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Impact of heavy vehicles on surrounding traffic characteristics

Sara Moridpour[1]*, Ehsan Mazloumi[1] and Mahmoud Mesbah[2]

[1]*School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Victoria, Australia*
[2]*School of Civil Engineering, University of Queensland, Brisbane, Queensland, Australia*

SUMMARY

This work examines the impact of heavy vehicle movements on measured traffic characteristics in detail. Although the number of heavy vehicles within the traffic stream is only a small percentage, their impact is prominent. Heavy vehicles impose physical and psychological effects on surrounding traffic flow because of their length and size (physical) and acceleration/deceleration (operational) characteristics. The objective of this work is to investigate the differences in traffic characteristics in the vicinity of heavy vehicles and passenger cars. The analysis focuses on heavy traffic conditions (level of service E) using a trajectory data of highway I-80 in California. The results show that larger front and rear space gaps exist for heavy vehicles compared with passenger cars. This may be because of the limitations in manoeuvrability of heavy vehicles and the safety concerns of the rear vehicle drivers, respectively. In addition, heavy vehicle drivers mainly keep a constant speed and do not change their speed frequently. This work also examines the impact of heavy vehicles on their surrounding traffic in terms of average travel time and number of lane changing manoeuvres using Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks (AIMSUN) microscopic traffic simulation package. According to the results, the average travel time increases when proportion of heavy vehicles rises in each lane. To reflect the impact of heavy vehicles on average travel time, a term related to heavy vehicle percentage is introduced into two different travel time equations, Bureau of Public Roads and Akçelik's travel time equations. The results show that using an exclusive term for heavy vehicles can better estimate the travel times for more than 10%. Finally, number of passenger car lane changing manoeuvres per lane will be more frequent when more heavy vehicles exist in that lane. The influence of heavy vehicles on the number of passenger car lane changing is intensified in higher traffic densities and higher percentage of heavy vehicles. Large numbers of lane changing manoeuvres can increase the number of traffic accidents and potentially reduce traffic safety. The results show an increase of 5% in the likelihood of accidents, when percentage of heavy vehicles increases to 30% of total traffic.

KEY WORDS: heavy vehicles; passenger cars; travel time; lane changing manoeuvre

1. INTRODUCTION

The effects of heavy vehicles on their surrounding traffic are greater than passenger cars. There is potential for heavy vehicles to have a substantial impact on macroscopic and microscopic traffic flow characteristics because of the interference effect they have on surrounding vehicles. Previous studies show that heavy vehicle and passenger car drivers have fundamentally different driving behaviour [1–3]. The heavy vehicle drivers' car-following and lane changing behaviour has been investigated, and models have been developed to estimate their driving behaviour [1, 4–6].

Although heavy vehicles comprise a small proportion of traffic stream, they have an important effect on traffic flow and produce a disproportionate effect particularly during heavy traffic conditions [7]. Heavy vehicles impose physical and psychological effects on surrounding traffic [8–11]. These effects are the results of physical characteristics of heavy vehicles (e.g. length and size) and their operational

*Correspondence to: Dr. Sara Moridpour, School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Victoria 3001, Australia. E-mail: sara.moridpour@rmit.edu.au

characteristics (e.g. acceleration/deceleration and manoeuvrability). The effect of heavy vehicles' operational characteristics becomes prominent under heavy traffic conditions.

The number of heavy vehicles on roadways of the USA has increased by 75% over the past three decades, and this trend is likely to continue over the next decade [12]. Heavy vehicles have transported around 60% of US trade in 2013 [13]. Typically, the proportion of heavy vehicles ranges from as low as 2% to as high as 25% of total traffic during the day [7]. According to a series of traffic surveys conducted in Australia, the proportion of heavy vehicles could increase to 20% of total vehicles in the peak periods on some freeways [14].

Despite the increasing number of heavy vehicles on highways and freeways, the influence of heavy vehicles on their surrounding traffic has received little attention. Because of the large size of heavy vehicles and their limited operational capabilities (e.g. speed and acceleration/deceleration), they have the potential to bring psychological disadvantages for their surrounding passenger car drivers. Previous studies show that passenger car drivers try to avoid being in the vicinity of heavy vehicles. They either try to provide large space gaps to the heavy vehicle ahead/follow or move into other lanes [4, 9]. According to the literature, number of lane changing manoeuvres is a good indicator of the potential for vehicular conflicts [15, 16]. Large numbers of lane changing manoeuvres can increase the number of accidents and potentially reduce traffic safety. Therefore, the safety analysis is essential for highways/freeways with high proportion of heavy vehicles or in heavy traffic conditions. The results of analysis can be used to define appropriate lane restriction strategies or safety policies in urban highways/freeways to enhance capacity and improve traffic safety [17].

The aim of this research is to investigate the differences in traffic characteristics of vehicles in the vicinity of heavy vehicles and passenger cars. The analysis focuses on heavy traffic conditions (level of service E) and makes use of trajectory data for a section of I-80 in USA. In this paper, space gaps and relative speeds of the vehicles in front/at the rear of heavy vehicles and passenger cars are analysed and compared. Furthermore, the speed changes of heavy vehicles and passenger cars are examined. After that, the influence of heavy vehicles on their surrounding traffic is investigated in terms of travel times and number of lane changing manoeuvres using Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks (AIMSUN) (Barcelona, Spain) microscopic traffic simulation package. In addition, a term related to heavy vehicle percentage is introduced into two different travel time functions to evaluate the direct impact of heavy vehicles on average travel time. The influence of heavy vehicles on traffic safety will also be measured.

This paper begins by explaining the trajectory data used in this study. Then, traffic characteristics of the vehicles in the vicinity of heavy vehicles and passenger cars are analysed. It is followed by a detailed examination of the influence of heavy vehicles on their surrounding traffic and identifying the influence of heavy vehicles on average travel time and traffic safety using microscopic traffic simulation. In addition, the influence of heavy vehicles on travel time and safety is measured. The final section summarises the insight from this study and identifies recommendations and directions for future research.

2. TRAJECTORY DATA

The trajectory dataset used in this study was made available by Cambridge Systematics Incorporated for the Federal Highway Administration (FHWA) as part of Next Generation SIMulation (NGSIM) project. NGSIM captured video images for a section of Berkeley Highway (I-80) in California. Subsequently, a comprehensive vehicle trajectory dataset was developed through processing the video images. The lane configuration of the section of I-80 is schematically shown in Figure 1.

The section of I-80 is 503 m long and comprises five main lanes with one auxiliary lane [18]. There is one on-ramp in this section and one exit off-ramp downstream of the section. There are no lane restrictions for heavy vehicles, and the grade is almost zero. The data were collected from 4:00 to 4:15 PM and 5:00 to 5:30 PM using a video capture rate of 10 frames per second. The dataset was provided in clear weather, good visibility and dry pavement conditions. The dataset has classified the vehicles as automobiles, heavy vehicles and motorcycles. Table I shows the traffic flow parameters for the section of I-80.

The trajectory dataset used in this study provides information on vehicles and their surrounding traffic characteristics. The vehicles for which information is available are presented in Figure 2. A heavy vehicle

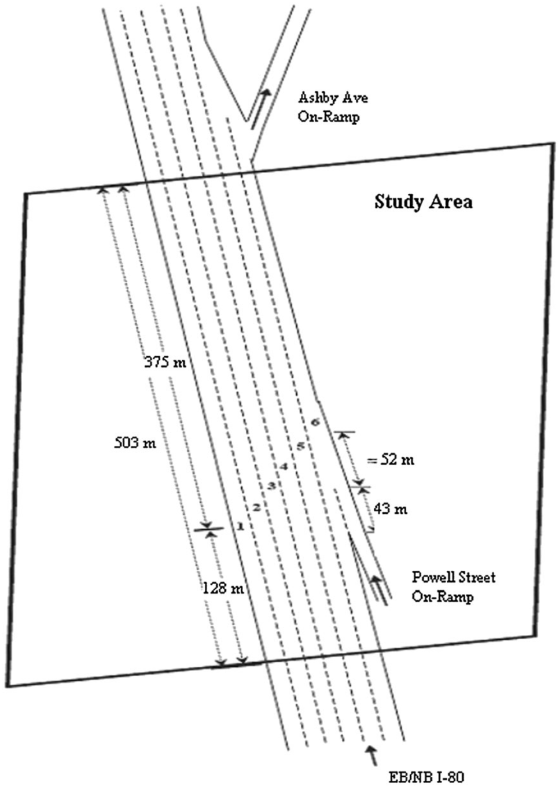

Figure 1. The schematic lane configuration of the section of I-80.

Table I. Traffic flow parameters in the section of I-80.

Time interval	Passenger car and motorcycle number (%)	Heavy vehicle number (%)	Traffic flow (veh/h)	Speed (km/h)	Density (veh/km)*	Level of service
4:00 to 4:15 PM	1956 (95.3)	96 (4.7)	8144	28.7	284	E
5:00 to 5:15 PM	1766 (96.2)	70 (3.8)	7288	22.6	322	E
5:15 to 5:30 PM	1741 (97.3)	49 (2.7)	7048	20.0	352	E
Total	5463 (96.2)	215 (3.8)	7493	23.8	315	E

*Density is calculated as the number of vehicles per kilometre length of all lanes.

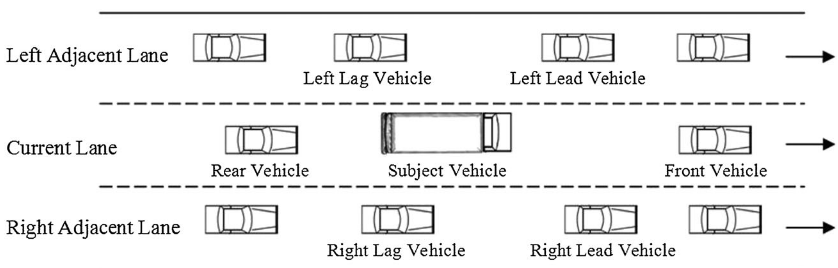

Figure 2. The subject vehicle and surrounding traffic.

and its surrounding traffic are presented in this figure. The trajectory dataset provides the opportunity to determine the physical characteristics (length and width), positions, speeds and accelerations/decelerations of individual vehicles and their surrounding traffic (Figure 2) as well as space gaps and relative speeds between each vehicle and the surrounding vehicles at discrete time points.

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3. COMPARISON OF HEAVY VEHICLE AND PASSENGER CAR BEHAVIOUR

As noted earlier, the length and size of heavy vehicles as well as the limitations in their manoeuvrability may cause physical and psychological effects on surrounding traffic. Initial analysis of heavy vehicles and passenger cars shows that some differences exist in traffic characteristics of vehicles in the vicinity of these two vehicle types [1, 9]. In this section, the traffic characteristics of vehicles in the vicinity of heavy vehicles and passenger cars are analysed and compared. To better understand the influence of heavy vehicles on their surrounding traffic, heavy vehicles are classified into two separate classes based on their length. Heavy vehicles with the length of equal to or greater than 15 m are classified as heavy trucks, and those with the length of less than 15 m are considered as light trucks. Over the period when the data were captured, a total of 30 heavy trucks, 30 light trucks and 30 passenger cars are analysed. To ensure a valid comparison, surrounding traffic characteristics of the selected heavy trucks, light trucks and passenger cars are close to each other. Moreover, the selected heavy trucks, light trucks and passenger cars passed the study area almost at the same time. To do this analysis, space gaps and relative speeds of the vehicles in front/at the rear of heavy vehicles (heavy trucks and light trucks) and passenger cars as well as the changes in the speeds of these two vehicle types are examined and compared.

As mentioned earlier, the trajectory dataset provides the opportunity to determine the positions, speeds and accelerations/decelerations of the subject vehicle and the surrounding traffic at discrete time points (0.1-s time interval). The position, speed and acceleration information cannot be extracted directly because of the noise in the NGSIM information. Therefore, the moving average method, which is a simple smoothing method, is used to reduce the noise of the NGSIM information. Meanwhile, the smoothing should be as weak as possible, to maintain the trends in driving behaviour. Therefore, the moving average with period of five is used in this study for the positions, and the moving averages with periods of 10 and 40 are used for the speeds and accelerations, respectively. According to previous studies on the NGSIM dataset, smoothing the positional information with period of five, speeds with the period of 10 and acceleration/deceleration with the period of 40 results in accurate outcomes [19].

In the following figures (Figures 3 and 4), the traffic flow characteristics are aggregated over a period of 20 s. In those figures, the length of vehicles is presented on *X*-axis (vehicle size), and observations are shown by triangles, crosses and dots for heavy trucks, light trucks and passenger cars, respectively.

Figure 3 shows the relationship between the front and rear space gaps and relative speeds in the vicinity of heavy vehicles and passenger cars. In this figure, the front/rear space gaps and relative speeds are defined as the subject vehicle position/speed subtracted from the front/rear vehicle positions/speeds. As it is shown in Figure 3a, the front space gaps for heavy trucks are considerably larger than the front space gaps for light trucks and passenger cars. The large space gaps between heavy trucks and front vehicles may be due to the limitations in manoeuvrability of heavy trucks. This is not observed in either light trucks or passenger cars. Furthermore, the large space gaps in front of heavy trucks occur because heavy truck drivers generally keep larger distances to their front vehicle in order to provide adequate distance to break safely. Heavy truck deceleration capabilities are more limited than those of passenger cars. Generally, the rear space gaps for heavy trucks are slightly larger than the rear space gaps for light trucks and passenger cars. This may be due to the safety concerns of rear vehicle drivers when following heavy trucks. This could also be partially due to the limited visibility of drivers in vehicles, which are immediately behind the heavy trucks.

The relationship between the front and rear relative speeds in the vicinity of heavy vehicles and passenger cars are presented in Figure 3b. The front/rear relative speeds are defined as front/rear vehicle speeds minus the subject vehicle speed. According to this figure, heavy trucks' speeds are generally lower than the speeds of their front/rear vehicles. This pattern is not observed for light trucks and passenger cars. It implies that the speed of heavy trucks is generally lower than the speed of their surrounding vehicles. The speed of heavy trucks is considerably lower than the speed of their front vehicles and is almost similar to their rear vehicles' speed. Because of limitations in acceleration/deceleration and manoeuvrability, heavy

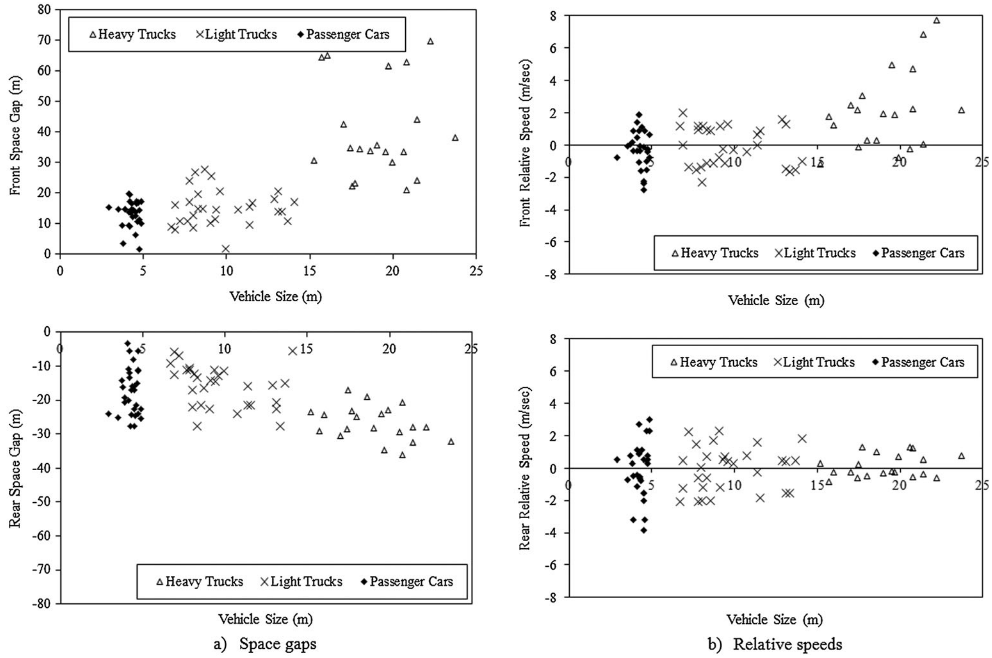

Figure 3. Traffic characteristics of the vehicles in front/at rear of heavy vehicles and passenger cars.

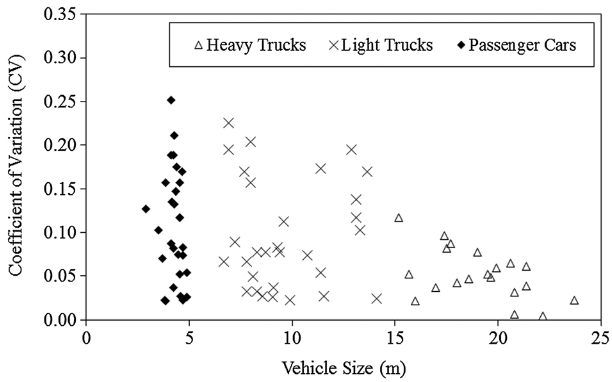

Figure 4. Speed changes of heavy vehicles and passenger cars.

trucks are generally unable to adjust their speeds according to the speed of front vehicles. Consequently, the following vehicles adjust their speed according to the speed of heavy trucks because of safety concerns.

To better understand the differences between heavy vehicles and passenger cars, their speed changes are calculated and compared. The Coefficient of Variation (CV), which is the ratio of standard deviation to mean speed, is used to analyse the speed changes of heavy vehicles and passenger cars. As it is shown in Figure 4, speeds of heavy trucks have small changes (CV of less than 0.1) while speeds of light trucks and passenger cars have considerable variation. The small values for CV of speed show that speeds of heavy trucks have inconsiderable changes while speeds of light trucks and specifically passenger cars change considerably. This implies that passenger car and light truck drivers mainly adjust their speeds according to the speeds of surrounding vehicles. However, it may be difficult for heavy truck drivers to adjust their speed according to the speed of their surrounding traffic. This may be due to the operational limitations of heavy trucks (acceleration/deceleration and manoeuvrability). Heavy truck drivers mainly keep a constant speed and do not change their speed frequently.

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Heavy trucks influence their surrounding traffic characteristics. The space gaps between heavy trucks and their front/rear vehicles are larger than the corresponding values in light trucks and passenger cars. Furthermore, speeds of heavy trucks are generally lower than the speeds of their front/rear vehicles, and they almost keep the same speed and do not change their speed frequently. This is not observed in light trucks and passenger cars, which mainly adopt their speed according to the speed of their surrounding traffic. The large space gaps in vicinity of heavy trucks and the limitations in adjusting their speed according to surrounding vehicles' speed produce a disproportionate effect on traffic flows. This problem is intensified when large percentage of heavy trucks exists in highways/freeways. Because light trucks and passenger cars have almost similar influence on their surrounding traffic and because of considerable influence of heavy trucks on their surrounding vehicles, the following section investigates the influence of different proportions of heavy trucks on traffic.

4. IMPACT OF HEAVY TRUCKS ON SURROUNDING TRAFFIC

As mentioned earlier, heavy trucks impose physical and psychological effects on surrounding traffic. Those effects result in an increase in the number of lane changing manoeuvres in vicinity of heavy trucks. The limited operational characteristics of heavy trucks as well as the frequent lane changing manoeuvres in their vicinity may cause repetitive variation of speed and traffic flow characteristics called speed and traffic flow oscillations [9, 10,20]. To better understand the influence of heavy trucks on surrounding traffic, average travel times and number of lane changing manoeuvres in the vicinity of heavy trucks are analysed in this section. In the following figures, the relationship between the number of heavy trucks, the average travel times and number of passenger car lane changing manoeuvres are investigated per individual lane at different time intervals.

The relationship between heavy truck volume and average travel times in each lane is presented in Figure 5. In this figure, the number of heavy trucks is presented as a proportion of total traffic volume on *X*-axis, and average travel times are presented on *Y*-axis. The average travel time is measured as the average time required for vehicles to pass the study area (503 m of the section of I-80).

As shown in Figure 5, proportion of heavy trucks has the highest value in lane 3. Heavy trucks have limited manoeuvrability and acceleration/deceleration characteristics, and therefore, it is difficult for heavy truck drivers to adjust their speed according to the speed of surrounding traffic. Therefore, heavy truck drivers avoid driving in the two fastest lanes (lanes 1 and 2). Meanwhile, a large proportion of vehicles in lanes 5 and 6 are the ones that took the on-ramp or wish to take the exit off-ramp. Thus, weaving manoeuvres occur in these two lanes, which may prevent heavy truck drivers from using these two slowest lanes. This may justify the larger proportion of heavy trucks in lane 3 compared with other lanes.

The average travel time rises when proportion of heavy trucks increases in each lane (Figure 5). In this figure, average travel times in lane 1 are considerably smaller than the corresponding values in other lanes. Because lane 1 is a high occupancy vehicle (HOV) lane, the average speeds are higher and the average travel times are smaller in this lane compared with other lanes. HOV lanes are restricted-use freeway lanes, which are reserved for vehicles with more than a predetermined number of occupants. According to this figure, heavy trucks comprise a small proportion of traffic in this lane. This implies that the small percentage of heavy trucks travelling in lane 1 can adjust their speed according to the average speed of passenger cars in that lane and therefore imposes less influence on travel times. Because video images are used in this research, information regarding the weight and power of heavy trucks is not available. Heavy trucks with higher power or smaller weight may use lane 1, which cannot be extracted from this research. In general, heavy trucks have lower speed compared with passenger cars. Increase in the proportion of heavy trucks in each lane may result in oscillations in the speed, reducing the average speed and therefore increasing the average travel time of that lane. This pattern is observed in lanes 2 to 6.

Figure 6 shows the relationship between the number of heavy trucks in each lane and the number of passenger car lane changing manoeuvres in that lane at 15-min time intervals in the section of I-80. In this figure, the number of heavy trucks per each lane is presented on the *X*-axis. *Y*-axis shows the number of passenger car lane changing manoeuvres from each lane.

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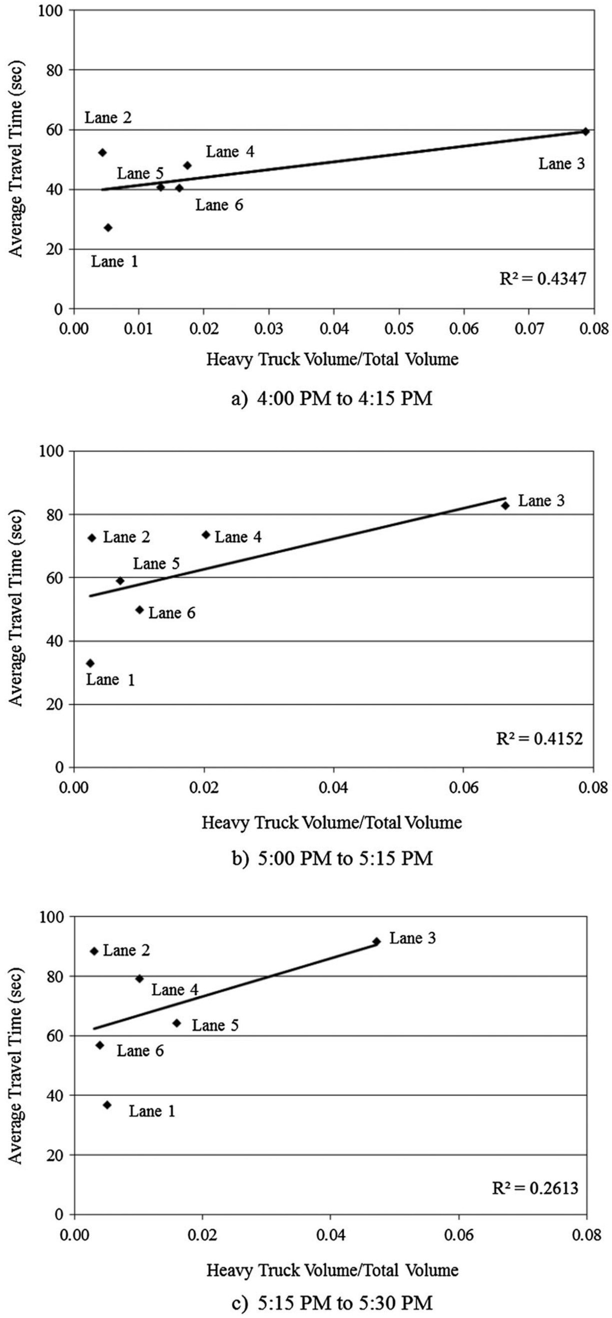

Figure 5. Relationship between heavy truck volume and average travel times.

According to this figure, the number of passenger car lane changing manoeuvres per each lane increases when more heavy trucks exist in that lane. Generally, there is a positive relationship between the number of heavy trucks in each lane and the number of passenger cars that execute a lane changing manoeuvre to move from that lane. This shows that passenger car drivers try to avoid being in the vicinity of heavy trucks, and therefore, they may try to move into other lanes. As mentioned earlier, the number of lane changing manoeuvres is a good indicator of potential for vehicular conflicts [16]. Large number of lane changing manoeuvres can increase the number of traffic accidents and potentially reduce safety. Therefore, increase in the number of heavy trucks may reduce traffic safety and increase the risk of accidents. The positive relationship between the number of heavy trucks and the number of passenger car lane changing manoeuvres is mainly observed in lanes 2 to 6. As mentioned before, lane 1 is a HOV lane

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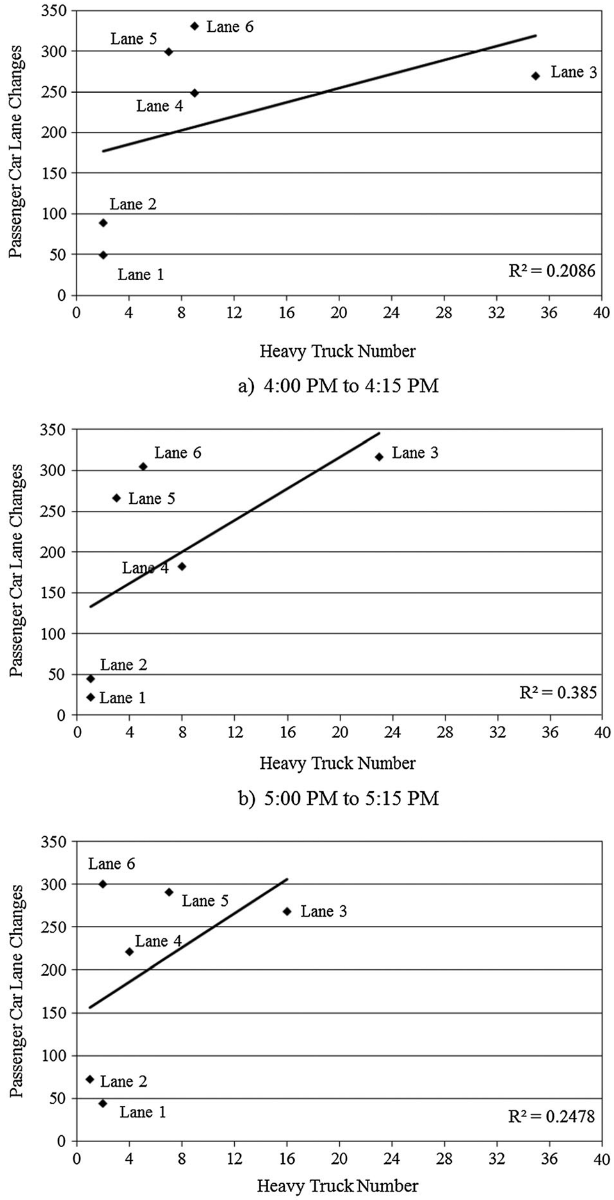

a) 4:00 PM to 4:15 PM

b) 5:00 PM to 5:15 PM

c) 5:15 PM to 5:30 PM

Figure 6. Relationship between heavy truck volume and number of passenger car lane changing.

with the highest average speeds (fastest lane), and vehicles in this lane are generally travelling with higher speeds compared with other lanes. The average speed in lane 1 is 48.3 km/h in the first 15-min time interval and 37.8 and 36.4 km/h in the second and third 15-min time intervals, respectively. Comparing these values with the results presented in Table I show that the average speeds in lane 1 are considerably higher than the average speeds in the study area. Therefore, passenger cars in lane 1 prefer to stay in that lane rather than moving to a slower adjacent lane (lane 2) despite the existence of heavy trucks in their vicinity. The number of passenger car lane changing manoeuvres has almost the maximum value in lane 6. In this lane, the observed lane changing manoeuvres mainly occur after taking an on-ramp or for taking the next exit off-ramp or to prevent being obstructed by weaving manoeuvres. This can justify the large number of passenger car lane changing in lane 6 compared with the corresponding values in other lanes.

According to the results obtained in this section, heavy trucks have pronounced effect on surrounding traffic characteristics. They reduce average speeds and consequently increase average travel times. This is due to the limitations in operational characteristics of heavy trucks. Furthermore, the existence of more heavy trucks can increase the number of passenger car lane changing manoeuvres. Generally, the vehicles in front of heavy trucks are more probable to change lanes because of psychological reasons. Passenger cars may try to prevent being followed by a heavy truck. The same behaviour is observed in passenger cars that are following heavy trucks. Passenger car drivers located behind the heavy trucks try to change lanes because they have limited vision because of the large size of heavy trucks. Besides, passenger cars avoid being obstructed by a slow moving heavy truck ahead.

The results provided in this section are based on a small proportion of heavy trucks. As shown in Table I, heavy vehicles comprise less than 5% of the traffic stream, and the proportion of heavy trucks (heavy vehicles with the length of equal to or greater than 15 m) is even smaller. To understand the influence of heavy trucks on surrounding traffic characteristics, larger proportion of heavy trucks should be analysed. However, providing a comprehensive trajectory dataset with high percentage of heavy trucks is very time consuming and costly. To this end, AIMSUN microscopic traffic simulation package is employed. The section of I-80 is simulated first. Then, proportion of heavy trucks is increased from the observed values to 30% of the total traffic using AIMSUN. Then, the influence of heavy trucks on the average travel times and number of passenger car lane changing manoeuvres is analysed in detail. The procedure is explained, and the results are presented in the following section.

5. AIMSUN SIMULATION RESULTS

The section of I-80, which is used in this study, is modelled using AIMSUN microscopic traffic simulation package. The microscopic traffic simulation model is calibrated and validated on the basis of an iterative heuristic approach. This approach is based on interactions between the driving behaviour, route choice and the O-D flows to iteratively calibrate the model. In each step, the corresponding set of parameters is calibrated, and the other parameters remain fixed at their previous values [21]. The calibration procedure, which is applied for the simulation model in this paper, is presented in Figure 7. The convergence happens, when the difference between the observed and the estimated traffic measurements ($TM^{obs} - TM^{est}$) is less than a value defined by user. Traffic measurements include traffic flows, average speeds and average travel times.

After simulating the section of I-80, the percentage of heavy trucks is increased from 2.2%, 1.7% and 1.3% of the total traffic in different time intervals in I-80 (Table I) to 30% at different stages

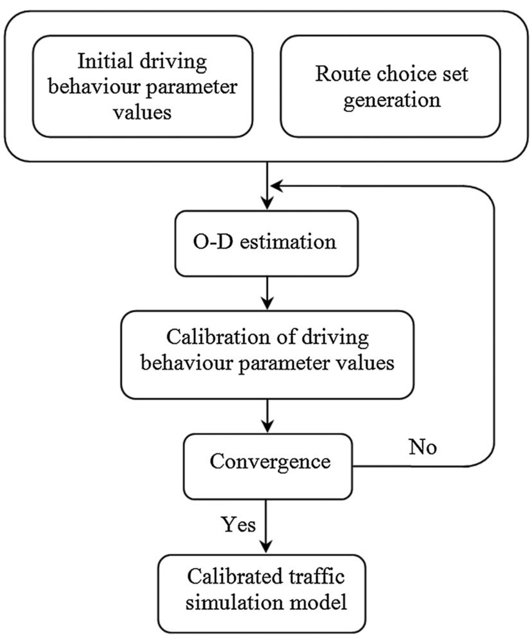

Figure 7. The calibration procedure for the microscopic traffic simulation model.

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(5%, 10%, 15%, 20%, 25% and 30%). Then, the influence of changes in proportion of heavy trucks on traffic flow characteristic is evaluated using AIMSUN. Because of stochastic nature of simulation models, the model is run for 10 times at each stage (5%, 10%, 15%, 20%, 25% and 30%). The average values of travel times and the number of lane changing manoeuvres obtained from 10 times running the model are calculated and used for comparison. In the following figures, percentage of heavy trucks is presented on *X*-axis, and average travel times and the number of passenger car lane changing manoeuvres are presented on *Y*-axis (Figures 8 and 9, respectively).

The relationship between the proportion of heavy trucks and average travel times is presented in Figure 8. As shown in this figure, the average travel times will increase as the percentage of heavy trucks increases. This is consistent with the results obtained in the previous section and can be a result of limited operational characteristics of heavy trucks. Likewise, increase in average travel times (which is the result of decrease in average speeds) is clearly observed in the last 15-min time interval in which

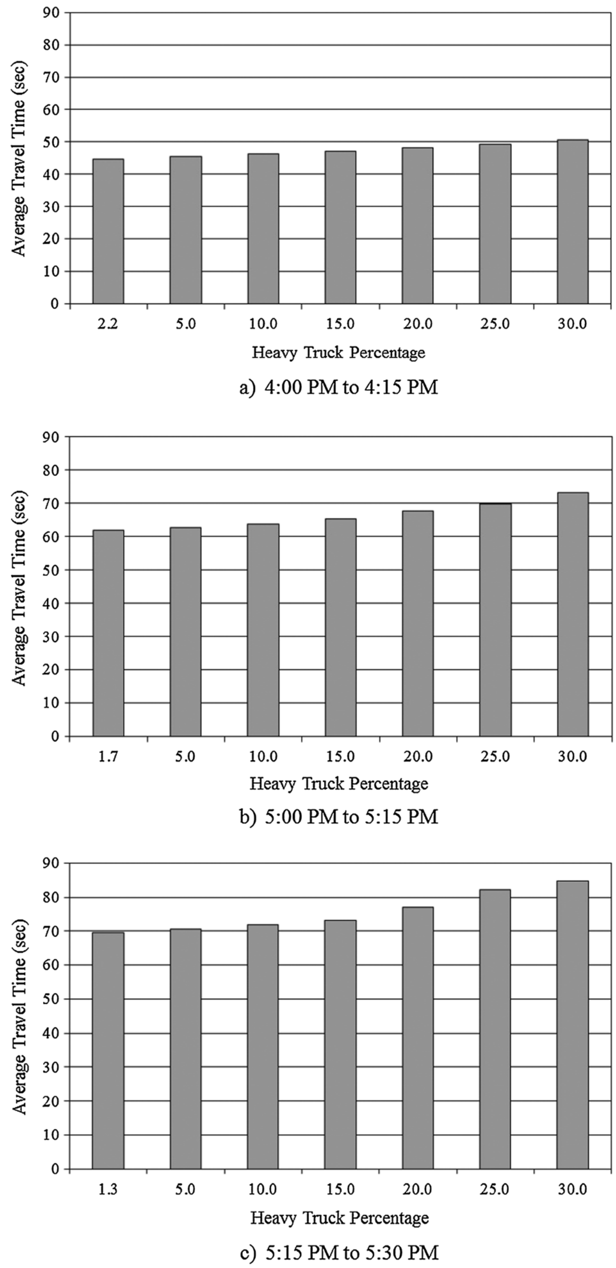

Figure 8. Relationship between the percentage of heavy trucks and the average travel time.

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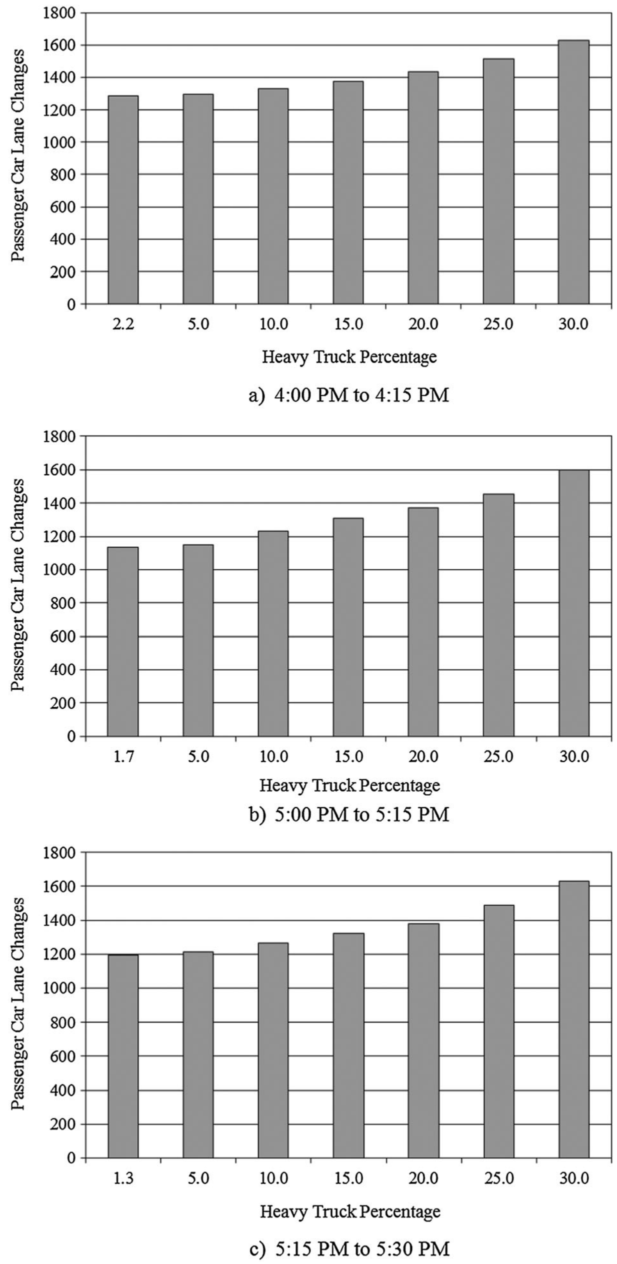

Figure 9. Relationship between the percentage of heavy trucks and number of passenger car lane changing.

the traffic congestion is higher. In this time interval, the average travel time increased from around 70 s to more than 80 s with the increase of around 30% in proportion of heavy trucks. This proves the substantial impact of heavy trucks on traffic flow characteristics in heavy traffic conditions.

Figure 9 shows the relationship between the proportion of heavy trucks and the number of passenger car lane changing manoeuvres. The number of passenger car lane changing manoeuvres increases with the increase in the number of heavy trucks. The growth is observable in higher proportions of heavy trucks. This increase is specifically observed in the last 15-min time interval (5:15 to 5:30 PM), when traffic density is higher (Table I). The number of passenger car lane changing manoeuvres increases from 1196 with the heavy truck percentage of 1.3% to 1632 when heavy truck percentage is 30% in the last time interval. This implies that heavy trucks have more influence on their surrounding traffic characteristics in higher traffic densities. The operational limitation of heavy trucks is more pronounced in higher congestion when stop and go traffic occurs.

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The results show that heavy trucks have pronounced influence on their surrounding traffic characteristics. Heavy trucks have influence on travel times (and average speeds). The average travel times are increased with the growth in the number of heavy trucks. This result is intensified in higher percentage of heavy trucks. Passenger cars in front/at rear of heavy trucks try to either provide large space gaps to heavy trucks or prevent being in front/at rear of heavy trucks and therefore move into their adjacent lanes. This may result in unsteady traffic condition or increase in the number of lane changing manoeuvres in vicinity of heavy trucks. According to the simulation results from AIMSUN, the influence of heavy trucks is prominent in higher congestion. In higher traffic densities, the number of passenger car lane changing manoeuvres has larger increase by the growth in percentage of heavy trucks. Larger numbers of lane changing manoeuvres cause higher vehicular conflicts and may enhance the probability of accidents and potentially reduce traffic safety.

The results of this section show that the increase in the number of heavy trucks can increase the average travel times as well as the number of passenger car lane changing manoeuvres. However, the influence of heavy trucks on travel time is generally ignored by travel time equations. In the following subsections, the influence of heavy trucks on travel times as well as their impact on likelihood of accidents is investigated in detail.

5.1. Influence of heavy trucks on travel time

The previous section suggests that heavy trucks have a pronounced effect on the average travel times, particularly during congestion. According to the literature, many studies have investigated the influence of heavy vehicles on travel time and speed. In these studies, the influence of heavy vehicles is mainly considered using a passenger car equivalency factor. However, heavy vehicles have psychological effects on their surrounding drivers. This may intensify the heavy vehicles' influence on traffic and cannot be estimated by simply using passenger car equivalency factors [22, 23].

Among all travel time equations in the literature, the Bureau of Public Roads equation is one of the traditional ones, which has a simple structure that estimates the link travel times and is extensively used in software packages [24]. The general type of the BPR travel time equation is shown in Equation (1). The BPR curve is close to parabolic curves in shape and is fairly sensitive to increase in traffic flows.

$$t = t_0\left[1 + \alpha\left(\frac{v}{c}\right)^{\beta}\right] \tag{1}$$

where

t = travel time for one kilometre length of road (minute)
t_0 = free travel time for one kilometre length of road (minutes)
v = traffic volume (passenger car units per hour per lane, pcu/h/l)
c = practical capacity (passenger car units per hour, pcu/h)

α and β are parameters.

In this research, the BPR travel time equation is used as a simple travel time equation to evaluate the influence of heavy trucks on travel time. To reflect the impact of heavy trucks on average travel time, a term related to heavy truck percentage is introduced into Equation (1) (Equation (2)). The new equation is used to estimate the average travel times in I-80. To ensure valid results, the parameters of the BPR travel time equation are calibrated at the first stage (α and β). Then, the heavy truck term is added to the calibrated model, and parameters of the heavy truck model are estimated (λ and δ). The free flow speed is assumed to be 130 km/h for I-80 in this procedure.

$$t = t_0\left[1 + \alpha \times f(HT) \times \left(\frac{v}{c}\right)^{\beta}\right] \tag{2}$$

f (HT) represents the influence of heavy trucks on travel time with the following structure (Equation (3)). To determine the general from of the following model, different structures were examined. Then, the structure, which resulted in the highest adjusted R^2 value and significant parameters, was selected.

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$$f(HT) = \lambda(HT)^{\delta} \quad (3)$$

where HT is equal to heavy truck proportion, and λ and δ are parameters.

To calibrate the parameters of the BPR travel time equation, the percentage of heavy trucks is increased from 2.2%, 1.7% and 1.3% of the total traffic in different time intervals to 30% with a 1% increment. Because of the stochastic nature of simulation models, the model is run for 10 times at each increment, and the average values of travel time obtained from 10 times running the model is calculated. The same dataset is used to estimate the parameters of heavy truck model, $f(HT)$.

To calibrate the heavy truck model, non-linear regression technique is adopted. Non-linear regression is a method of extracting a non-linear model based on the relationship between the dependent variable and a set of independent variables. Non-linear regression produces the least square estimates of the parameters for models in which the relationship between the variables is non-linear [25]. The estimation results for the calibrated BPR travel time equation as well as the heavy truck model are summarised in Table II. In this table, the *t*-statistic for each parameter is calculated as the ratio of estimated value for that parameter through non-linear regression model to the standard error.

In the BPR travel time equation and the heavy truck model, all the estimated parameters are significant at 95% confidence level. The results show that heavy trucks have a fundamental influence on travel times. According to the results summarised in Table II, using passenger car equivalency units is insufficient to replicate the influence of heavy trucks in heavy traffic conditions. Using an exclusive term for heavy trucks in BPR travel time equation can better estimate the travel times for more than 10% (adjusted R^2 has increased from 0.723 to 0.831).

As mentioned earlier, the BPR travel time function has a simple structure. However, this model is accurate in $\frac{v}{c}$ of less than 1 (unsaturated conditions). When congestion starts ($\frac{v}{c}$ is close to 1) and traffic volume, v, decreases because of lower speeds, the BPR function is not reliable in travel time prediction and results in unrealistic values. Because the current research focuses on heavy traffic conditions (level of service E), the Akçelik's time dependant travel time function [26, 27] is also used in this paper to estimate the link travel times (Equation (4)). The Akçelik's travel time functions can be used at different congestion levels.

$$t = t_{of} + 0.25T_p\left[z + \sqrt{z^2 + \frac{m_c \times x}{Q \times T_p}}\right] \quad (4)$$

where

t = travel time for one kilometre length of road (seconds)
t_0 = $3600/v_{of}$ (seconds) (v_{of} is the zero-flow travel speed in kilometres per hour or km/h)
T_p = peak flow (analysis) period in hours, which is 45 min or 0.75 h in this research
Q = practical capacity (passenger car units per hour, pcu/h)
z = $x - 1$
x = q_a/Q (q_a is the demand flow rate in passenger car units per hour or pcu/h)
m_c = delay parameters.

Similarly, a term related to heavy truck percentage is introduced into Equation (4), which reflects the impact of heavy trucks on average travel time (Equation (5)). The new equation (Equation (6)), which

Table II. Estimation results of the (BPR) travel time equation and heavy truck model*.

BPR travel time equation			Heavy truck model		
Parameter	Parameter value	*t*-statistic	Parameter	Parameter value	*t*-statistic
α	0.408	13.61	λ	4.262	3.78
β	3.754	6.48	δ	2.297	5.92
Adjusted R^2		0.723	Adjusted R^2		0.831

*Number of observations = 90.

has a similar structure to Equation (3), is used to estimate the average travel times in I-80. To ensure valid comparison, m_c is estimated first. Then, the heavy truck term is added to the calibrated model, and parameters of the heavy truck model are estimated (γ and μ). The free flow speed is assumed to be 130 km/h for I-80 in this procedure.

$$t = t_{of} + 0.25T_p\left[z + \sqrt{z^2 + \frac{m_c \times f(HT) \times x}{Q \times T_p}}\right] \tag{5}$$

$$f(HT) = \gamma(HT)^{\mu} \tag{6}$$

where HT is equal to heavy truck proportion, and γ and μ are parameters.

Similar to the BPR function, the percentage of heavy trucks is increased from 2.2%, 1.7% and 1.3% of the total traffic in different time intervals to 30% with a 1% increment in order to calibrate the parameters of the Akçelik's travel time equation. Because of the stochastic nature of simulation models, the model is run for 10 times at each increment, and the average values of travel time obtained from 10 times running the model is calculated. The same dataset is used to estimate the parameters of $f(HT)$. The estimation results for the calibrated Akçelik's travel time equation as well as the heavy truck model are summarised in Table III. In this table, the t-statistic for each parameter is the ratio of estimated value for that parameter through non-linear regression model to the standard error.

In the Akçelik's travel time equation and the heavy truck model, all the estimated parameters are significant at 95% confidence level. According to the results, heavy trucks have a fundamental influence on travel times. Considering the direct influence of heavy vehicles by using an exclusive term for heavy trucks can improve the accuracy of the Akçelik's travel time function in estimating the travel times by around 12% (adjusted R^2 has increased from 0.738 to 0.852).

5.2. Influence of heavy trucks on traffic safety

As mentioned earlier, the limited operational characteristics of heavy trucks as well as the frequent lane changing manoeuvres of passenger cars in their vicinity may cause speed and traffic flow oscillations [9, 10, 20]. Frequent lane changing manoeuvres along with traffic flow and speed oscillations will increase the risk of accidents.

Previous safety studies mainly used aggregated accident data. Those studies mainly focused on the relationship between traffic accidents and corresponding variables such as traffic volume, speed and geometry conditions [28, 29]. It was identified that in locations with high heavy truck volumes, accidents occur frequently because of passenger car/heavy truck interactions. For instance, heavy trucks are about three times more likely to be struck in the rear than passenger cars [28, 29]. In this research, rear-end accidents are analysed as a common type of accidents involving heavy trucks. Some previous studies considered safety surrogate measure in developing accident trigging factors. This measure is used for rear-end accidents, which is the most common form of accidents on highways/freeways. The surrogate measure includes a safe headway distance (SHD) and a time to collision [30, 31]. In this measure, the minimum stopping distance of the leading vehicle should be larger than the minimum stopping distance of following vehicle. The same measure is used in this paper to investigate the likelihood of rear-end accidents caused by heavy trucks (Equations (7) and (8)).

Table III. Estimation results of the Akçelik's time dependant travel time equation and heavy truck model*.

Akçelik's travel time equation			Heavy truck model		
Parameter	Parameter value	t-statistic	Parameter	Parameter value	t-statistic
m_c	16.922	7.92	γ	4.156	4.83
			μ	1.834	7.12
Adjusted R^2		0.738	Adjusted R^2		0.852

*Number of observations = 90.

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Minimum stopping distance of leading vehicle > *Minimum stopping distance of following vehicle* (7)

$$2.366\times(v_{lead}\times h)+\left[\frac{v_{lead}^2}{30\times\left(\frac{acc}{g}\pm Gr\right)}\right]>2.366\times\left(v_{follow}\times PRT\right)+\left[\frac{v_{follow}^2}{30\times\left(\frac{acc}{g}\pm Gr\right)}\right] \quad (8)$$

where

v_{lead} = leading vehicle's speed (kilometres per hour, km/h)
v_{follow} = following vehicle's speed (kilometres per hour, km/h)
acc = deceleration rate (metres per second square, m/s^2)
g = gravity acceleration ($9.81\ m/s^2$)
Gr = grade (%)
h = time headway (seconds)
PRT = perception reaction time of the following vehicle (seconds).

Using Equation (8), an individual SHD for a pair of two consecutive vehicles can be defined as the difference of two minimum stopping distances of vehicles as follows:

$$diff_i = 2.366\times\left(v_{lead}\times h - v_{follow}\times PRT\right)+\left[\frac{v_{lead}^2 - v_{follow}^2}{30\times\left(\frac{acc}{g}\pm Gr\right)}\right] \quad (9)$$

$$SHD_i = \max\left(-diff_i,\ 0\right) \quad (10)$$

where

i = index of a pair of two consecutive vehicles
SHD_i = safe headway distance of the i^{th} vehicle pair
$Diff_i$ = difference of two minimum stopping distances of the i^{th} vehicle pair.

Safe headway distance indicates the likelihood of accident for two pair of vehicles. The larger SHD indicates the greater likelihood that the following vehicle will collide with the lead vehicle. In this research, perception reaction time of the following vehicle is assumed as 1.7 s, which is consistent with the previous studies [32–35]. The influence of heavy trucks on the number of accidents is evaluated at two stages. At the first stage, the SHD values for each pair of vehicles are calculated using observed trajectory data. Then, the SHD values are calculated using AIMSUN simulation results after increasing the heavy truck volume to 30% of total traffic with 5% increments. The proportion of positive SHD values is considered as an indicator of likelihood of accidents involving heavy trucks. These results are presented in Table IV.

According to the results from Table IV, the likelihood of accidents rises by around 5% with the increase in proportion of heavy trucks in I-80 (30% heavy trucks). This confirms the results obtained from the previous studies. Existence of heavy trucks increases the likelihood of accidents, and the increase in proportion of heavy trucks intensifies the likelihood of accidents and therefore reduces the traffic safety. As mentioned earlier, the section of I-80 is about 503 m long between an on-ramp and an exit off-ramp. It should be noted that the auxiliary lane and its adjacent lane between the on-ramp and off-ramp are the locations of vehicles' acceleration/deceleration and weaving manoeuvres. Frequent accelerations/decelerations and weaving manoeuvres increase the risk of accidents. However, it is ideal to have longer sections for the safety analysis.

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Table IV. The proportion of positive safe headway distance values (in %) at different heavy truck percentages.

	Heavy truck (%)						
Time interval	Observed values*	5.0	10.0	15.0	20.0	25.0	30.0
4:00 to 4:15 PM	1.7	2.3	2.8	3.1	3.7	4.5	5.6
5:00 to 5:15 PM	1.2	1.9	2.2	2.6	3.3	4.1	4.9
5:15 to 5:30 PM	1.0	1.5	1.9	2.1	2.9	3.8	4.6

*The observed percentage of heavy trucks is 2.6%, 1.7% and 1.3% for 4:00 to 4:15 PM, 5:00 to 5:15 PM and 5:15 to 5:30 PM, respectively.

6. CONCLUSIONS AND RECOMMENDATIONS

Heavy vehicles have more influence on surrounding traffic compared with passenger cars. They impose physical and psychological effects on surrounding traffic because of their physical and operational characteristics. Despite the increasing number of heavy vehicles on highways and freeways, the influence of heavy vehicles on their surrounding traffic has received little attention. In this paper, the surrounding traffic characteristics of heavy vehicles and passenger cars were analysed and compared. To examine traffic characteristics of vehicles in the vicinity of heavy vehicles and passenger cars, space gaps and relative speeds of the vehicles in front/at the rear of heavy vehicles and passenger cars as well as changes in the speed of heavy vehicles and passenger cars were examined and compared. The trajectory data used in this study was made available for a highway section in USA with heavy traffic conditions (level of service E).

To better understand the influence of heavy vehicles on their surrounding traffic, they were classified into two separate classes based on their length. Heavy vehicles with the length of equal to or greater than 15 m were classified as heavy trucks, and those with the length of less than 15 m were considered as light trucks. The results showed larger front space gaps for heavy trucks compared with the front space gaps for light trucks and passenger cars. The existence of larger front space gaps may be due to the limitations in manoeuvrability of heavy trucks. The rear space gaps for heavy trucks were slightly larger than the rear space gaps for light trucks and passenger cars. This may be due to the safety concerns of the rear vehicle drivers when following heavy trucks. This could also be partially due to the limited visibility of drivers in the vehicles, which are immediately behind heavy trucks. Furthermore, the heavy trucks' speeds were generally lower than the speed of their surrounding vehicles. Analysing the speed changes of heavy trucks, light trucks and passenger cars showed that some variations exist in the speed of light trucks and passenger cars. This implies that drivers of these two vehicle types mainly adjust their speeds according to the speeds of their surrounding vehicles. However, heavy trucks' speed had less variation. Heavy truck drivers mainly keep a constant speed and do not change their speed frequently.

Light trucks and passenger cars had almost similar influence on their surrounding traffic characteristics, and therefore, the influence of heavy trucks on surrounding traffic was examined in this paper. The average travel times increased when the proportion of heavy trucks increased in each lane. In general, heavy trucks have lower speeds compared with passenger cars. Therefore, the increase in the proportion of heavy trucks may result in oscillations in the speed and increase the average travel times particularly in higher traffic densities and larger proportion of heavy trucks. To reflect the impact of heavy trucks on average travel time, a term related to heavy truck percentage was introduced into two different travel time equations including BPR and Akçelik's travel time functions. At the first step, the parameters of the BPR function were estimated. After estimating the parameters of the BPR equation, the results showed that using an exclusive term for heavy trucks in that travel time equation can better estimate the travel times for more than 10% (adjusted R^2 has increased from 0.723 to 0.831). BPR travel time equation has a very simple structure. However, this model is accurate in unsaturated traffic conditions. When congestion starts, the BPR function is not reliable in travel time prediction and results in unrealistic values. Because the current research focuses on heavy traffic conditions (level of service E), the Akçelik's travel time function was also used to estimate average travel times. The Akçelik's travel time equation was calibrated, and the heavy truck term was added to the equation.

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According to the results, heavy trucks have a fundamental influence on travel times. Using an exclusive term for heavy trucks could improve the accuracy of the Akçelik's travel time function in estimating the travel times by around 12% (adjusted R^2 has increased from 0.738 to 0.852).

BPR and Akçelik's travel time functions were used in this research as examples to evaluate the influence of heavy trucks on average travel time. This research can be applied to other travel time equations to investigate the influence of having an exclusive term for heavy vehicles on the accuracy of the estimation results. In addition, different model structures can be used for the heavy truck exclusive term. Based on the results, it is recommended that travel time equations be modified in traffic analysis/studies and simulation software packages in order to directly consider the influence of heavy trucks on average travel times. This is more important under heavy traffic conditions or when heavy vehicles comprise a large proportion of traffic.

Furthermore, the number of passenger car lane changing manoeuvres per lane increased when more heavy trucks existed in that lane. This implies that passenger car drivers try to avoid being in the vicinity of heavy trucks and therefore may attempt to move into other lanes. The influence of heavy trucks on the number of passenger car lane changing manoeuvres is intensified in higher traffic densities and larger percentage of heavy trucks. Number of lane changing manoeuvres is a good indicator of the potential for vehicular conflicts. Large numbers of lane changing manoeuvres can increase the number of traffic accidents and potentially reduce traffic safety. To evaluate the influence of heavy truck existence on the chance of accidents, surrogate measure was used to evaluate the likelihood of rear-end accidents in I-80 (the most common form of accidents on highways/freeways). The results showed an increase of 5% in the likelihood of accidents, when proportion of heavy trucks increased to 30% of total traffic. Increase in proportion of heavy trucks intensified the likelihood of accidents and therefore reduced traffic safety.

The results in this paper showed that heavy trucks have pronounced effect on traffic characteristics (e.g. average travel time and average speed). The existence of larger percentage of heavy trucks can increase the likelihood of accidents and reduce traffic safety. To reduce travel time and improve traffic safety in highways/freeways, heavy trucks can be restricted from particular lanes especially during congestion. Defining those lane restriction strategies for heavy trucks and evaluating the influence they have on traffic characteristics and likelihood of accidents would be another direction for future research.

7. LIST OF ABBREVIATIONS

BPR	Bureau of Public Roads
AIMSUN	Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks
FHWA	Federal Highway Administration
NGSIM	Next Generation SIMulation
CV	Coefficient of Variation
SHD	Safe Headway Distance

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