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.

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\cite{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\cite{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\cite{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\cite{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\cite{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\cite{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
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

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

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

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.
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 deployed 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.

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

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.

<table>
<thead>
<tr>
<th>Performance measure variable</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>Time needed to evacuate Arafat from all pilgrims in loop1</td>
<td>hours</td>
</tr>
<tr>
<td>E2</td>
<td>Time needed to evacuate Muzdalifah from all pilgrims in loop2</td>
<td>hours</td>
</tr>
<tr>
<td>D1</td>
<td>Duration of the one-way trip in loop1</td>
<td>minutes</td>
</tr>
<tr>
<td>D2</td>
<td>Duration of the one-way trip in loop2</td>
<td>minutes</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>E1</th>
<th>E2</th>
<th>D1</th>
<th>D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real system</td>
<td>8.25 h</td>
<td>10 h</td>
<td>33.1 min</td>
<td>18.8 min</td>
</tr>
<tr>
<td>Simulation model</td>
<td>8 h</td>
<td>9.7 h</td>
<td>34 min</td>
<td>17 min</td>
</tr>
<tr>
<td>Percentage difference</td>
<td>–3%</td>
<td>–3%</td>
<td>3%</td>
<td>–9%</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Decision variable</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>The number of main shuttle buses used to transport pilgrims from Arafat to Muzdalifah in loop1</td>
<td>Buses</td>
</tr>
<tr>
<td>N2</td>
<td>The number of main shuttle buses used to transport pilgrims from Muzdalifah to Mina in loop2</td>
<td>Buses</td>
</tr>
<tr>
<td>I1</td>
<td>The average inter-dispatching time of shuttle bus caravans in loop1</td>
<td>Minutes</td>
</tr>
<tr>
<td>I2</td>
<td>The average inter-dispatching time of shuttle bus caravans in loop2</td>
<td>Minutes</td>
</tr>
</tbody>
</table>

Table 5. Output quantities of interest.

<table>
<thead>
<tr>
<th>Output quantity</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>The average number of rounds made by the main shuttle buses in loop1</td>
<td>Round</td>
</tr>
<tr>
<td>R2</td>
<td>The average number of rounds made by the main shuttle buses in loop2</td>
<td>Round</td>
</tr>
</tbody>
</table>

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 $E_1$ 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 \textit{D1} and the number of main shuttle-buses \textit{N1}. This figure shows that raising the number of buses from about 400 to 608 buses leads to a steady increase in \textit{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.](image)

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

![Average Trip Time Per Hour in Minutes](image)

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-
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...
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

![Figure 11. The relationship between the average one-way trip time and the number of buses used in loop2.](image)
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.
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
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.

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References


دراسة محاكاة لنظام النقل التردد للحجاج بين المشاعر المقدسة
في موسم حج ۱۴۲۲ هـ

سهل عبد الله سرور الصبان و حسام محمد رمضان
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 100,000 حاج من مجموع حوالي مليوني حاج في الموسم الواحد. وقد شاءت وزارة الحج بالمملكة العربية السعودية من خلال هذه الدراسة مراجعة الخبرات المكتسبة من هذا المشروع وفهم المحددات والمعايير المرتبطة به. وتقدم هذه الورقة وصفي لنظام النقل بالرحلات الترددية لموسم حج ۱۴۲۲ هـ (2022م). إضافة إلى تصميم موزع حمائية حاسوبي تم برمجته باستخدام نظام المحاكاة (أرنا)، مع استخدام موزع الحمائية لإجراء سلسلة من التجارب المصممة بهدف تحقيق فهم أفضل لتفاصيل النظام ومحدوداته. ومن المتوقع أن يساهم هذا الفهم في تحقيق تشكيل أكثر كفاءة لهذا النظام والتخطيط الأفضل للتوسعات المستقبلية لمشروع النقل التردد.

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