Simulating the Effects of Type and Spacing of Traffic Calming Measures on Urban Road Capacity

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Received: 09. 10. 2016 Accepted: 24. 04. 2017

Abstract

One of the major reasons for accidents is speed. Inappropriate speed has been identified as the most important causal factor for serious traffic accidents. Traffic calming measures (TCMs) are engineering measures that are widely implemented to improve road safety by considerably reducing vehicle speed. TCMs have been widely used in urban areas to reduce vehicle flow rates and especially speed, and hence, to bring down the number and severity of traffic accidents. Despite numerous studies in literature, little attention has been paid to the effects of speed reduction using TCMs on network capacity regarding the main traffic operation parameters, including delay time, average speed of vehicles passing through the network, and vehicle fuel consumption. In response to this need, in this study drivers' behavior in the presence of TCMs, based on different types and spacing of TCMs, was investigated using Aimsun software. For this purpose, the effects of number of TCMs and their locations in the network were simulated in various scenarios and their capacity and operation performance parameters on urban roads were calculated accordingly. Consequently, according to the technical criteria, the scenarios in which the TCMs were implemented presented a better design quality. On the other hand, according to the results obtained in the different scenarios of this research, delay time and average fuel consumption of vehicles substantially increased while the average speed was reduced. It was found that TCMs have a direct effect on the network capacity and changing in the number and location of measures can change network capacity.

Keywords: Traffic simulation, traffic calming measures, safety, capacity, fuel consumption

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1. Introduction

Accidents and losses caused by them are among the current challenges of human communities, which impose considerable economic costs on countries. Speed is one of the major reasons for accidents. The effect of speed in other means of transportation like railway has been sufficiently investigated [Sadeghi and Hasheminezhad, 2013, Sadeghi, Hasheminezhad and Essmayil Kaboli, 2015]. Road traffic injuries in Iran including costs due to fatality and disability, which are related to lost social products has been investigated using an estimate based on disability-adjusted life years index [Behnood, Haddadi and Sirous, 2016]. Currently, various traffic calming methods are used to control speed and traffic volume. Traffic calming is a set of strategies used by urban planners and traffic engineers to reduce speed on urban roads. In order to improve the safety of roads, various methods of traffic calming should be used. The high volume of research on traffic calming methods underlines the importance of these methods in accident prevention, especially on urban roads. Direct outcomes include increase in traffic safety, especially for passengers and bikers. Since implementation of calming plans may change roads traffic trend, especially on local roads, calming measures and appropriate sections for their implementations must be carefully selected. In case of inappropriate implementation, problems like increased probability of accident due to the sudden speed reduction of vehicles, capacity reduction, increased fuel consumption, increased delay time, increased noise pollution due to the change in vehicle movement type, and increased vehicle wear and tear rate may occur. One of the most significant advantages of using TCMs is their effectiveness especially in reducing the speed of vehicles and increasing the probability that a vehicle will provide for pedestrians who want to cross the street. However, among the disadvantages of TCMs is that they can hinder street cleaning and snow plowing, they may also influence drainage systems of streets, and may slow the response time of emergency vehicles especially in the case of disasters like earthquakes [Stevenson et al. 2008].

2. Literature Review

Several studies have been carried out to investigate the effect of TCMs on traffic operation. Mao and Koorey investigated the effects of TCMs on traffic volume and speed on urban local streets [Mao and Koorey, 2010]. A total of 11 sites in Christchurch, each equipped with street calming devices, were evaluated using field surveys and network modelling using TrafikPlan, and the results were compared with findings from the literature. As a result, road safety noticeably improved after the installation of the traffic calming devices, with average crash reductions of 15-20%. In terms of network performance TrafikPlan modelling seems promising for estimating traffic volume and speed changes on the considered local streets and adjacent arterial roads. Seven different layouts were analysed using traffic micro simulation. Average vehicle delay on the exit path was calculated and the capacity was obtained. Capacities ranged from 1,600 to 2,000 vehicles per hour in a one-lane exit ramp. Martínez, Garcia and Moreno carried out a traffic micro simulation study to evaluate the effect of type and spacing of traffic calming devices on capacity [Martínez, Garcia and Moreno, 2011]. Capacity of a cross-town road ranged between 810 and 1,300 vehicles per hour with traffic calming devices spaced at 25-400 meters. Astarita et al. presented the calibration and validation technique of a micro simulation model for short-term road safety analysis [Astarita et al. 2012]. The developed microscopic model allows the estimation of road safety performance through a series of indicators (crash potential index, deceleration rate needed to avoid crash, maximum available deceleration rate, time to collision, etc.), representing interactions in real time between different pairs of vehicles belonging to the traffic stream. Pardon and Average assessed the effectiveness of implementing traffic calming in the Masvingo central business district and the high-density residential areas of Mucheke and Rujeko. They found that speed humps are the most preferred and widely used TCMs in Masvingo city and reduced road accidents about 70% [Pardon and Average, 2013]. Mehar, Chandra and Velmurugan provided PCU values for different types of vehicles typically found on interurban multilane highways in India at different levels of service (LOS) [Mehar, Chandra and Velmurugan, 2013]. The traffic simulation model VISSIM was used to generate the traffic flow and speed data for conditions that are difficult to obtain in field observations. Garcia et al. in their research estimated the effect of TCMs on ambulance response time for different types of services (emergency or nonemergency transfers, with or without a patient), in different traffic conditions (free flow or forced flow), and over entrance ramps with different slopes [Garcia et al. 2013]. To evaluate the impact of TCMs, the speed of ambulances in TCMs, secondary delay, and total time were calculated, compared, and evaluated. They found that response time was influenced by the presence of TCMs. Ariën et al. examined the impact of TCMs on major roads in rural and urban areas. More specifically, the effect of gate constructions located at the entrance of the urban area and horizontal curves within the urban area on driving behavior and workload was investigated [Ariën et al. 2013]. It was concluded that both curves and gate constructions can improve traffic safety. Nevertheless, the decision to implement these measures will depend on contextual factors such as whether the road has a traffic function rather than a residential one. Ziolkowski investigated the impact of TCMs on drivers' behavior in Bialystok, Poland [Ziolkowski, 2014]. The research included a group of commonly applied measures such as speed humps, speed cushions, speed cameras, raised median islands, raised pedestrian crossings, and raised intersections. Instantaneous speed, acceleration, deceleration, and route tracking data were measured for the investigation. It was found that TCMs, when applied appropriately, can be an extremely effective method of speed management, but depending on the type of measure, their influence on drivers' behavior is totally different and can cause a hazardous reaction. Recently, Juhász and Koren analysed the safety effects of traffic calming initiatives at a city level for larger Hungarian cities [Juhász and Koren, 2016]. The results indicated that traffic calming initiatives have a very significant role in enhancing road safety of urban areas.

TCMs are often implemented on urban roads in order to reduce the frequency and the severity of crashes by lowering the speed, but their effectiveness on urban road capacity has not been adequately evaluated. Review of the literature indicates that despite of various studies in the last decade; statistical values of speeds around TCMs have not been thoroughly investigated. Furthermore, effects of location and number of TCMs on capacity in terms of traffic operation parameters on urban roads have not been analysed. This research aims to respond to these needs, determine the effects of TCMs on urban roads capacity, and evaluate network traffic parameters. The main objectives of this research include observation and analysis of drivers' behavior in Hamedan Be'sat Boulevard-between Saeediye junction and Pajuhesh square-with existing TCMs using GPS trackers and calibration of microsimulation models. In addition, scenarios were applied for various traffic demands to investigate the effects of TCMs on capacity and to evaluate and compare traffic parameters such as delay time, fuel consumption, and average vehicle speed in different TCMs application conditions. To this end, AIMSUN 6.0.5 simulator software was utilized and software calibration was used to simulate various scenarios and finally traffic indices-including capacity, delay time, average speed in a network, and fuel consumption of vehicles-were analysed and discussed.

3. Methodology

3.1 Traffic Microsimulation Program

Aimsun is an integrated tool for transportation modelling applications especially 2D and 3D traffic microsimulation. Traffic network analysis using Aimsun is an appropriate method for improving road infrastructure, reducing emissions, cutting congestion, and designing urban environments for vehicles and pedestrians. Aimsun microsimulation can significantly improve the accuracy and relevance of travel-time forecasts. Because it takes the capacity of change and network effect into account, it is the only technique that can allow operators to compare the effectiveness of complex alternative traffic management strategies quickly and objectively, which can make the incident management more effective and efficient.

The aim of this study is to use a traffic microsimulation model to investigate the factors that affect TCMs operations in terms of reducing travel time in major junctions through minimizing delays and maximizing capacity. The primary objective of this study is to carry out traffic surveys at a site near a priority junction and then use the results for developing, calibrating, and validating a microsimulation model using the Aimsun software. In the current research, in order to obtain more matched results with traffic conditions and behavior of drivers default parameters used in Aimsun have been modified through field studies in Hamedan city, Iran. In addition, various scenarios were defined, and the effect of TCMs on network capacity and traffic operation parameters such as delay time, average speed, and fuel consumption of total vehicles available in the network were evaluated. Finally, the traffic indices of different simulated scenarios were compared and evaluated.

3.2 Research Area

The research area included the Hamedan Be'sat Boulevard-between Saeediye Junction and Pajuhesh Square-with an approximate length of 1,650 m. This area was one of the main and most crowded boulevards in Hamedan city and a large number of different vehicles passed through it. This area had four lanes for each traffic direction, and the opposite direction of lane was analysed(two lanes total, one travelling in one direction, and one travelling in the opposite direction). The reason was due to the fact that this direction was equipped with four types of TCMs, each of which had specific and different conditions in terms of geometry and physical features. These TCMs included speed hump with passage one-way narrowing and U-turn, Central Island in pedestrian crossing (pedestrian passage), speed hump with passage two-way narrowing (with U-turn), and speed dump. These TCMs influence the speed of vehicles passing through this area. Figure 1 gives a view of the area under study.

Figure 1. The area under study

3.3 Data Collection

In this research, data were collected using two techniques-video recording and speed recording of vehicles. First, the current status of traffic flow was recognized, and then the traffic of vehicles on entrance and exit paths of Be'sat Boulevard, at time intervals of normal traffic flow, was recorded in the presence of TCMs. Traffic flow observation and video recordings in junctions, ramps, intersections, and U-turns in time intervals are given in Table 1. Figures 2 and 3 show the camera images during video recording.

Figure 2. Camera images at the Honarestan Street and Be'sat Boulevard junction

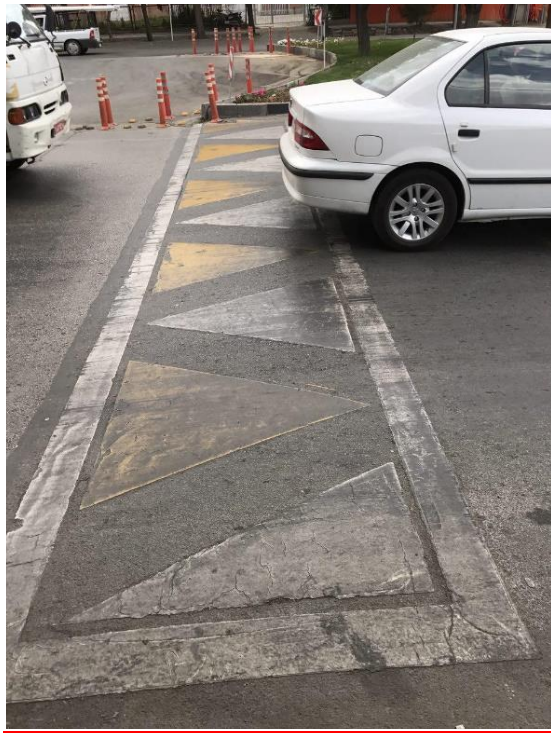
Figure 3. Camera images at the Saeediye intersection

Table 1. Characteristics of collecting basic information

Number	Area Name	Shooting range	Date	The number of counted vehicles
1	Besaat Boulevard to Saeediye intersection and exit to the Pajuhesh	10:15 to 10:30	2015/5/11	209
2	Upper -Saeediye to the entrance of Saeediye intersection and exit to Pajuhesh	10:15 to 10:30	2015/5/11	219
3	Return path entrance to the Saeediye intersection and turn to back route	10:15 to 10:30	2015/5/11	3
4	Ramp of Saeediye intersection entrance to Pajuhesh	10:15 to 10:30	2015/5/11	51
5	The first U-turn entrance to Be’sat Blvd.	10:35 to 10:50	2015/5/11	90
6	Outlet of Be’sat and Honarestan intersection	10:15 to 10:30	2015/5/12	125
7	Entrance of Be’sat and Honarestan intersection	10:15 to 10:30	2015/5/12	175
8	The second U-turn exit from Be’sat Blvd and entry to the back route	10:15 to 10:30	2015/5/12	81
9	The third U-turn exit from back route and entry to the going route	10:15 to 10:30	2015/5/12	68
10	Outlet of Be’sat Blvd intersection and Shokriyeh Street	10:35 to 10:50	2015/5/12	113
11	Entrance of Be’sat Blvd intersection and Shokriyeh Street	10:35 to 10:50	2015/5/12	86
12	Outlet of Be’sat Blvd intersection and Rohani Street	10:15 to 10:30	2015/5/13	55
13	Entrance of Be’sat Blvd intersection and Rohani Street	10:15 to 10:30	2015/5/13	80

Traffic calming measures used in this study has been shown in Figure 4. The data about the speed of vehicles was taken as it follows, firstly in order to record the speed data, GPS essentials software was installed on Android phone. Vehicles were then counted in time intervals. Data were collected using GPS Essentials for five scenarios with different TCM types and spacing. Speed data for each private or public vehicle in the area under study was recorded through subtle control for several days. To this end, 27 speed profiles were recorded, seven of which were eliminated for different reasons such as stopping or exiting the path. Following the recording of vehicle speed in the ‘Tracks’ section of the software, recorded data including situation, start time and end time, highest and lowest distance from the sea level, maximum and average speed on the track, chart related to speed versus location, and time diagram were also obtained. In this chart, speed profiles indicate that the speed of vehicles is influenced by TCMs therefore has a decreasing trend. Drivers decelerated while approaching them and again accelerated after passing them. Thus, 20 speed profiles were collected which were related to individual vehicles, and data related to speed in the area were recorded. Investigation of profiles indicates that speed of most vehicles was affected by TCMs at 30m before and after. Figure 5 illustrates an example of speed diagram in the TCMs vicinity, related to the speed profile recorded by GPS Essentials software. S1 (speed hump with narrowing one-way traffic lanes), S2 (pedestrian refuge), S3 (speed hump with narrowing two-way traffic lanes), and S4 (speed hump) shown in the Figure 5 are the existing calming measures.

S1



S2

S3

S4

Figure 4. Traffic calming measure used in this study

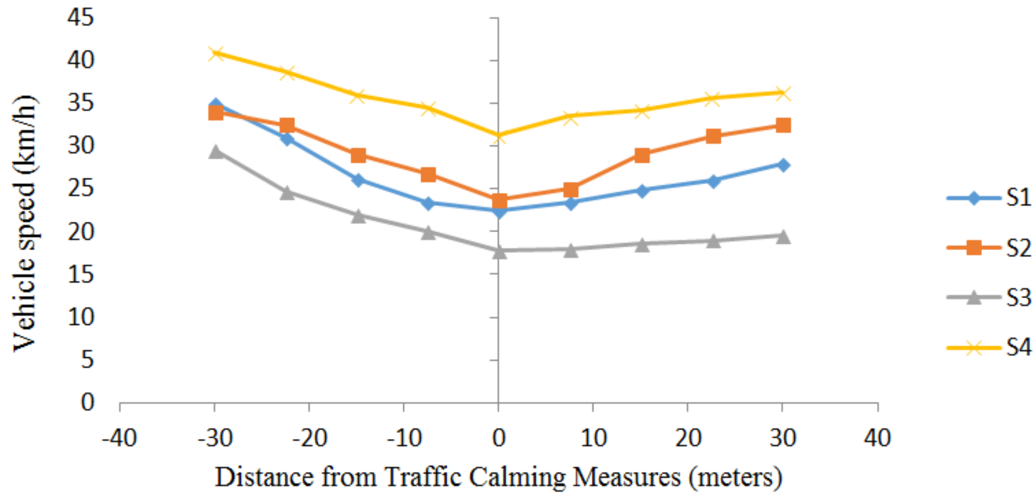


Figure 5. Speed profile in TCM vicinity

After performing video-recording as discussed in the previous part, the one with the highest number of vehicles was identified. Then, based on the observation of the video related to the respective section, the vehicles were counted and their type specified. The total number of vehicles was 482. By searching automotive manufacturer groups, data such as width, length, maximum speed and acceleration were obtained for 100 vehicles. In the next step, the frequency of each type of vehicle among the counted vehicles was specified. Finally minimum, maximum, mean and weight standard deviation of each of the parameters was calculated.

In order to enter and apply the area under study in the Aimsum software, the AutoCAD map of Hamedan city, as shown in Figure 6, was utilized.

Table 2. Parameters related to characteristics of 482 counted vehicles

Car Names	Frequency	Length (mm)	Width (mm)	Maximum speed (km / h)	Acceleration of 0 to 100(m/s^2)
Pride	113	3935	1605	160	2.072968
Pride111	12	3615	1605	160	2.072968
Peykan	22	4345	1620	140	1.827485
Peykan Vanet	18	4332	1620	140	1.851851
Peugeot 405	66	4408	1694	182	2.525252
Peugeot Pars	41	4498	1704	190	2.525252
Tondar 90	20	4250	1740	183	2.72331
Peugeot 206	42	3822	1652	170	1.970055
Peugeot 206SD	23	4188	1655	193	2.436647
Samand	49	4502	1903	185	1.956181
Xantia	4	4524	1755	203	2.696871
Megan	4	4498	1777	195	2.645502
Vanet Zamyad	9	4690	1660	160	1.736111
Renault PK	4	3500	1610	130	1.851851
Tiba	5	4105	1635	170	2.136752
Vanet Mazda	8	4820	1620	180	2.314814
Mazda 2	2	3920	1694	185	2.596054
Lifan X60	4	4325	1790	170	2.480158
KIA Sportage	3	4440	1855	194	2.986857
Santa Fe	2	4746	1890	190	3.086419
Roniz	4	4560	1830	161	1.827485
Prado	2	4795	1855	188	2.955082
Lifan 620	1	4550	1705	180	2.645502
Hyundai Elantra	1	4530	1775	202	2.723311
Mazda 3	2	4490	1755	210	3.052503
Maxima	2	4930	1780	255	3.086419
Daewoo Cielo	3	4482	1662	185	2.314814
Jeep Sahara	2	3745	1740	130	1.704158
Capra	2	5080	1750	140	1.736111
Optima	2	4840	1830	202	2.923976
Suzuki (Grand Vitara)	1	45000	1810	185	2.374169
Minibus	2	5655	2020	137	1.543209
Rio	1	4240	1675	175	2.354048
MVM110	1	4139	1686	160	2.104377
Hyundai Avante	1	4525	1725	208	3.306878
Hyundai Tucson	1	4400	1820	193	2.955082
MVM110	2	3550	1495	130	1.624431
Hyundai Sonata	1	4820	1833	210	3.561253
Benz E230	1	4725	1786	203	2.670940
Maximum		5655	2020	255	3.56
Minimum		3500	1495	130	1.54
Average		4230	1690	172.33	2.41
Deviation of Standard Weight		331	99.8	18.08	1.4

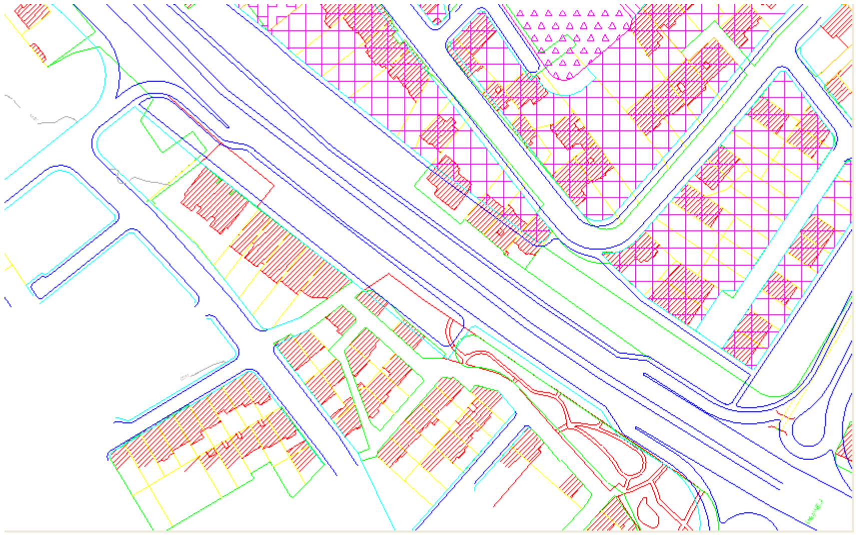


Figure 6. AutoCAD map of area under study in Hamedan city

4. Micro-simulation Modelling

The traffic micro-simulation model of Aimsun 6.0.5 was selected to analyse traffic parameters, considering the available TCMs available in the path. This research, through selecting Aimsun traffic software for micro-simulation of traffic flow, attempted to evaluate the effect of TCMs, such as speed control measures on network capacity and other traffic operational parameters like delay time, average speed, and fuel consumption of vehicles in the network. This was done by considering various scenarios in the network under study. First, the current status of traffic flow was determined. Then, vehicle traffic data on the entrance and exit paths of Be'sat Boulevard in the respective time period was obtained. The software calibration results of previous part were used to modify and calibrate the default parameters, including drivers' behavior and the traffic flow characteristics of local drivers.

After software calibration process, Aimsun software was used to model the area under study, and consequently the traffic flow in this network was simulated. The traffic micro-simulation program was described and developed as a reliable representative of the behavior observed in reality. Thus, the model was also calibrated. Hamedan Be'sat Boulevard-between Saeediye Junction and Pajuhesh intersection-was studied for model calibration. Data set for the model included traffic flow, speed profile, and characteristics of vehicles. Speed profile was defined in 30 m spacing before and after TCMs. These values were obtained using speed profiles prepared in field studies from 20 samples in the previous part. Hence, behavior of drivers in confrontation with TCMs was assigned to the software. Furthermore, the traffic flow was obtained from the frequency of traffic of vehicles in the entrance and exit of Be'sat Boulevard, and was defined to the software. Finally, the collected characteristics of vehicles were entered into the software. When the simulated model was calibrated, various scenarios were defined to analyse the effect of TCMs on traffic capacity and parameters. The scenario is a general outline of the natural or anticipated event. In the following section, the scenarios defined in the software are introduced and investigated.

Scenario is the outline of general events which is natural or expected. Each of these scenarios has different requirements in terms of the number and location of TCMs which were distributed over 1650 meters. The scenarios selection was based on conditions that were applicable in real traffic or has been studied previously in that network.

Scenario 1 (Basic, Scn1)

In this scenario, the network was studied and analysed for the existing conditions. In this state, there were four types of TCMs with different characteristics in terms of spacing. This scenario was defined to analyse the network and compare it with the real situation.

Scenario 2 (Scn2)

In this scenario, there was one type of TCM, with the characteristics of fourth TCMs type available in the path (speed hump) of the network. It was placed between the third and fourth measures after Be’sat junction and Shokriyeh Street in the network. The reason for using this scenario is as follows. The vehicles passing through Be’sat Boulevard with relatively high speed had to reduce their speed due to vehicles entering Be’sat Boulevard from Shokriyeh Street; therefore, they had lower speed. In fact, adding this section led network eliminated then network was analysed. The reason for this scenario was to observe to reduced distance between TCMs and change in traffic capacity and parameters.

Scenario 3 (Scn3)

In the third scenario, the first traffic calming section was placed in the network, while other TCMs were eliminated from the network. This was done to reduce the speed of vehicles moving from Saeediye Junction towards Pajuhesh Junction, so that they did not collide with vehicles entering Be’sat Boulevard from Honarestan Street, which had relatively lower speed.

Scenario 4 (Scn4)

This scenario was designed to place the first and third calming measures in the network and eliminate other measures. The reason for this scenario is as follows. According to field studies of pertaining to the first and third calming measures, these measures influenced the speed of vehicles passing through the network under study more than the second and fourth measures, due to their geometry. Thus, they were more effective in the speed reduction of vehicles. Furthermore, this scenario increased the spacing between calming measures.

Scenario 5 (Scn5)

In the last scenario, the network was free of any calming equipment. All TCMs available in the changes in traffic capacity and parameters with significant changes in geometric and physical conditions.

Software outputs were classified into several classes-parameters estimated for the whole network, parameters obtained from part of the network, parameters collected from each street, and parameters obtained from counters. In the general state, parameters such as average flow volume, vehicle density, average speed, delay time in the network, stop time and total expired time of vehicles, number of vehicles that exited the network, etc. can be also estimated for the whole network and for the network lines.

5. Results and Discussion

First, by considering the field studies and data recorded by GPS trackers related to speed profile of 20 vehicles, some tables were prepared. Then, the behavior of each driver in coping with different TCMs available on the path was studied. The speed profiles as shown in Figure 7 indicated that TCMs can influence the behavior of most drivers for 30 m before and after these measures, i.e. drivers decelerated while approaching them and again accelerated after passing them. Thus, speed of each driver 30 m before and 30 m after TCMs was investigated. The diagrams related to the speed profile of vehicles in the area of calming measures indicate higher standard deviation in the behavior of drivers while coping with S2 calming measures

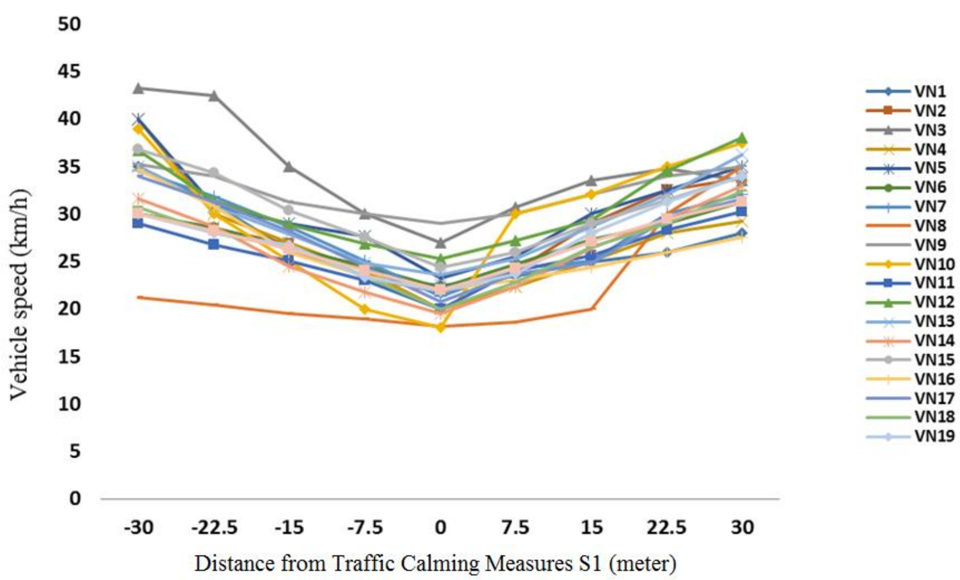


Figure 7. Speed profile of all vehicles in first TCM

Table 3. Mean standard deviation of vehicles speed

Number of Equipment	S1	S2	S4	S3
Average vehicle speed SD	3.264	5.882	4.473	**4.066**

Table 4. Average speed reduction percent versus beginning of TCMs area

Number	S1	S2	S3	S4
Average speed reduction percent versus beginning of traffic calming measures area	16.64	9.13	17.92	16.66

It means that they acted more optionally towards S2 compared to other calming measures (S1, S3, and S4). Reality also depicts this fact, because S2 is not merely a speed hump; it also imposes limitation on the speed of passing vehicles when passengers are passing confrontation Furthermore, in the third calming area, the speed of vehicles was lower. It means that the speed hump, with its geometric conditions (two-way reduction of passage width) led to further reduction in the speed of vehicles. On the other hand, by studying the values and diagrams related to reduction percent versus the beginning of measures area, average speed reduction percent versus the beginning of calming measure area was calculated. These values are given in Table (4). On the basis of field observation, total data, including traffic volume of vehicles, speed of vehicles in the calming area, and characteristics of vehicles, were entered in the software. Then respective scenarios were simulated in the study network and outputs were documented. Since the Aimsun software does not directly calculate network capacity, different flow coefficients were applied on network capacity in the 'Traffic Demand' section in order to determine the network capacity. Flow coefficient is the parameter that increases and decreases the traffic flow value proportionate to the vehicles counted in specific time intervals and applied on the software. After applying each factor in the 'Network Summary' section, different types of data, such as delay time, average speed, fuel consumption, number of vehicles that exited the network, number of lost vehicles, number of vehicles staying in the network, etc. were extracted. At each stage, a parameter known as the number of vehicles that were produced but maintained was increased from zero by the flow coefficient increase. This parameter took a value when the network reached the capacity level and no more vehicles could enter the network. In order to calculate capacity, two parameters (number of vehicles exiting the network and number of vehicles staying in and passing through the network) were summed and considered as the simulated scenario capacity. It should be noted that when the parameter of number of vehicles that were produced but maintained was increased from zero, the sum of the two parameters were considered as the capacity. In order to improve the accuracy of the results, each scenario was simulated with five iterations and finally the outputs of the iterations were averaged.

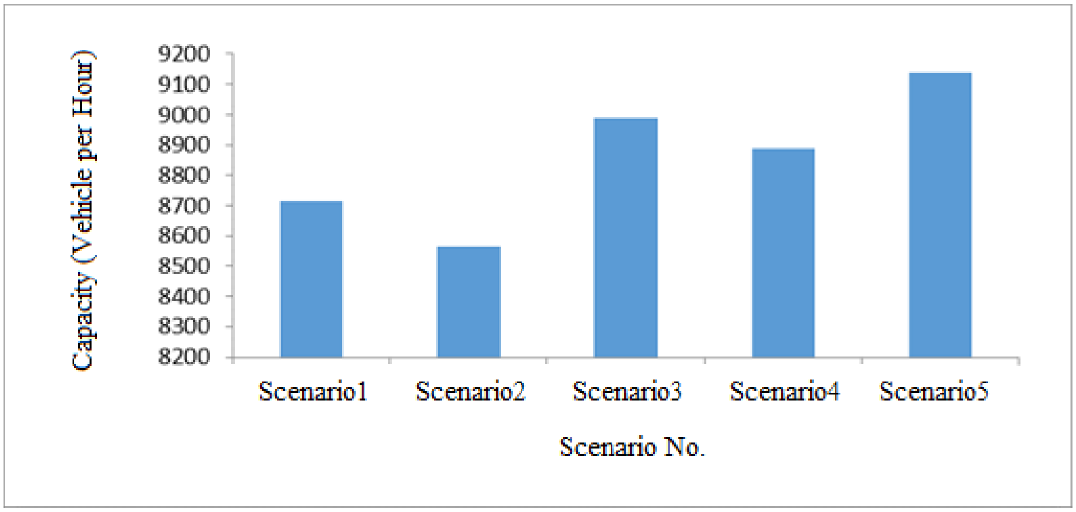


Figure 8. Capacity diagram related to each of the simulated scenarios

Results related to passing vehicles (capacity) in each scenario were analysed and it was observed that the diagram initially had an ascending trend due to an increased flow coefficient (factor) to reach a capacity level, and then went back to its descending trend again. The peak point of the diagram was considered as the capacity level in each of the scenario. The obtained capacities were compared and evaluated in Figure 8. The difference in the capacity values of each simulated scenario was because of the different conditions along with the specific characteristics, including the number of speed humps and different locations in the network under study. This capacity was calculated in terms of the number of vehicles per hour. The capacity in the fifth scenario (without TCMs) was actually the maximum flow rate, which indicated 426 vehicles per hour more than the first scenario (basic scenario), with about five percent increase. In addition, in the second scenario (adding another speed confining factor to the basic scenario), the capacity was decreased by 147 vehicles per hour compared to the basic scenario. In the third and fourth scenarios, available in the network as S1 and (S1, S3), 276 and 174 more vehicles respectively passed through compared to the basic scenario per hour. The comparison of scenarios indicated that TCMs, by influencing the speed of passing vehicles had direct effect on the network capacity, which led to considerable reduction of number of vehicles.

In addition, it was found that the parameter of the number of vehicles that were produced but maintained, takes a zero value when the scenario does not reach the capacity level and increases from zero when the scenario reaches capacity level, due to an increase in flow coefficient. Therefore, this parameter increases linearly with an increase in flow coefficient for each scenario.

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Table 5. Results related to traffic parameters for different scenarios

	Coefficient	Delay (seconds per km)	Fuel consumption (liters)	Average speed (mph)
First scenario	100	6.113	339.842	**43.6085**
Second scenario	100	6.712	364.456	**43.019**
Third scenario	100	3.822	236.281	**46.5502**
Fourth scenario	100	5.39	296.588	**44.426**
Fifth scenario	100	3.001	203.213	**47.8346**

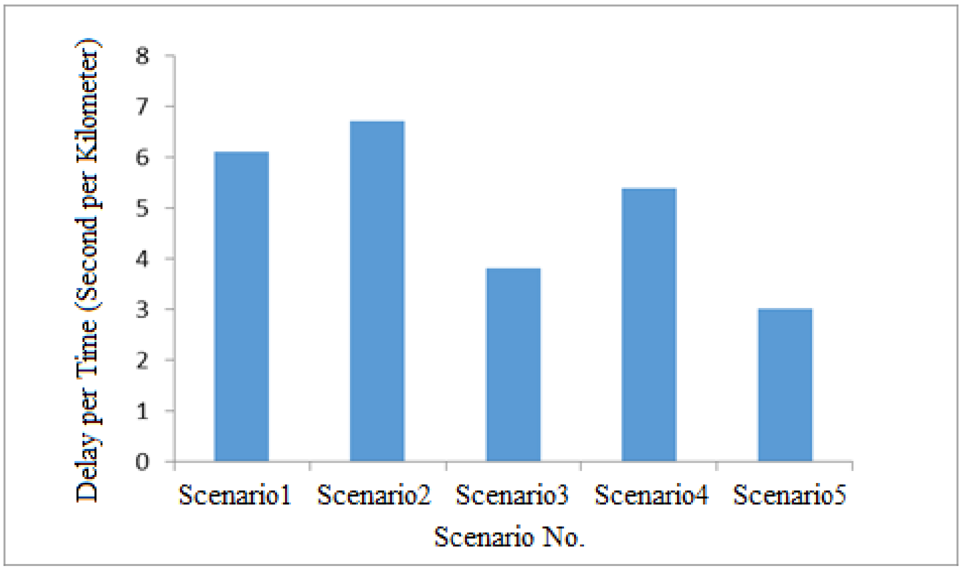

Figure 9. Diagram of average delay time obtained from scenarios (coefficient 100)

Operational parameters, including delay time, fuel consumption, and average speed were investigated at each scenario, and results are given as follows. Figure 9 shows that the delay time of each scenario varies in different conditions. Delay time of scenarios at flow coefficient 100 varies between 3.001 sec/km and 6.712 sec/km. In the fifth scenario, with no calming measures in the network, delay time reduced to 3.11 sec/km (49% of the basic scenario). Delay time increased by 0.6 sec/km (9.8%) in the second scenario, in which a speed hump was added to the basic scenario's TCMs. Also, as indicated in Figure 8, the third and fourth scenarios showed reduction in delay time by 2.292 sec/km (37.5%) and 0.72 sec/km (11.8%) respectively versus the basic scenario.

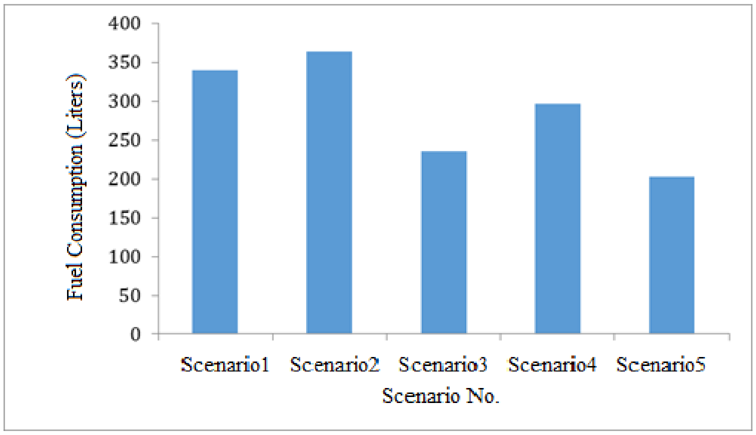

Figure 10. Diagram of vehicles' fuel consumption in different scenarios (coefficient 100)

In Figure 10, it is observed that the fuel consumption of vehicles in each scenario is different. This difference results from the presence or absence of TCMs as well as location of measures. In the fifth scenario, with no speed control measures, fuel consumption is reduced by 136.629 L (40%) compared to basic scenario, which indicates the effect of TCMs on increasing the fuel consumption of vehicles. In the second scenario, where a speed confining factor was added to the basic scenario, fuel consumption increased by 24.6142 L (7.2%). Furthermore, in the third and fourth scenarios, 103.561 L (30%) and 43.254 L (12.7%) reductions in fuel consumption respectively compared to the basic scenario were observed.

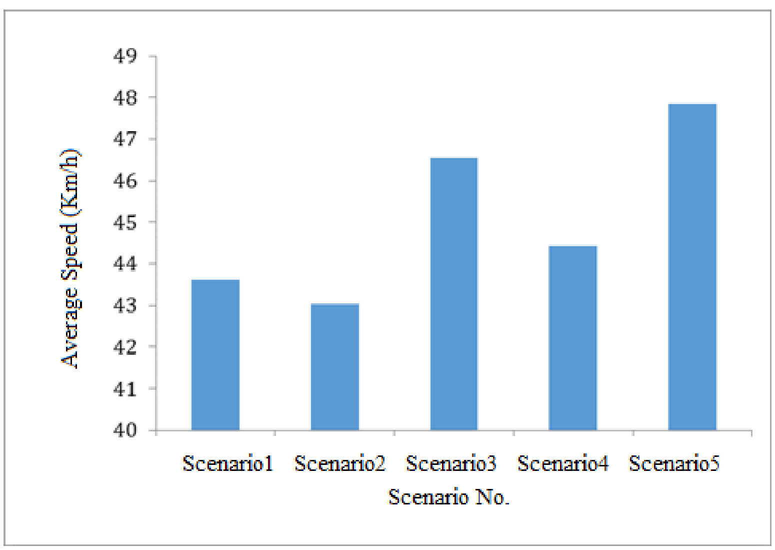

Figure 11. Diagram of average speed in each scenario (coefficient 100)

Table 6. Comparing average speeds

Speed average obtained from field studies (km/h)	40.725
Speed average obtained from software output (km/h)	43.6085

Figure 11 summarizes the results, in which average speed of vehicles increased by 4.22 km/h (9.7%) in the fifth scenario compared to the basic scenario, which indicates the effect of TCMs on reducing average speed of vehicles. In addition, average speed of vehicles in the network in the third and fourth scenarios, which had fewer TCMs compared to the basic scenario, increased by 2.9417 km/h (6.74%) and 0.8 km/h (1.88%) respectively.

In order to investigate the calibration effect of different parameters on outputs and examining agreement between modeling results and reality, speed average of software output resulting from the basic scenario was compared with a speed average of 20 vehicles, which was stored in GPS while recording the speed of vehicles. After that, average speed of 20 vehicles in field study was compared with the average speed of software output resulted by applying the basic scenario. Results are given in Table 6.

According to table 6, with regard to average speeds, the difference in values between field results and software output results was 2.8835 km/h (6.61%).

6. Conclusions

Traffic calming is one of the most effective ways to attain safe road traffic. The purpose of this method is to reduce accidents and their severity by reducing speed and sometimes traffic flow. TCMs have been widely used in urban areas to reduce vehicle flow rates and especially speed, and hence, to bring down the number and severity of traffic accidents. The main findings of this research are as follows:

1. Calming measures S1 (speed hump with one-way narrowing passage) and S3 (speed hump with two-way narrowing passage) caused a higher speed reduction in vehicles given their geometric conditions.
2. A highest standard deviation was observed in calming area S2 (central island in pedestrian crossing), in which drivers generally reduced their speed only when pedestrians were passing.
3. Through applying different flow coefficients in the software for each scenario, the capacity of simulated scenarios varied between 8,566 and 9,139 vehicles per hour, which were proportional to the number of TCMs in the network and their location.
4. The obtained results related to capacity indicated that the network reached maximum capacity when it lacked any TCM. In other words, by comparing the capacities of the scenarios, it was found that TCMs have a direct effect on the network capacity, therefore network capacity can be as a result of any change in the number and location of measures.
5. Delay time reduced by 49% in the scenario with no calming measures in the network compared to the basic scenario, suggested that these measures had a significant effect on the delaying of vehicles. The value of this parameter is highly crucial and important for public transportation, ambulances, fire trucks, and police cars. While designing urban passages using calming measures, these measures should

be designed and implemented in appropriate places so that losses due to increased delay time are minimized. The utilization of TCMs increases fuel consumption of vehicles in the network, the main reason for which is frequent deceleration and acceleration.

6. Fuel consumption was reduced by 40% when network lacked any calming measures compared to basic status.

7. Average speeds of scenarios varied between 43.019 km/h and 47.8346 km/h, which is an indication of the effect of TCMs on average speed reduction of vehicles. This speed reduction varied due to the number and spacing of the measures.

7. References

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