Analyzing the Effect of Driving Speed on the Performance of Roundabouts

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Abstract: *Roundabouts are introduced at intersections to improve traffic flow and enhance safety. Nevertheless, studies and field observations demonstrated that roundabouts, due to their special design, could significantly affect the efficiency of the overall traffic network, especially in the case of increased traffic volumes. For this reason, researchers and practitioners have conducted several studies to alleviate the negative impact of saturated traffic. In these studies, different characteristics of traffic flow and roundabout topologies are analyzed to show their impact on the overall performance. In this paper, we present two simulation studies to investigate the effect of driving speed on the performance of roundabouts with different geometrical characteristics. The results from the two case studies indicate that speed control and the distribution of traffic volumes on the arms of the roundabout are two important factors that affect the performance of roundabouts. Moreover, the results also show that the driving speed factor correlates with roundabouts' geometrical characteristics. Further, the individual driving behavior plays a major role in the performance of roundabouts.*

Keywords: *Roundabout, traffic simulation, congestion.*

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1. Introduction

The number of vehicles on road stretches and highways is continually increasing, reaching a limit that surpasses available road capacities. Such increase in the number of vehicles deployed results in severe congestion problems and violates other safety protocols. Furthermore, it creates increased conflicting traffic at intersections, which complicates the traffic issue still further.

Roundabouts are introduced at intersections to improve traffic safety and efficiency [11]. A roundabout is a type of intersection where traffic flows in one direction around a central island. The flow priority is given to the vehicles within the roundabout. However, traffic congestion at roundabouts is becoming a troubling issue that traffic engineers must address rather more seriously. Several factors were shown to affect the performance of roundabouts that include their geometrical features and driving behavior and the speeds involved.

Over the past few years, several studies were conducted to evaluate the performance and capacity of roundabouts using different metrics such as the radius of the roundabout, traffic volumes, and traffic flow rates [7, 8, 21]. The findings of these studies suggest that the

Performance of roundabouts is greatly affected by their geometrical design and citizens driving styles. On the Other hand, other studies have tried to compare the performance of intersections using roundabouts and traffic lights [6, 23]. According to the results of these studies, traffic volume plays a significant role in determining which type of intersection outperforms the other. Furthermore, researchers and practitioners have commonly investigated several techniques that employ traffic lights [10, 22] and coordinated driving behavior

[12] to improve the performance of roundabouts. Despite the promising results of these studies, none of them has, in fact, investigated the effect of speed control on the performance of roundabouts.

According to the Federal Highway Administration (FHWA), optimization of roundabouts design depends on operational speed [16], which is the driving speed for most vehicles through the roundabout. Several studies have been conducted to investigate the relationship between the average driving speed and the geometrical characteristics of roundabouts [1, 5, 15]. Other studies have compared the actual measured speeds on roundabouts and the design speeds [13, 14, 19]. Nevertheless, these studies aimed to investigate the effect of roundabouts geometry on the speed of traffic at roundabouts.

In this paper, we investigate the effect of speed control at congested arms on the capacity of roundabouts. To this effect, we have designed a simulation study using the microscopic traffic simulator, Simulation of Urban Mobility (SUMO) [9]. SUMO is an open-source microscopic traffic simulation suite that has been used to simulate a variety of traffic scenarios such as vehicular communication, traffic light control techniques, and traffic demand modeling, among others. In this work, we used SUMO to design and execute traffic scenarios for a roundabout with four arms (see Figure 1.) Traffic volume on arms of the roundabout and speed limits are changed to evaluate the effect of speed control on the performance of a roundabout. This paper is a revised and expanded version of a paper entitled 'Simulation study of speed control at congested arms of roundabouts' presented at the 22nd International Arab Conference on Information Technology (ACIT), Muscat, Oman. December 2021, pp. 1-5 [17].

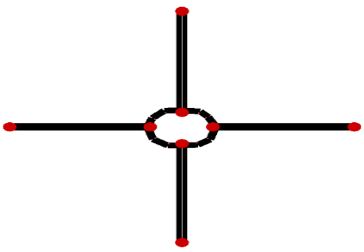

Figure 1. A roundabout in SUMO with four arms.

2. Research Method

To evaluate the effect of driving speed on the performance of roundabouts, we conducted two case studies using SUMO. We used a roundabout with four arms that connect four incoming and four outgoing flow directions for both scenarios. In this work, we used Net edit 1.9.2 to create the traffic network with its routes.

2.1. The First Case Study

In the first case study, we used a simplified version of the roundabout where all arms are assumed to have two lanes. Also, we performed two simulation scenarios. In the first scenario, the right arm has 40% of the traffic, while the other 60% is equally distributed across the three other arms. In the second scenario, 60% of the traffic is distributed equally on the left and right arms, while the remaining 40% are distributed evenly on the top and bottom arms (See Figure 2). To define these scenarios in SUMO, we used the file "randomTrips.py" provided in the SUMO installation.

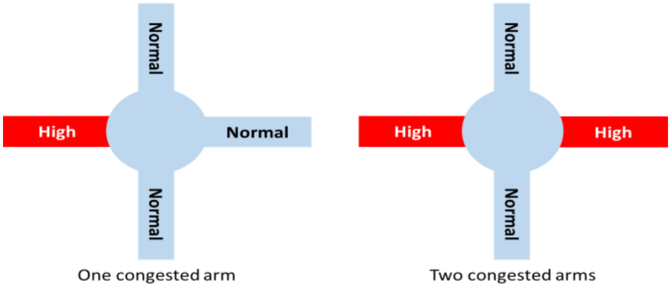

Figure 2. Network topologies of the two simulated scenarios.

For both simulation scenarios, we executed the simulation schema ten times using 1000 vehicles, and we recorded the following properties:

- Total travel time: The average total time vehicles spend to reach their destinations (measured in seconds).
- Waiting time: The average time in which the vehicles' speeds were below or equal 0.1 meter/second (scheduled stops do not count)
- Time loss: The average time lost by vehicles due to driving below their ideal speeds.

An ideal speed in SUMO is defined by an individual speed factor, which is drawn from a speed distribution at the start of the simulation. Table 1 illustrates the simulation parameters we used in our experiments, where:

- vType: refers to the type of vehicle used in the simulation.
- Length: is the length of vehicle type in meters.
- Max speed: is the maximum speed of the simulated vehicles (measured in meters/second)
- Minimum Gap: is the minimum gap distance between any two consecutive vehicles in the simulation
- Car following model: refers to a vehicle's choice of acceleration or deceleration according to the positions and velocities of its neighboring vehicles
- Maximum Acceleration: is the acceleration ability of the simulated vehicles (measured in meters/second2)
- Minimum Deceleration: is the deceleration ability of vehicles (measured in meters/second2)
- tau: is the driver's reaction time (measured in seconds)

Here, it is worthy of noting that SUMO does not include models of pedestrians. Hence, we cannot assess the effect of crossing pedestrians on the overall performance of a roundabout.

Table 1. Simulation parametrs of the first case study.

Traffic Simulation Parameters	
Simulation Parameter	***Value***
vType	Car
Length (meter)	5
Max Speed (meter/second)	30
Minimum Gap (meter)	2.5
Car Following Model	Krauss
Maximum Acceleration (m/s^2)	1.5
Minimum Deceleration (m/s^2)	4.5
tau	1

2.2. The Second Case Study

In the second case study, we set up a traffic network that consists of a single roundabout, and we run the simulation using the following parameters:

- The number of lanes: In this case study, we defined roundabouts with 2, 3, and 4 lanes.
- The radius of the roundabout: We defined roundabouts with three different sizes: small, medium, and large.
- Traffic speed: In this study, we executed the simulation using three different driving speed profiles: low-speed (max speed is 15 m/s), medium-speed (max speed is 30 m/s), and high-speed (max speed is 45 m/s).
- The number of slow vehicles: we inject the traffic volume with slow driving vehicles in this study. By slow vehicles, we mean vehicles that drive at a maximum speed that equals half of the normal speed. For example, in the case of medium-speed traffic, where vehicles drive at a maximum speed of 30 m/s, low-speed vehicles drive at a maximum speed of 15 m/s. In this study, we run the simulation using 0, 10, 20, 30, and 40 low-speed vehicles for all simulation settings. Here, it is important to note that we set the maximum number of slow vehicles to 40, which is equivalent to 4% of the total traffic volume. The small percentage is meant not to affect the average travel time significantly.

We executed the simulation schema ten times using 1000 vehicles for all simulation scenarios. We recorded the total travel time, which is the average time vehicles spend to reach their destinations (measured in seconds). For all simulation runs, we used the simulation parameters given in Table 2.

Table 2. Simulation parametrs of the second case study.

Traffic Simulation Parameters	
Simulation Parameter	***Value***
vType	Car
Length (meter)	5
Minimum Gap (meter)	2.5
Car Following Model	Krauss
Maximum Acceleration (m/s^2)	1.5
Minimum Deceleration (m/s^2)	4.5
tau	1

3. Simulation Results of The First Case Study

3.1. Total Travel Time

Figures 3 and 4 give the Total travel time for the one and two congested arms, respectively. As shown in Figures 3, 4. The total travel time decreases as the speed factor increases at the congested arms. This is to be expected as the increased speed for part of the traffic minimizes the travel time. Nevertheless, the decrement becomes marginal in the case of 125% and 150% speed factors, especially in the case of the two congested arms. For instance, Figure 3 shows that the total travel time in the case of the one congested arm decreases by 10% after increasing the speed factor on the congested arm from 100% to 125%. However, in the case of increasing the speed factor from 125% to 150%, the total travel time decreases by 2.8%. In the case of the two congested arms, increasing the speed factor from 100% to 125% reduces the travel time by 3.8%, while incrementing the speed factor from 125% to 150% lowers the travel time by 1.3%.

In general, the results given in Figures 3 and 4 show that increasing the speed on congested arms of the roundabout can minimize the total travel time. However, after a certain threshold, the improvement becomes marginal. As more arms become crowded, the increment threshold becomes smaller.

The results given in Figures 3 and 4 also show that for the same traffic volume, i.e., 1000 vehicles, the total travel times in the case of the one congested arm are lower than that for the case of the two congested arms for all of the simulated speed factors. This observation leads us to conclude that traffic volumes on the arms of roundabouts are an essential factor that must be considered in designing adaptable plans for improving the efficiency of roundabouts.

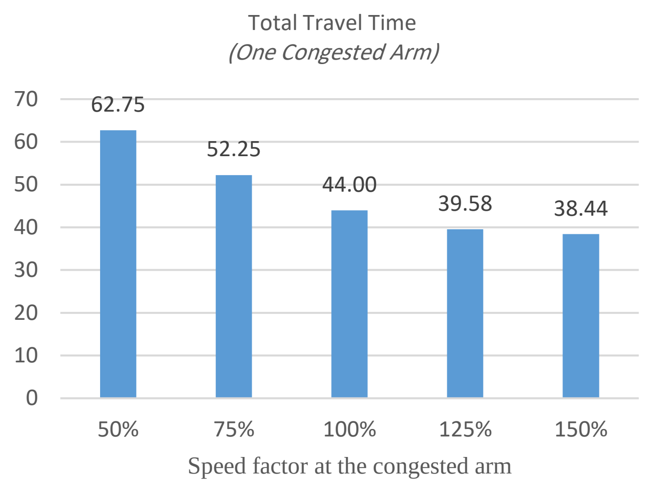

Figure 3. Total travel time-one congested arm.

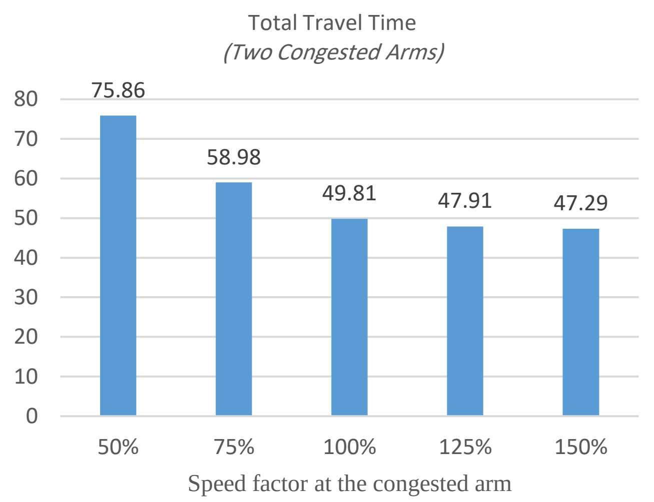

Figure 4. Total travel time-two congested arms.

3.2. Waiting Time

The waiting times for the cases of the one and the two congested arms are given in Figures 5 and 6 respectively. As was the situation in the case of the total travel time, an increase in the speed factor minimizes the average waiting time of vehicles. Furthermore, the decrement in the waiting time becomes marginal after reaching a certain threshold. For example, Figure 5 shows that the total waiting time in the case of a speed factor of 100% is equal to 10.18 seconds. When the speed factor on the congested arm is increased to 125%, the waiting time drops by 24.6% and becomes 7.67 seconds. However, when the speed factor is incremented by 150%, the waiting time decreases by only 1.8% and becomes 7.53 seconds.

On the other hand, in the case of the two congested arms (see Figure 6), the waiting time with a speed factor of 100% is 11.67 seconds. After incrementing the speed factor to 125%, the waiting time drops by 7.1% to become 10.89 seconds. Nevertheless, to the contrary of total travel time, after incrementing the speed factor on the two congested arms to 150%, the waiting time increases by 5.2% to become 11.46 seconds. This is explained by the fact that the increment in the speed factor on the two congested arms results in a larger volume of conflicting traffic at the roundabout. In this case, the conflicting vehicles must yield to other vehicles inside the roundabout before they would resume the trips to their destinations.

The results given in Figures 5 and 6 also show that the average waiting times in the case of the one congested arm are less than the average waiting times in the case of the two congested arms for all the simulated speed factors. The results also indicate that the difference between the waiting times in the cases of the one and the two congested arms becomes larger as the speed factor increases. For instance, in the case of a speed factor of 100%, the waiting time in the case of the one congested arm is less than that for the case of the two congested arms by 1.49 seconds. However, the difference becomes 3.22 and 3.93 seconds in the cases of speed factors of 125% and 150%, respectively.

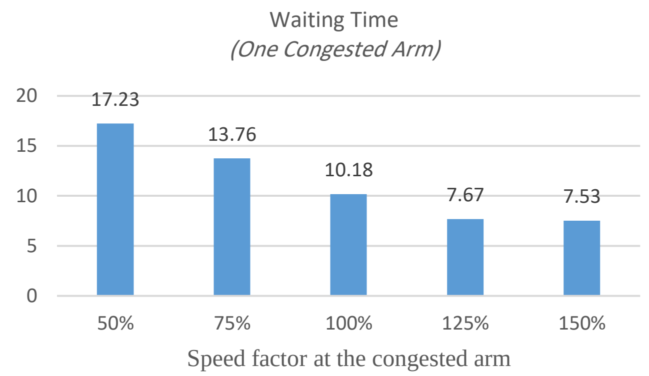

Figure 5. Waiting time-One congested arm.

3.3. Time Loss

The average time losses in the case of the one congested arm and the two congested arms are captured in Figures 7 and 8. In conformance with the total travel time and waiting time results, increasing the speed factor minimizes the travel time loss. Moreover, after raising the speed factor above a certain threshold, any improvement in time loss becomes marginal. For example, Figure 7 shows that the time loss drops by 9.6% and becomes 30.63 seconds after increasing the speed factor to 125%. However, the time loss drops by only 1.3% and becomes 30.22 seconds after incrementing the speed factor to 150%.

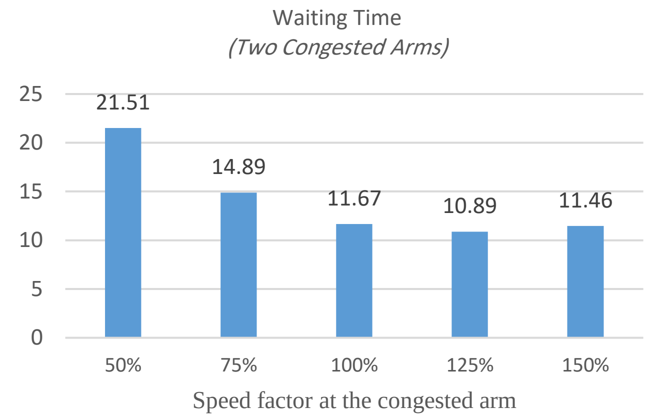

Figure 6. Waiting time-Two congested arms.

On the other hand, in the case of the two congested arms see Figure 8, increasing the speed factor on the two congested arms to 125% decreases the time loss by only 0.5% to become 39.46. Nevertheless, in the case of increasing the speed factor to 150%, the time loss rises by 1.1% and becomes 39.9 seconds. In this case, an increase in time loss comes in accordance with an increase in the waiting time for the same simulation scenario See Figure 6.

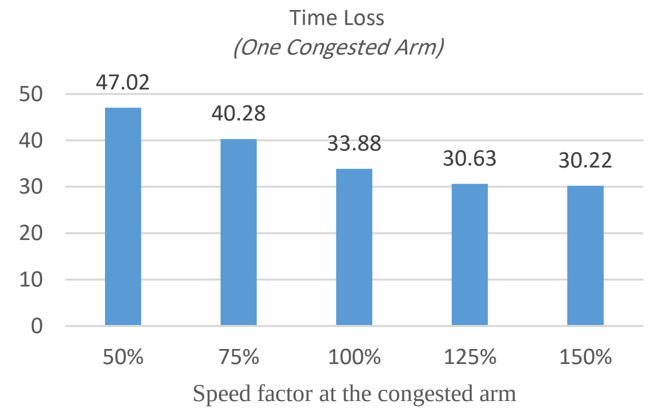

Figure 7. Time loss-One congested arm.

As in the cases of the total travel and waiting times, the results given in Figures 7 and 8 show that time lost in the case of the one congested arm is less than that for the lost time in the case of the two congested arms for all values of the simulated speed factors. This observation fosters our previous finding that the distribution of traffic volumes on the arms of a roundabout is a major factor affecting its performance.

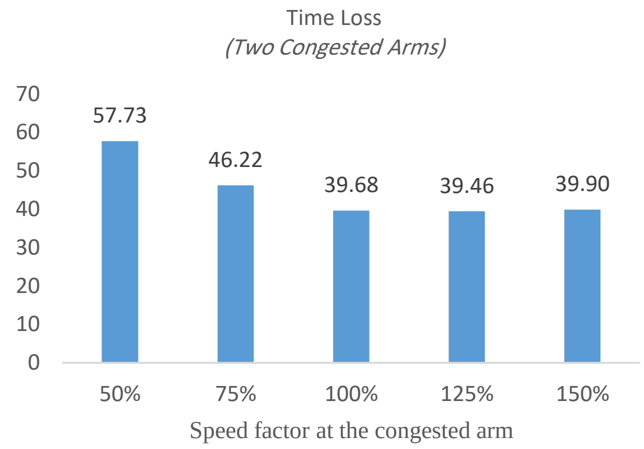

Figure 8. Time loss-Two congested arms.

4. Simulation Results of the Second Case Study

Figures 9, 10 and 11 show the average total travel time for all simulation settings used in the second case study. In this Figure, the black lines represent the two-lane roundabout, the red lines represent the three-lane roundabout, and the blue lines represent the four-lane roundabout. On the other hand, the dotted lines represent small roundabouts, solid lines represent medium-sized roundabouts, and dashed lines represent large roundabouts.

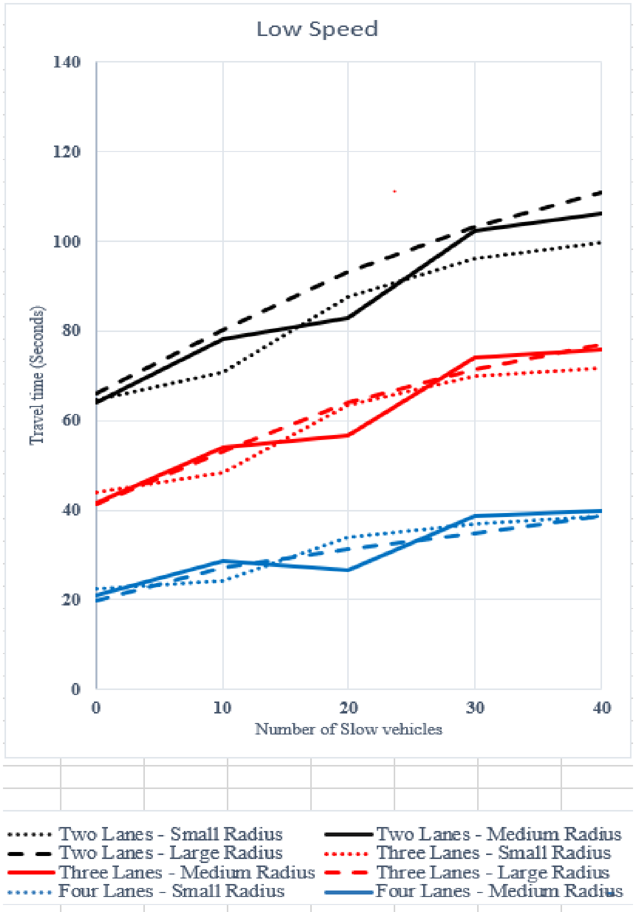

Figure 9. Average Taravel Time- Low speed setting.

4.1. The Effect of Drinig Speel

Figures 9, 10 and 11 also show that the travel time decreases for all simulation settings as the speed increases. For instance, in the case of simulating vehicles driving at low speed on a medium-size two-lane roundabout and without having slow vehicles (See Figure 9), the average travel time was approximately 66 seconds. Using the same settings but with vehicles driving at a medium speed, the average travel time drops to 47 seconds (See Figure 10). However, when using the same simulation settings but with vehicles driving at a higher speed, the travel time drops to 43 seconds (See Figure 11). The same observation applies to other simulation settings used in this case study.

As can be noticed, the results obtained by this experiment align with the results from the first case study, which suggests that increasing the speed above a certain threshold will not help improve the performance of roundabouts. The increased vehicle speed results in a larger traffic volume that drives on the roundabout within the same period. Hence, there is a higher probability of conflicting traffic. Consequently, there is a delay in the flow within the roundabout that affects the performance of the traffic network.

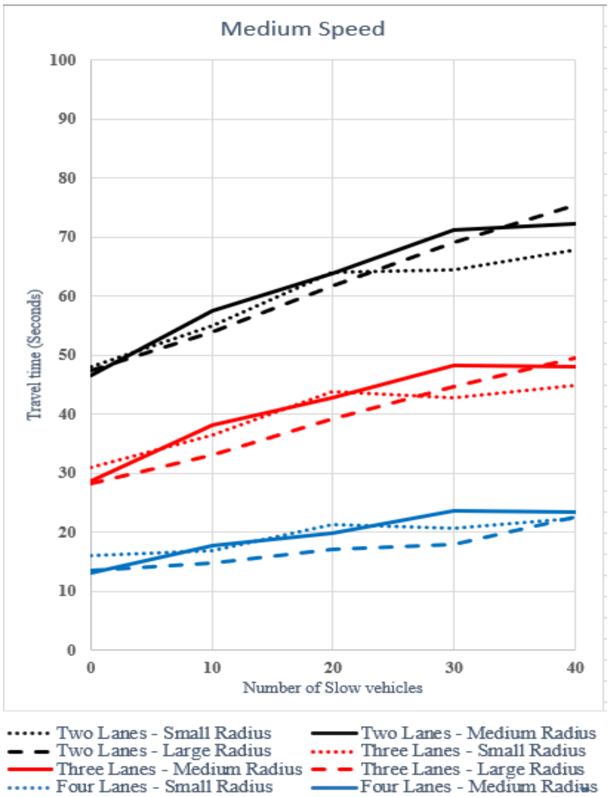

Figure 10. Average taravel time -medium speed setting.

Slow driving vehicles have a negative impact on the traffic flow in general. The results from the second case study clearly illustrate this impact. For example, the average travel time for vehicles driving at medium speed on a three-lane medium-sized roundabout and without having slow vehicles, the average travel time was approximately 29 seconds. However, the average time increases to around 38 seconds when having 10 slow vehicles and 47 seconds when having 40 slow vehicles see Figure 10.

This study also shows that the effect of slow vehicles becomes less evident with the additional number of lanes. For instance, the results in Figure 10 show that in the case of medium-speed vehicles and medium-sized roundabouts, the average travel time in the case of a two-lane roundabout increases from 47 seconds with no slow vehicles to 72 seconds with 40 slow vehicles. On the other hand, in the case of a four-lane roundabout, the average time increases from 12 seconds with no slow vehicles to 21 seconds with 40 slow vehicles. From these results, we can notice that the additional number of lanes helps in alleviating the effect of slow vehicles and improve the traffic flow as the fast vehicles can bypass the slow vehicles more easily.

4.2. the Effect of the Traffic Network Topology

The results presented in Figures 9, 10 and 11 show that the average travel time decreases for all simulation settings as the number of lanes increases. This decrement is expected as the additional number of lanes provides an extra road capacity that minimizes traffic congestion and improves traffic flow.

The results also show that as the size of the roundabout increases, the travel time decreases even though vehicles have to travel longer distances. This is explained by the fact that a larger roundabout size allows vehicles to drive with less opportunity to conflict with other vehicles driving on the roundabout simultaneously.

Nevertheless, smaller size roundabouts might outperform larger size roundabouts in the case of low-speed vehicles. For example, the results in Figure 9 show that the travel time in the two-lane small size roundabout (the dotted black line) consistently outperforms the travel time of the large size roundabout (the dashed black line). The results in Figure 9 also show that the three-lane small size roundabout (the dotted red line) outperforms the three-lane small size roundabout (the dashed red line) for all simulation settings. However, as the number of lanes increases, the results start to converge, and in the case of the four-lane roundabouts, the large size roundabout (the blue dashed line) starts to outperform the small size roundabout the blue dotted line.

The phenomena mentioned above can be explained by the fact that in the case of low-speed vehicles, the larger size roundabouts result in an additional number of vehicles inside the roundabout and might result in a higher probability of conflicts. Hence, the additional number of lanes helps in mitigating such conflicts and improving the overall performance.

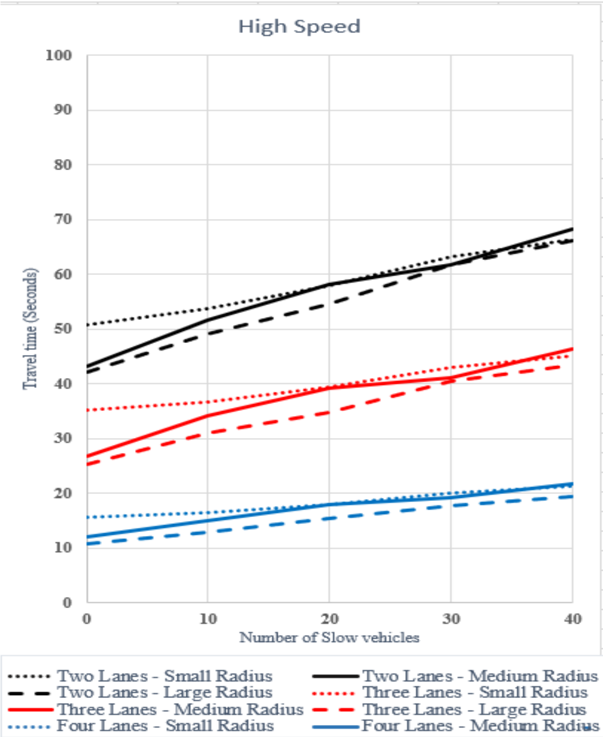

Figure 11. Average taravel time-high speed setting.

5. Conclusions and future works

In this paper, we presented two simulation studies to investigate the effect of driving speed on the performance of roundabouts under different roundabout settings. The results from the first case study indicate that increasing the speed on the roundabout's congested arms by a certain threshold helps improve the traffic flow and minimizes the travel time. Moreover, the results show that the distribution of traffic volumes on the arms of the roundabout affects its performance.

On the other hand, the results from the second case study show that the increased driving speed can improve the performance of the roundabout. Nonetheless, increasing the speed will not help after a certain speed threshold. The second study's results show that small size roundabouts can perform well in the case of low-speed traffic. However, small size roundabouts will fail to cope with larger inbound traffic volumes as the traffic speed increases. The results also show that larger size roundabouts and the extra number of lanes provide an additional road capacity that can alleviate the effect of high-speed traffic. Finally, the results indicate that the individual driving behavior plays a major role in the performance of roundabouts.

Our future work includes investigating dynamic techniques that adjust speed regulations on roads to adapt to the highly dynamic traffic conditions. Such techniques should take driving speed and the distribution of traffic volumes into consideration in its design. Nevertheless, evaluating these techniques requires traffic simulation tools that support the modeling and simulation of future ITS devices that can communicate with each other to implement plans at the network level, such as MATISSE [3, 20], MATSIMLab [4, 18, 20]. Several studies have employed these simulators to simulate and evaluate adaptive traffic plans used in modern smart cities [2].

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