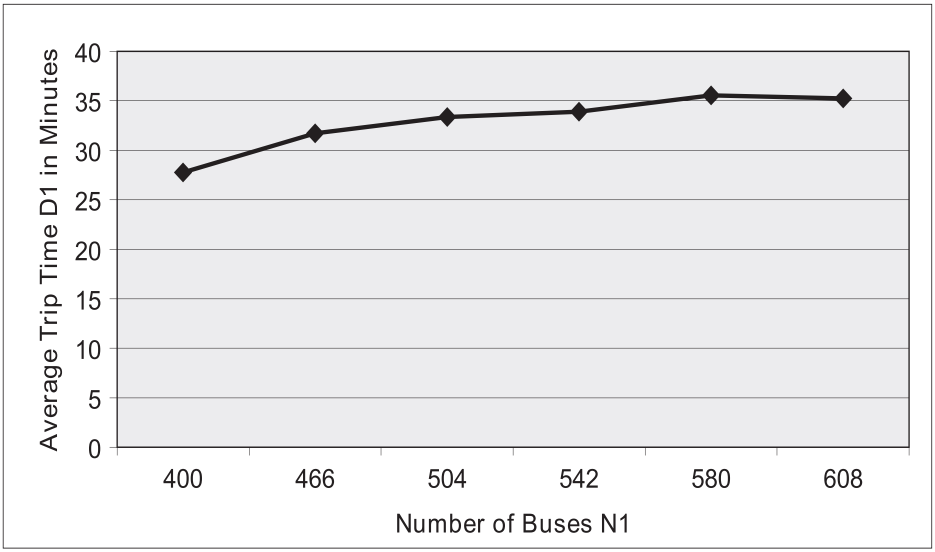

Fig. 5. The relationship between the average one-way trip time and the number of buses used in loop1.

Figure 6 illustrates the relationship between the time needed to evacuate *Arafat* from all pilgrims E1 and the average inter-dispatching time of shuttle-bus caravans I1, whereas Fig. 7 shows the relationship between the average duration of the one-way trip D1 and the average inter-dispatching time of shuttle-bus caravans I1. It can be concluded from these two figures that the average inter-dispatching time of shuttle-bus caravans has limited effect on the E1 and D1 performance measures. However, a slight increase of about five minutes in D1 is observed in the case when a small value (*e.g.* 1 minute, which is much smaller than the average time needed to load one bus) is used for I1. The reason for this increase is that such a small I1 value amounts to the flooding of the road with buses at a rate higher than the rate of loading buses at *Arafat* gates. This situation will eventually lead to filling the narrow *Arafat* road exit with a long line of loaded buses, which would create an unnecessary traffic jam and thus increase the average trip delay.

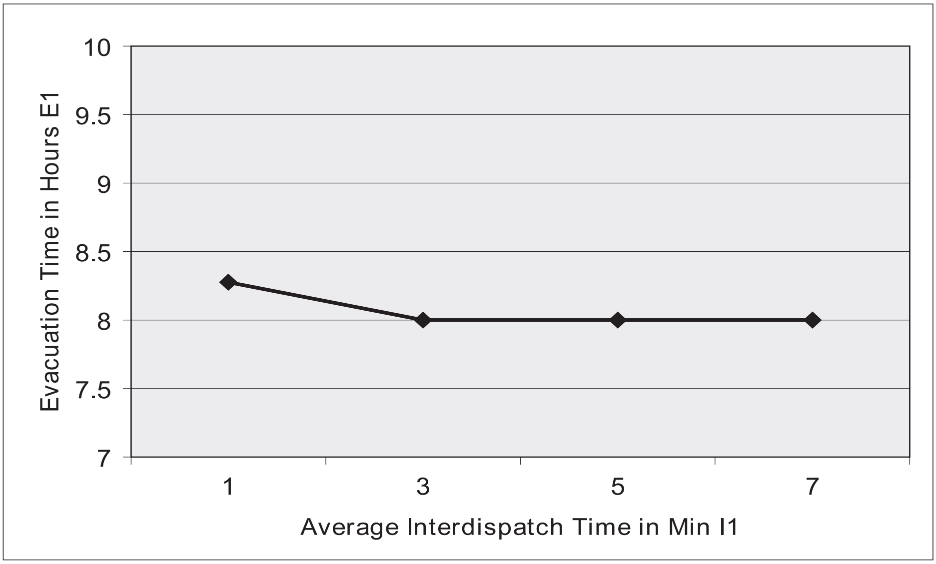

Fig. 6. The relationship between the time needed to evacuate arafat and the inter-dispatch time for bus caravans in loop1.

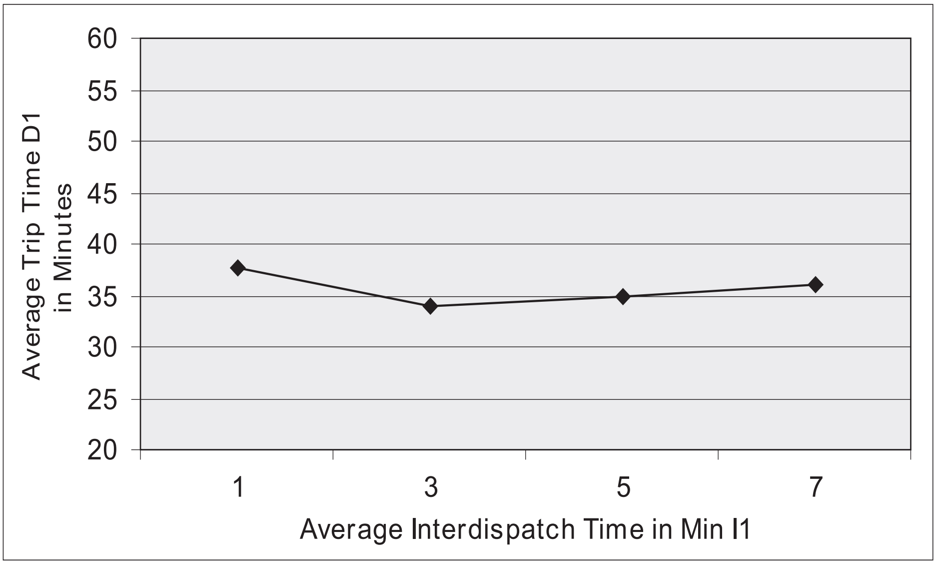

Fig. 7. The relationship between the average one-way trip time and the inter-dispatch time for bus caravans in loop1.

Figure 8 shows the change in the value of D1 on an hourly basis during loop1 when using the same values of N1 and I1 that were actually applied during the 2002 *Hajj* season. This figure gives an additional insight into how traffic delay, as measured by D1, varies over time during loop1. It can be seen that the longest average one-way trip time occurred during the peak hour between 1 AM and 2 AM. At that time, many of the main buses of loop2 were released to carry pilgrims from *Muzdalifah* to *Mina* while a significant number of loop1 buses were still transporting pilgrims from *Arafat* to *Muzdalifah.*

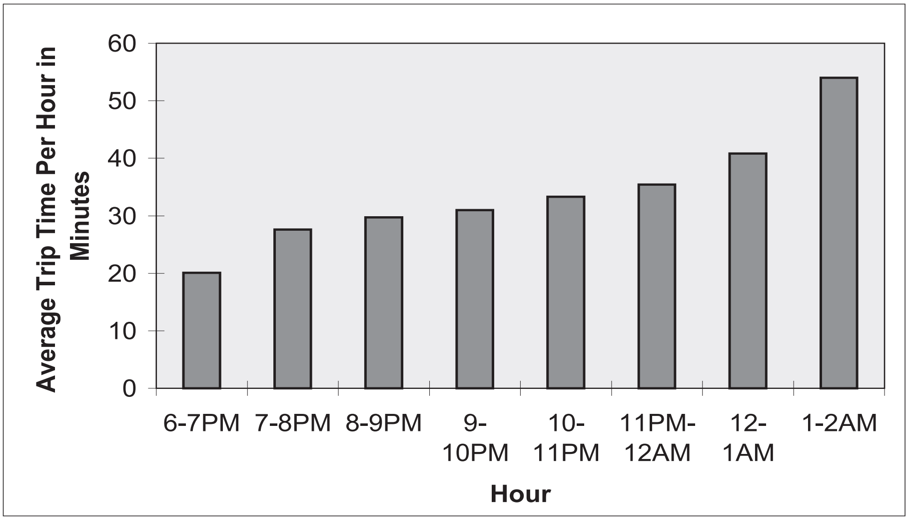

Fig. 8. The hourly variation of the average one-way trip time during loop1.

Finally, Fig. 9 shows the relationship between the average number of rounds executed by each bus R1 and the number of main buses N1. A decrease in R1 is observed from 7.5 rounds to about 4.7 rounds per bus on the average as N1 is increased from 400 to 608 buses. This observation suggests that more than one driver may be used for each bus to overcome the expected problem of high number of average rounds per bus if a decision is made to reduce the number of buses used in loop1.

6.2 *Loop2: Muzdalifah-Mina*

Figure 10 illustrates the relationship between the time needed to evacuate *Muzdalifah* from pilgrims E2 and the number of shuttle buses used N2. It can be seen that there exists a value of N2 below which E2 increases rapidly up to 10.3 hours, since there will not be enough seating capacity to transport the remaining pilgrims from *Muzdalifah* to *Mina.* On the other hand, E2 shows a slow increase for values of N2 greater than 297 buses. At such high values of N2, the exces-

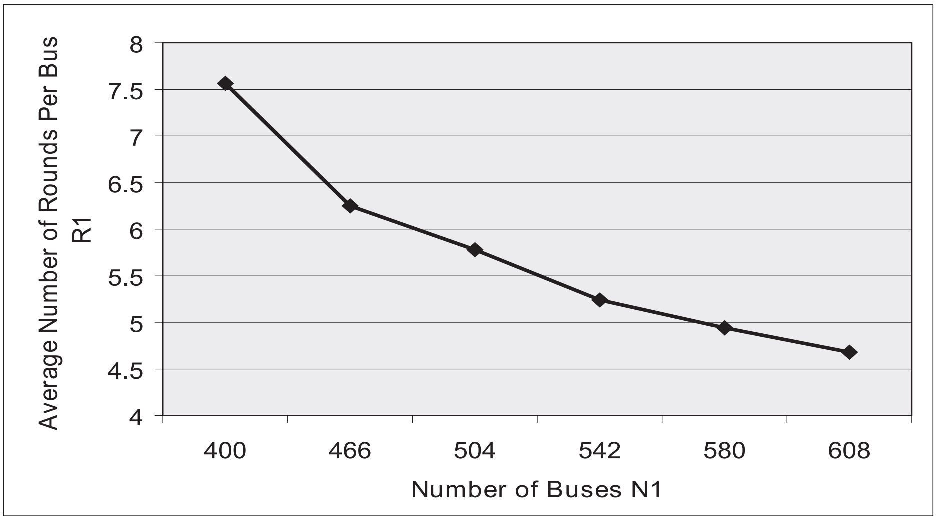

Fig. 9. The relationship between the average number of rounds per bus and the number of buses used in loop1.

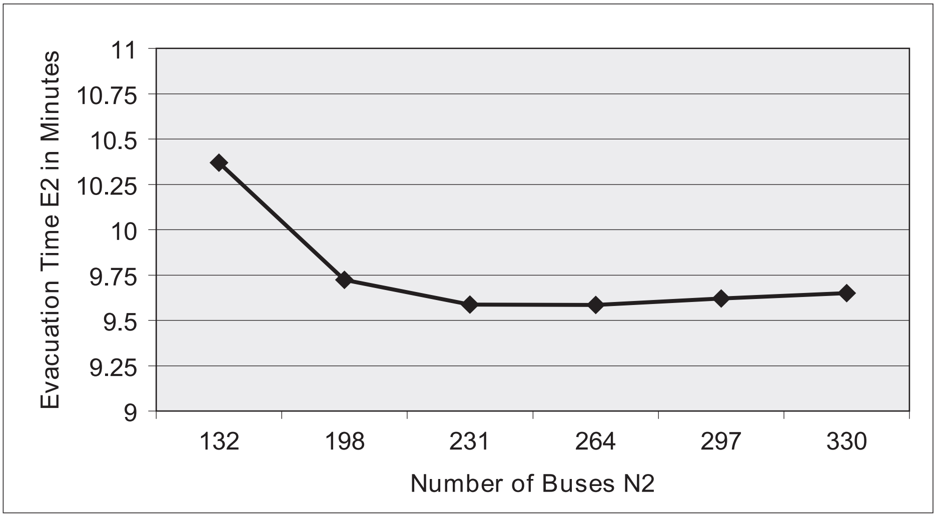

Fig. 10. The relationship between the time needed to evacuate *Muzdalifah* and the number of buses used in loop2.

sive traffic delays resulting from the road-capacity overload start to affect the time needed to transport the required number of pilgrims from *Muzdalifah* to *Mina.* Figure 11 shows the relationship between the average duration of the one-way trip D2 and the number of main shuttle buses N2. This figure shows

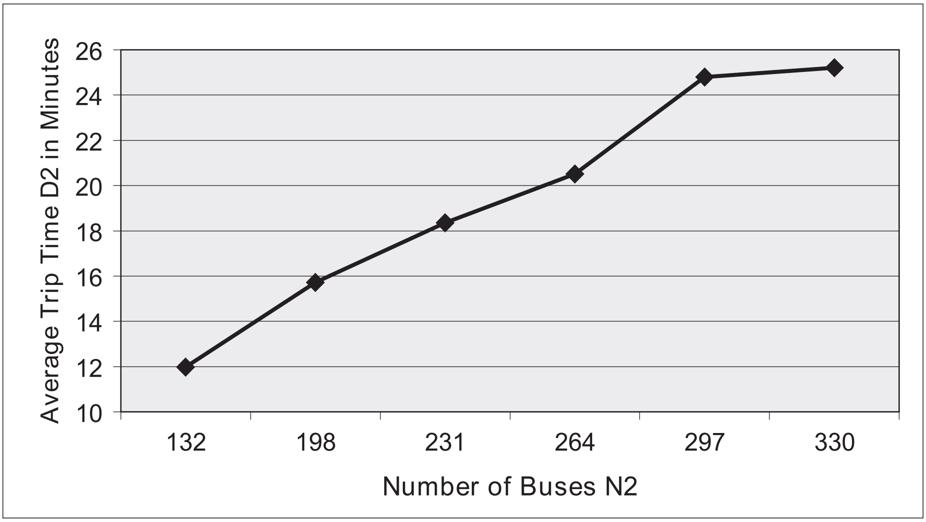

Fig. 11. The relationship between the average one-way trip time and the number of buses used in loop2.

that D2 will increase almost linearly with increasing N2 in loop2, due to the small road capacity between *Muzdalifah* and *Mina* and pedestrian problem. Since decreasing N2 from 297 to about 231 buses was seen from Fig. 10 to have no effect on the evacuation time E2, it can be concluded that N2 may be safely reduced to figures around 230 buses in order to relieve the road from excessive congestion, which would result in reducing the average one-way trip time D2.

Figure 12 illustrates the relationship between the time needed to evacuate *Muzdalifah* from all pilgrims E2 and the average inter-dispatching times of shuttle-bus caravans I2, whereas Fig. 13 shows the relationship between the average duration of the one-way trip D2 in loop2 and the average inter-dispatching times of shuttle-bus caravans I2. Note that I2 here is an ordered pair ($I2_1$, $I2_2$), where $I2_1$ is the inter-dispatching time for midnight caravans whereas $I2_2$ is the inter-dispatching time for the 3 AM caravans. It can be concluded from these two figures that the average inter-dispatching times of shuttle-bus caravans have almost no effect on the E2 and D2 performance measures. However, a slight increase of about five minutes in D2 is observed when a large value (*e.g.* (35, 8) or higher) is used for I2. This increase is due to the fact that postponing the dispatching of bus caravans by long periods of time in loop2 will push the loop2 service period further into the peak-time interval of intense pedestrian activity in the *Mina* area. This will, in turn, cause the average one-way trip time D2 to increase. Figure 14 shows the change in D2 on an hourly basis during loop2 when using the same values of N2 and I2 that were actually applied during the 2002 *Hajj* season. This gives additional insight into how traffic delay, as measured by D2, varies over time during loop2. It can be seen that the longest average one-way trip time occurred between 6 AM and 7 AM when the pedestrian-crossing activity was at its peak in the *Mina* area.

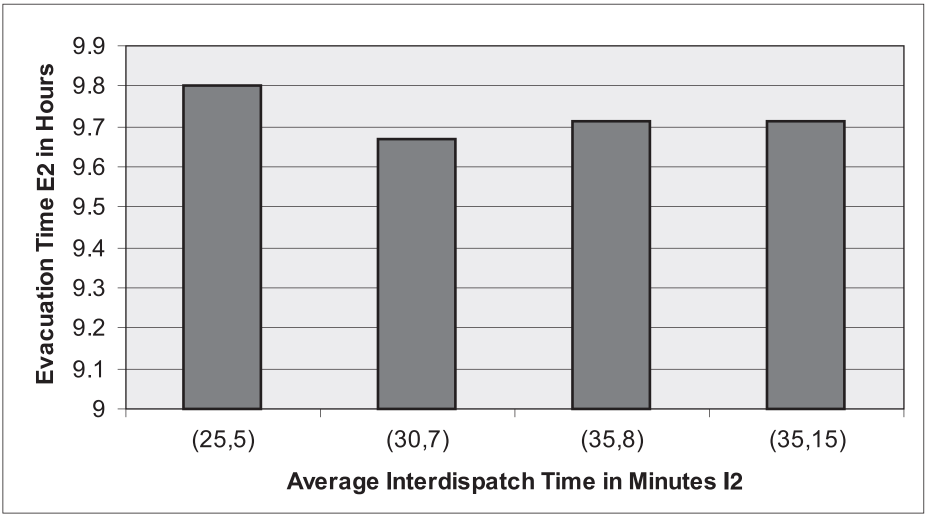

Fig. 12. The relationship between the time needed to evacuate *Muzdalifah* and the inter-dispatch time for bus caravans in loop2.

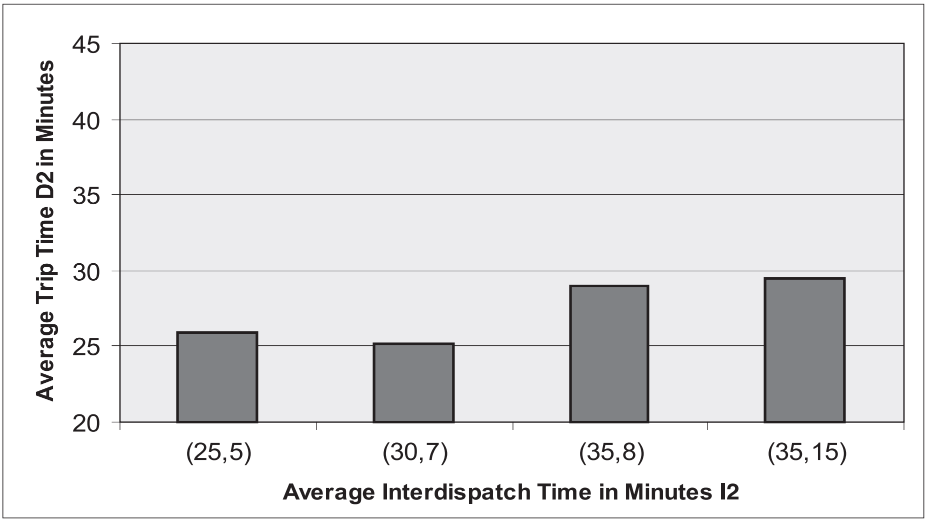

Fig. 13. The relationship between the average one-way trip time and the inter-dispatch time for bus caravans in loop2.

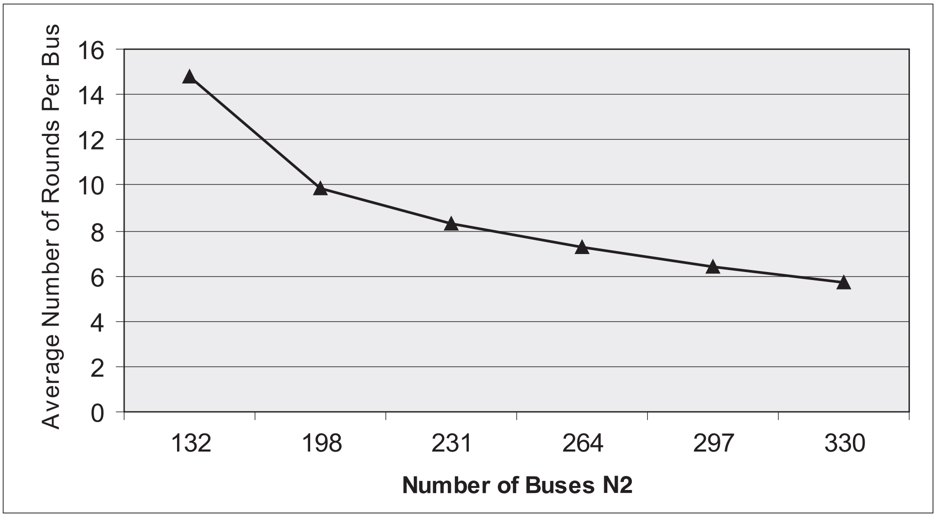

Fig. 14. The hourly variation of the average one-way trip time during loop2.

Finally, Figure 15 shows the relationship between the average number of rounds executed by each bus R2 and the number of main buses N2. As was seen in loop1, an exponential decrease in R2 from 14 rounds to about 6 rounds per bus on the average is observed as N2 is increased from 132 to 330 buses. This observation may, again, suggest that more than one driver may be used for each bus in order to overcome the expected problem of high number of average rounds per bus if a decision is made to reduce the number of main buses used in loop2. This suggestion is not expected to significantly raise the overall cost since the cost of adding an extra driver per bus is much smaller (less than 5%) than the cost of operating one bus.

7. Conclusions

Our experience indicates that the developed simulation model has succeeded in giving useful insights into the characteristics and suitable operational strategies for the shuttle-bus pilgrim transportation system of the 2002 *Hajj* season. In the experiments described in this study for loop1 of *Al-Nafrah*, simulation results suggest that in order to maintain a reasonable *Arafat* evacuation time, one should not attempt to decrease the number of buses below a limit of about 500 buses. Moreover, one should not use very small inter-dispatch times between successive bus caravans, as this may affect the system performance negatively by increasing the average one-way trip time from *Arafat* to *Muzdalifah.*

For loop2, simulation results indicate that in order to reduce the average one-way trip time from *Muzdalifah* to *Mina* without increasing the total *Muzdalifah*

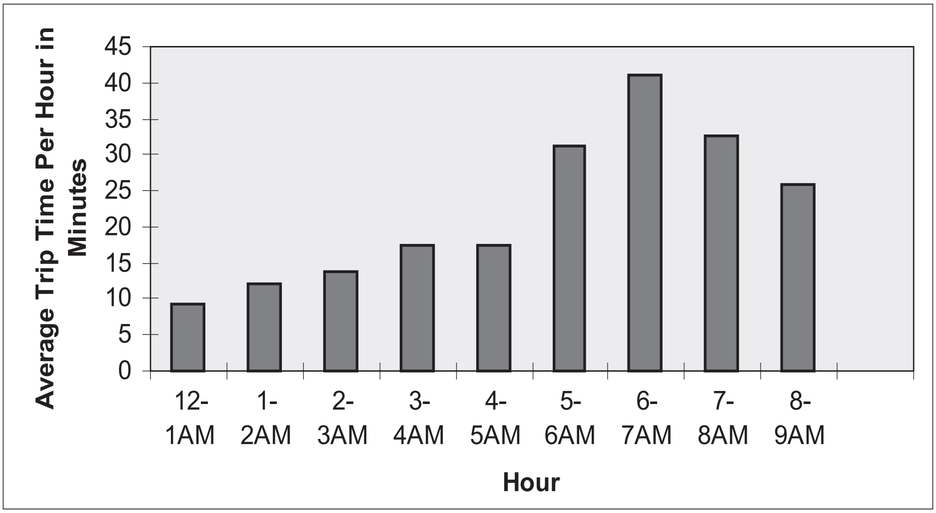

Fig. 15. The relationship between the average number of rounds per bus and the number of buses used in loop2.

evacuation time, one should reduce the number of main shuttle-buses used to the least possible value between 231 and 297. In order to accommodate the high number of average rounds per bus expected when the number of shuttle-buses is reduced, it is suggested that two drivers per bus be used on a time-shift basis. Moreover, one should not use large inter-dispatch times between successive bus caravans as this may affect the system performance negatively by increasing the average one-way trip time from *Muzdalifah* to *Mina.* As an example, a reduction in the number of main shuttle buses in loop2 from 356 buses (the number used in the 2002 *Hajj* season) to 224 buses is expected to result in a reduction in the average one-way trip time from *Muzdalifah* to *Mina* by about 10 minutes and in an increase in the average number of rounds per bus to 8 rounds, without any noticeable increase in the total *Muzdalifah* evacuation time.

Acknowledgments

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References

[1] **Al-Baar, O.F.,** Future of Transportation between the Holy Sites: Transportation Using Shuttle Buses (In Arabic), *Technical Report, CTHM Hajj Research Institute, Um Al-Qurah* University, Makkah, Saudi Arabia (1999).

[2] **Abdul-Majeed, A.T.,** Evaluating Vehicle Movement During Nafrah to Muzdalifah – *Hajj* 1412H (In Arabic), *Technical Report, Research Center for Applied and Engineering Sciences*, Um Al-Qurah University, Makkah, Saudi Arabia (1992).

[3] **Abdul-Majeed, A.T.** and **Burhameen, S.Y.,** *Evaluating Vehicle Movement During Nafrah to Muzdalifah – Hajj 1413H* (In Arabic), Technical Report, Hajj Research Center, Um Al-Qurah University, Makkah, Saudi Arabia (1993).

[4] **Bafaqeeh, R., Tanir, A.** and **Mufti, R.,** *Shuttle Bus System to Transport Pilgrims from Arafat to Muzdalifah* (In Arabic), Technical Report, Ministry of Transportation, Riyadh, Saudi Arabia (1992).

[5] **Othman, F.,** *Bus Transportation System between Hajj Ritual Sites through a Closed Loop and Its Integration with Pedestrians* (In Arabic), Technical Report, Ministry of Transportation, Riyadh, Saudi Arabia (1993).

[6] **Hariri, M. *et. al.*,** *A Feasibility Study of Using Shuttle Buses as a Transportation System between the Holy Sites* (In Arabic). Technical Report, Hajj Research Center, Um Al-Qurah University, Makkah, Saudi Arabia (1996).

[7] **Andijani, A.A. *et. Al.*,** Simulation Model of Bus Movement During Al-Nafrah (In Arabic), *Proceedings of the Second Annual Haj Research Forum*, CTHM *Hajj* Research Institute, Um Al-Qura University, Makkah, Saudi Arabia (2002).

[8] **Andijani, A.A., Duffuaa, S.O.** and **Seliaman, M.E.,** The Use of Shuttle Bus in *Hajj* to Transport Pilgrims: A Simulation Study, *Proceedings of the Seventh ISSAT International Conference on Reliability and Quality in Design*, International Society for Science and Technology (ISSAT), Washington, D.C., USA (2001).

[9] **Ministry of Hajj,** *The South-East Asian Shuttle-Trip Pilgrim Transportation Project* (Arabic Preliminary Report), Dar Al-Handasah Design and Technical Consultants, Saudi Arabia (2000).

[10] **Al-Sabban, S.A.** and **Al-Qurashi, T.K.,** A Study of the South-East Asian Shuttle-Trip Pilgrim Transportation Project (In Arabic), *Proceedings of the Transportation in Haj Symposium*, The Research & Studies Centre, King Fahad Security College, Riyadh, Saudi Arabia (2001).

[11] **Kelton, W.D., Sadowski, R.P.** and **Sadowski, D.A.,** *Simulation with Arena*, McGraw-Hill, Singapore (2002).

[12] **Ramadan, H.M.** and **Abduh, O.I.,** Applications of Computer Simulation in Evaluating the Feasibility of Intiating New Transportation Patterns Between the Holy Sites (In Arabic), *Proceedings of the Second Annual Hajj Research Forum*, CTHM *Hajj* Research Institute, Um Al-Qura University, Makkah, Saudi Arabia (2002).

[13] **Ramadan, H.M.** and **Abduh, O.I.,** Evaluating the Feasibility of Extending the Shuttle-Bus Pilgrim Transportation System During *Nafrah* Using Computer Simulation (In Arabic), *Proceedings of the Transportation in Hajj Symposium*, The Research & Studies Centre, King Fahad Security College, Riyadh, Saudi Arabia (2001).

[14] **Coordinating Council for Transportation with Shuttle Trips (CCTST),** *Ministry of Hajj. Bus Operational Plan for the Pilgrims of Turkey and the Muslims of America, Europe, and Australia Using Shuttle Trips for the 2002 (1422H) Hajj Season* (In Arabic), Ministry of *Hajj*, Makkah, Saudi Arabia (2002).

[15] **Law, A.M.** and **Kelton, W.D.,** *Simulation Modeling and Analysis*, McGraw-Hill, Singapore (2000).

دراسة محاكاة لنظام النقل الترددي للحجاج بين المشاعر المقدسة في موسم حج ١٤٢٢هـ

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شؤون المشاريع والمشاعر المقدسة ، وزارة الحج ، مكة المكرمة

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المستخلص. يعتمد نظام النقل بالرحلات الترددية في المشاعر المقدسة في فريضة الحج الإسلامية السنوية على استخدام مسارات مغلقة ذات اتجاهين بين المشاعر المقدسة من عرفات إلى مزدلفة في المرحلة الأولى، ومن مزدلفة إلى منى في المرحلة الثانية. وقد تم استخدام حافلات الرحلات الترددية بنجاح خلال السنوات السبع الماضية لنقل فئة من الحجاج تفوق ١٦٠,٠٠٠ حاج من مجموع حوالي مليوني حاج في الموسم الواحد. وقد شاءت وزارة الحج بالمملكة العربية السعودية من خلال هذه الدراسة بمراجعة الخبرات المكتسبة من هذا المشروع وفهم المحددات والعوامل المرتبطة به. وتقدم هذه الورقة وصفا لنظام النقل بالرحلات الترددية لموسم حج ١٤٢٢هـ (٢٠٠٢م)، إضافة إلى تصميم نموذج محاكاة حاسوبي تم برمجته باستخدام نظام المحاكاة (أرينا)، مع استخدام نموذج المحاكاة لإجراء سلسلة من التجارب المصممة بهدف تحقيق فهم أفضل لتفاصيل النظام ومحدداته .ومن المتوقع أن يساهم هذا الفهم في تحقيق تشغيل أكثر كفاءة لهذا النظام والتخطيط الأفضل للتوسعات المستقبلية لمشروع النقل الترددي.