MODELING LEAD VEHICLE DYNAMICS THROUGH TRAFFIC SIMULATION AND FIELD DATA

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Abstract

The majority of existing driver-behavior and car-following data sets, upon which many models are based, are relatively old and focus primarily on the following vehicle instead of the lead vehicle. Therefore, the purpose of this study was to look at how lead vehicle speed varies along basic uniform roadway segments, with grade and with horizontal curvature in the microscopic traffic. The simulation results showed that lead vehicle speed will remain constant under any circumstances, irrespective of slope or grade, or road type. The simulation results may not, however, reflect real lead vehicle dynamics in the real world. The behavior of a lead vehicle at an intersection with a traffic signal was also investigated. When approaching a red light, a linear regression was drawn between lead vehicle deceleration distance and its original speed, i.e., the speed before deceleration. The study showed that at higher roadway speeds, more lead vehicles slowed down to pass the intersection with a green light. Moreover, this study examined how a change in speed for all vehicles in a curve is caused by the change in speed of the lead vehicle. The study, calibrated using field data, was carried out by an Application Programming Interface function in the advanced simulation model, namely AIMSUN. The results showed that if the speed of all of the lead vehicles is influenced by roadway curvature, i.e., there is a reduction in speed, the overall average speed of the traffic network will be affected in the same manner regardless of the volume and speed limit.

Introduction

In traffic engineering, increased computer power has resulted in increasing use of more microscopic traffic simulation models over larger traffic networks. Older models used primarily macroscopic traffic analyses, which involved the aggregate behavior of a traffic stream, characterized by its volume, speed, and density. Recently, microscopic traffic simulation models which track the temporal locations and velocity patterns of individual vehicles in small time steps—that could be as small as 0.10 second in some cases—have been attracting increased attention and receiving increased use. Microscopic simulation models use "car following theory" [1] to capture the changes in an individual vehicle's velocity and, thus, its location in response to the vehicle it is following; a lead vehicle. Recent work [2], [3] has indicated that assumptions regarding car following rules make a difference in emissions estimates and also to the overall aggregate traffic parameters produced by traffic simulation models. The majority of existing driver-behavior and car-following data sets are relatively old and focus primarily on the following vehicle instead of the lead vehicle.

While almost all microscopic traffic simulation models are stochastic based, very little attention has been paid to the lead vehicle dynamics. In other words, the models assume that every vehicle/driver has a relatively constant desired free-flow speed. This desired speed typically varies between simulated vehicles and is often a function of the speed limit on a given link. The percentile of a given driver on the desired speed distribution is assigned stochastically. If the vehicle is not following another vehicle, in other words it is leading, it travels this desired speed. Some models, such as PARAMICS, alter this speed due to horizontal curvature when it is coded into the network but, for the most part, this speed is assumed constant over time with no relationship to its surroundings. In reality, it is obviously reasonable to assume that grade and curvature also affect lead vehicle speed variability. Moreover, transportation planning researchers have illustrated that surrounding land use [4], as well as road and shoulder width, can affect speed.

Since the behavior of lead vehicles is the main input for second-by-second operations of the following vehicle via the car-following theories of microscopic traffic simulation models, studying the lead vehicle dynamics is important. This is especially true since the vehicle dynamics or modes are the new key input variables for emission models. It is essential to get the lead vehicle dynamics to replicate real-world driver behavior to make traffic simulation models useful for modal emission modeling. Some researchers have pointed to the need to collect lead vehicle data [2], but to date none have been collected. Most car-following tests that have been carried out in an effort to advance car-following models were conducted on test-track facilities and in vehicular tunnels [5]. In these tests, lead vehicle speed usually followed a predetermined speed pattern, including constant, random, or sinusoidal patterns [6-8]. Therefore, there is not a complete understanding of how lead vehicle speed varies with grade, with horizontal curvature, or as vehicles accelerate or decelerate within the network along basic uniform roadway segments.. In addition, it is unknown whether the behavior of all drivers is relatively the same, or if variation from person to person is large enough that a certain number of distinct driver categories must be established for modeling purposes.

The critical second-by-second vehicle operations in a simulation model are dictated by microscopic flow theory or so-called car-following models. The majority of existing driver-behavior and car-following data sets, upon which these models are based, are relatively old and focus primarily on the following vehicle instead of the lead vehicle. In addition, simulation models typically assume that lead vehicles travel at a relatively constant desired speed with minor, random acceleration or deceleration changes. The limited study of lead vehicles is surprising because the behavior of lead vehicles is the most fundamental input to the microscopic car-following theories and, therefore, affects accuracy. As such, it is necessary to understand the lead vehicle dynamics over different roadway and traffic conditions and to use this information to replicate real-world driver behavior. Furthermore, the lead vehicle typology developed in this current study will be essential for establishing the type and size of driver samples needed for future real-world driving data collection.

Objectives

If a vehicle is not following another vehicle, it can be seen as a lead vehicle. A lead vehicle should travel at its desired speed, the maximum allowable speed. In reality, it seems reasonable to assume that the desired speed might not be fixed but in fact vary with each basic roadway segment, grade, and horizontal curve. To test such an assumption, microscopic traffic simulation models that are based on 'car -following theory' appear easy to employ due to their conceptual similarities with the assumption.

The purpose of this study, then, was to evaluate how lead vehicle speed varies along basic uniform roadway segments, with grade and with horizontal curvature in the microscopic traffic simulation environment, using AIMSUN. The next section presents the experimental method of capturing lead vehicle information, and the three subsequent sections focus on testing the three hypotheses, which are:

Hypothesis 1: Lead vehicle velocity is influenced by horizontal curvature over all kinds of roadway types.
Hypothesis 2: Lead vehicle velocity is influenced by grade over all kinds of roadway types.
Hypothesis 3: Lead vehicle deceleration rate is influenced at intersections with signals for both green and red lights.

In addition, the study investigated how the change in speed at a curve for all vehicles is caused by the change in the speed of the lead vehicle using field data.

Detect Lead Vehicles in Simulation

Lead vehicle means the vehicle is unconstrained by a vehicle in front of it. In this simulation study, a lead vehicle was defined as one where no other vehicle has passed the current position in the same lane within the past 5 seconds. This definition is consistent with the one used in the field data collection process, where constrained driving was considered when the driver was following another vehicle with less than a five-second headway or the brake lights illuminated on a vehicle ahead of the instrumented vehicle [8]. Additionally the five-second time interval/headway is equivalent to a 330ft headway on an urban road with an average speed 45 mph, or 513 feet on a freeway with an average speed of 70 mph.

Lead Vehicle Dynamics on Horizontal Curves

Lead vehicle dynamics on horizontal curves were studied using AIMSUN as the simulation tool. As shown in Figure 1, a study area in the city of Hartford, CT, was selected including a segment of I-91 with both on and off ramps, several urban streets with eight signalized intersections, one stop sign, and one yield control. The traffic was comprised of cars, trucks, and buses.

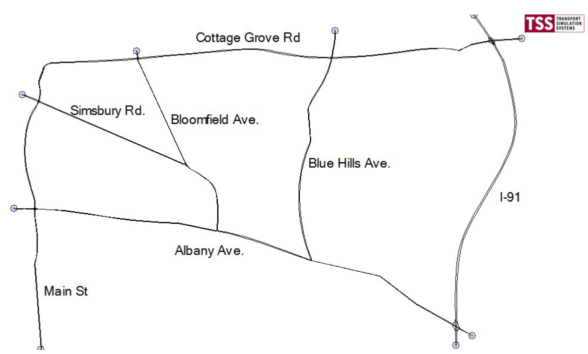

Figure 1. Traffic Network of the Study Area

Figures 2 and 3 detail the placement of detectors on two horizontal curves on an urban street—Cottage Grove Road (Figure 2); and the I-91 freeway (Figure 3), in order to determine whether or not the horizontal curvature affects the velocity of a lead vehicle. One detector was set before the curve and the other within the curve. The speed of the lead vehicle was measured and compared by these two detectors as it passed them.

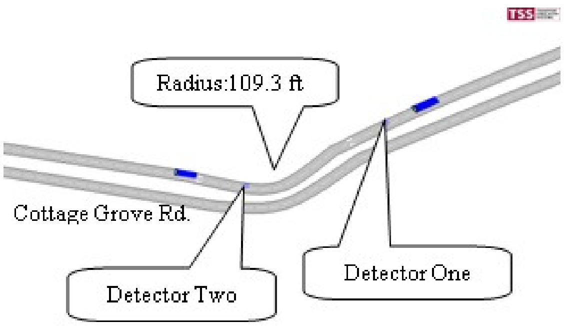

Figure 2. Lead Vehicle Velocities with Urban Street Horizontal Curves

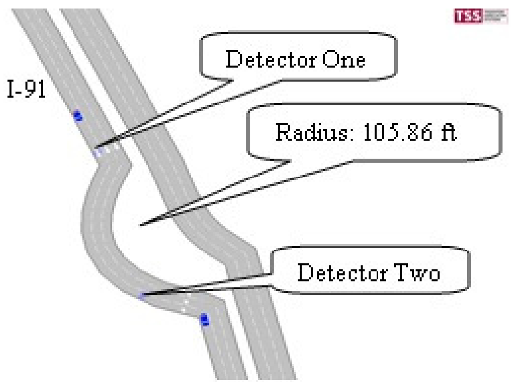

Figure 3. Lead Vehicle Velocities with Freeway Horizontal Curves

The simulation was run for 20 minutes. In total there were 75 lead vehicles going through the curve on the urban street, all of which showed no change in velocity (less than 1 mile per hour). Similarity, the 164 lead vehicles detected on the freeway segment also exhibited no change in velocity. The study showed that lead vehicle speeds will stay constant on a curved road on any type of roadway in the simulation environment, AIMSUN.

Lead Vehicle Dynamics on Roadway Grades

Lead vehicle behavior affected by grade was examined using AIMSUN. As shown in Figures 4 and 5, a segment on Blue Hill Avenue (Figure 4), an urban street with an 8.02 percent grade, and a segment on I-91 (Figure 5), a freeway with a -8.52 percent grade, were chosen. Two detectors were placed in each segment: one in advance of the grade and the other on the peak of the grade. The simulations were run for 20 minutes. Based on the data recorded by the detectors, including the number of vehicles and their speeds, sixty-six lead vehicles were captured going past the Blue Hill Avenue detector and eighty-seven lead vehicles were recorded on the freeway. None showed any change in speed. The results of the simulation using AIMSUN showed that neither lead vehicle behavior nor speed was affected by grade.

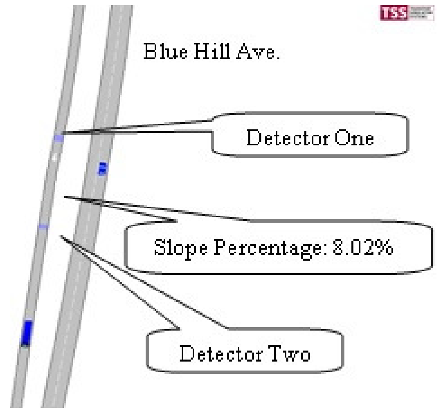

Figure 4. Lead Vehicle Velocities with Urban Street Slopes

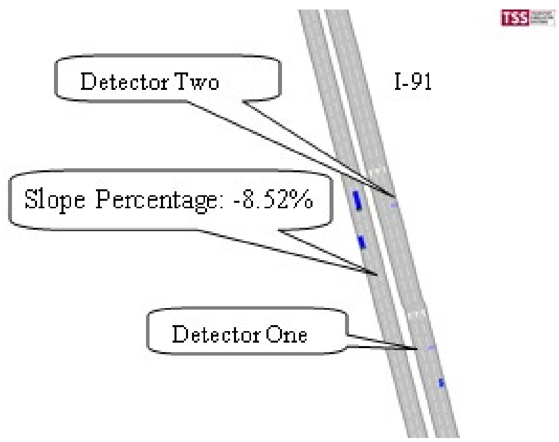

Figure 5. Lead Vehicle Velocities with Freeway Slopes

Lead Vehicle Dynamics at Intersections

In this section, the behavior of a lead vehicle at an intersection with a traffic light was investigated. Two scenarios were considered: one was to study how a lead vehicle responds to a red light, while the other was how it reacts to a green light when approaching the intersection.

Approaching a Red Light

It was found that all vehicles would reduce their speed when approaching a red light. Without the interference of other vehicles ahead, the extent to which a lead vehicle responds to this scenario is simply a function of its perception of and reaction to the red stop signal. This experiment studied the deceleration distance of a lead vehicle since it was easier to measure and more intuitive to understand. The deceleration distance measures the distance that a lead vehicle travels from its current speed to a dead stop with a constant rate of deceleration. The intersection at Main Street and Albany Avenue was studied, as illustrated in Figure 6. The approach roads were selected so that road design elements such as grade and curvature would not affect the vehicles' change in speed.

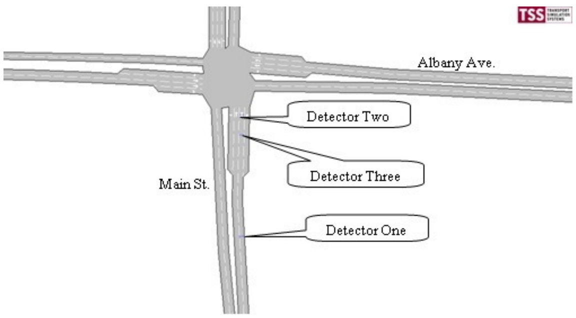

Figure 6. Lead Vehicle Deceleration Distance with Traffic Signal

Detector One (Figure 6) was placed 305.9 feet away from the stop line of the intersection. A vehicle was determined to be leading if no other vehicle passed the detector within 5 seconds of that vehicle. For a lead vehicle approaching a red traffic signal, its speed was tracked and measured at every simulation step as it traveled to the stop line. Once the lead vehicle started to decelerate, the distance to the stop line was determined to be the deceleration distance.

In order to study the relationship between vehicle speed and deceleration distance, three speed ranges were examined: 20~30 mph, 30~40 mph, and 40~50 mph. A simulation of 20 minutes was used for each scenario. A total of 129 lead vehicles approaching a red light were evaluated and their corresponding deceleration distances were measured. Figure 7 shows the relationship between lead vehicle speed before deceleration (mph) and the deceleration distance (feet).

A linear regression was performed on the experimental data and the following equation was derived:

$$y = 5.547x - 41.712 + \varepsilon$$

where

y = Lead vehicle deceleration distance while approaching the red light (feet)

x = Lead vehicle speed before deceleration while approaching the red light (mph)

ε = A normal distribution with a mean of 0 and a standard deviation of 38.68 feet

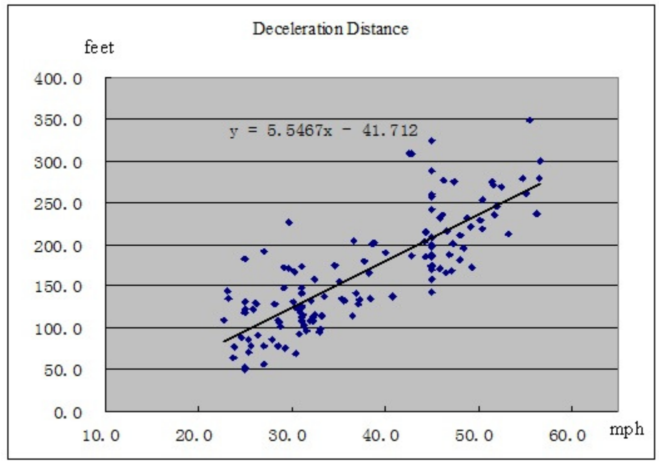

Figure 7. Lead Vehicle Speed before Deceleration vs. Deceleration Distance

The R value in this regression model was 0.809. Moreover, both the ANOVA and T-test showed that the P-value of the coefficient of the slope was 4.15×10^{-31}, which means that there was a strong linear relationship between the lead vehicle deceleration distance and its speed before deceleration. In addition, the domain of this model was that x was between 10 and 60 mph, as this was on an urban road.

Approaching a Green Light

How a lead vehicle changes its speed when approaching a green light at an intersection is discussed in this section. The hypothesis was that 'aggressive' lead drivers would speed up at a green light, while 'safe' lead vehicle drivers would slow down. At the intersection of Main Street and Albany Avenue, two more detectors were added on the intersection approach: Detector Two and Detector Three, as shown in Figure 6. Detector One was still used to test whether or not a vehicle was a lead vehicle, based on the 5-second rule. Once the detector captured a lead vehicle while the traffic light was green, then the vehicle would be tracked as such. When the tracked lead vehicle passed through Detector Two with the same green light, its speed was compared with that from Detector One. If a reduction or increase in speed of 2 mph or more occurred, the speed change was noted.

This study excluded the following two scenarios:

1) The traffic light switched to red while the lead vehicle was passing through Detector Two.

2) If there was a significant number of queued vehicles ahead of the lead vehicle that prevented it from traveling freely through the intersection. The scenarios could be easily detected with Detector Three, which was placed close to the stop line in order to measure any queued vehicles.

A series of vehicle original speeds (speed before slowing down or speeding up) were examined and are presented in Table 1. It was found that no lead vehicle changed its speed passing the junction with an original speed of less than 30 mph. The higher the original speed, the higher the percentage of vehicles that slowed down. When the original speed reached 45 mph, all of the lead vehicles slowed down at the intersection. It is worth pointing out that at speeds above 50 mph, one vehicle sped up while the rest slowed down.

Table 1 Variation of Lead Vehicle Speed at Green Light Intersection

Original Speed	Number of vehicles speed unchanged	Number of vehicles speed decreased	Number of vehicles speed increased
0~30 mph	13	0	0
30~35 mph	18	2	0
35~40 mph	12	5	0
40~45 mph	4	12	0
45~50 mph	0	15	0
50mph and above	0	13	1

Figure 8 illustrates how the speed decreased compared with various approaching speeds. The x axis in the figure shows the speed before slowing down, while the y axis is the speed reduction when the vehicle went through the intersection with a green light.

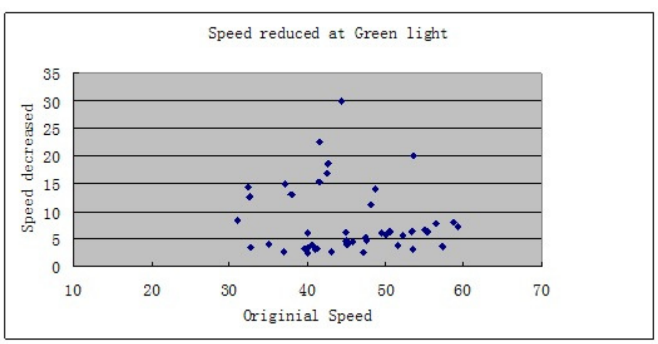

Figure 8. Speed Reduction at Green Light versus Vehicle Approaching Speed

The ANOVA analysis showed that the data were randomly distributed and there was no obvious linear or other relationship discovered between these two factors.

Simulation using Field Data

Change of Lead Vehicle Speeds in the Simulation by Application of a Programming Interface (API)

The simulation study showed that lead vehicle speeds are NOT affected either by horizontal curvature or grades on various types of roadways (with different posted speed limits). The field study suggested that there were statistically significant differences in speed and acceleration patterns for older and younger lead drivers [8].

This section reviews how the speed at a curve for all vehicles, caused by the change in the lead vehicles' speed, changed. A segment on the study route used in the Belz and Aultman project [8] was selected. As shown in Figure 9, the radius of the curve was 175.35 feet. The total length of the curved road was then set to be 601.56 feet. The speed limit of the road was 40 mph, one lane per direction. The study period was 9:00am to 9:20am. The traffic composition was 90% cars and 10% trucks. As shown in Figure 9, two detectors were planned, one at the beginning and the other at the end of the curve.

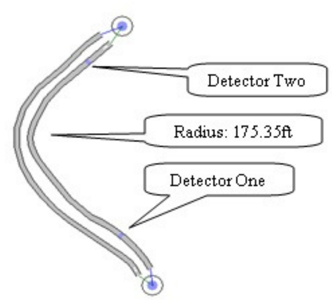

Figure 9. Study Scenario

Since the simulation software, similar to AIMSUN, does not automatically change the speed of a vehicle when it negotiates a curve, the study applied an Application Programming Interface (API) to manually change the speed of all lead vehicles. The flowchart of Figure 10 describes how the API was applied in order to achieve this purpose.

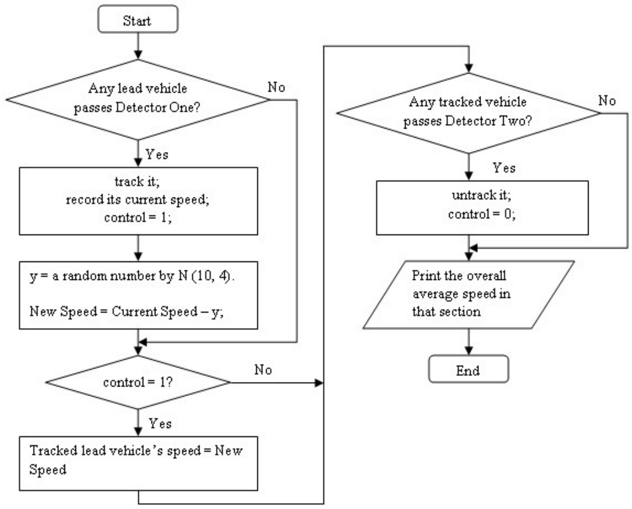

Figure 10. Flowchart of API to Manually Control the Speed of Lead Vehicle

An API is available as an advanced feature in some simulators such as AIMSUN to provide an interface connection between user-defined applications and the simulation environment. The flowchart of Figure 10 was repeated in every simulation step. It showed that once Detector One captured a lead vehicle, it would be tracked and its speed reduced. The reduction is stochastically assigned following a Normal Distribution with a mean of 10 mph and a standard deviation of 4. The vehicle traveled at this reduced speed within the curve. After it passed the curve and Detector Two, the vehicle would be released from its "tracking" status and allowed to resume a speed automatically assigned by the simulation software based on its characteristics and the speed limit of the roadway.

Impact of Lead Vehicle Speed Change to the Overall Network given a Speed Limit of 40 mph

Table 2 presents the average speed of all vehicles passing that section during a 20-minute period where the roadway speed limit was 40 mph. Two scenarios were considered: one without API control to represent that there would be no change in lead vehicle speed, and one with API control to show where all lead vehicles are forced to slow down according to the distribution explained in Figure 10. The overall average speed of all vehicles in that section without API control and with API control under different traffic volumes were compared and summarized in Table 2. Here, API only controls the speed of the lead vehicles.

Table 2. Overall Average Speed affected by Lead Vehicle Speed Changes

Volume Vehicles per hour	Overall Average Speed without API	Overall Average Speed with API	Difference
200	43.56	36.25	7.31
600	42.57	37.68	4.89
1000	41.70	37.26	4.44
1400	40.31	36.77	3.54
1800	38.09	36.03	2.06

(Roadway: Speed limit = 40 mph)

The results shown in Table 2 clearly indicate that the overall average network speed decreased when the network traffic got heavier, if there was no change on lead vehicle speed (i.e., without API control in the simulation). However, the situation was quite different for the case where the lead vehicles did change their speed in order to negotiate the curve (i.e., with API control in this experiment). The simulation showed that the overall speed fluctuated between 36 and 37 mph. Since the speed of the lead vehicles was reduced by a random value with a standard deviation of 4 mph, compared to the speed standard deviation of 0.58 mph in Table 2, it was believed that traffic volume was independent of overall average speed. The finding suggests that if the speed of all lead vehicles is affected by the curvature, i.e., resulted in a reduction in their speed, all of the vehicles in the entire network would be affected in the same manner, regardless of the volume.

Impact of Lead Vehicle Speed Change to Overall Network for Various Speed Limits

This section presents the results of whether or not the roadway speed limit affected the results. Table 3 shows the results for a local road of 25 mph and a freeway of 60 mph. Both cases showed consistent results with the speed limit of 40 mph. The overall average speeds decreased while the traffic volume increased. However, with a drop of lead vehicle speed, there seemed to be little impact on the overall network speed by the change of volume.

As shown in Tables 2 and 3, the differences in average speed (the last column) were approximately the same in terms of a variety of traffic demands. It means that API reduced almost the same amount of speed from its original speed under different speed limits. Hence, the reduction of network speed by API is independent of the speed limit.

Table 3. Overall Average Speed affected by Lead Vehicle Speed Changes

Speed limit mph	Volume Vehicles per hour	Overall Average Speed without API	Overall Average Speed with API	Difference
60	200	62.49	55.96	6.53
	600	61.21	55.52	5.69
	1000	59.84	55.38	4.46
	1400	58.46	55.90	2.56
	1800	55.95	54.43	1.52
25	200	27.14	19.83	7.31
	600	26.19	20.72	5.47
	1000	25.33	19.87	5.46
	1400	24.55	19.96	4.59
	1800	23.06	20.42	2.64

(Roadway: Speed limit = 60 mph and 25 mph)

Impact of Each Vehicle Speed Change to the Overall Network

An interesting experiment was conducted to study how the network would behave if each vehicle would respond to the curvature by reducing its speed following a statistical distribution, explained in Figure 10. Table 4 presents the comparison of two cases for a roadway of 40 mph: one with speed control of each vehicle, and one with speed control of the lead vehicle only.

Table 4 A Comparison of Overall Average Speed

Volume Vehicles per hour	Overall average speed with control of each vehicle	Overall average speed with control of lead vehicles
200	33.95	36.25
600	10.40	37.68
1000	6.87	37.26
1400	3.60	36.77
1800	3.54	36.03

(Roadway: Speed limit = 40 mph)

It was surprising to discover that the overall average speed with a control of each vehicle's speed decreased very quickly with an increase of traffic volume. The reason is that with an application of normal distribution, the speed reduction of each vehicle is randomly assigned (so that some vehicles slow down much more than others do). As a result, a vehicle with a current speed of 40 mph might be forcefully slowed down to 15 mph, which would create a bottle-network or slow-moving queue scenario in the traffic and, therefore, have a more profound impact on the entire network.

Conclusion

The simulation results showed that lead vehicle speed will remain constant in any circumstances, whether with slope or grade changes and on all selected road types. With real-life experience, it is reasonable to assume that lead vehicle speed and acceleration are affected by the curvature and grade of the road. These hypotheses were also validated by field studies [9], [10]. Hence, the results generated by the microscopic traffic simulation model do not match the proposed hypotheses. It is believed that the simulation does not reflect lead vehicle dynamics in the real environment. Some detailed findings and justifications about the simulation study are provided below:

First, in AIMSUN, when a car is travelling on a horizontal surface, its speed will be affected by three factors: maximum desired speed of the vehicle, speed acceptance of the vehicle, and speed limit of the section or turn. The maximum desired speed is a maximum value between a speed generated by the characteristics of the driver and a speed imposed by the presence of a vehicle in front of it, neither of which take into account road geometric information. Speed acceptance of a vehicle is part of a driver's characteristics which still do not include effects of the geometry of the section. The only geometric information of the sections is the speed limit of the section that is unfortunately a fixed value, so it becomes very easy to understand why the vehicle speed will not be affected by any horizontal curvature of the section.

Secondly, in AIMSUN, when a vehicle is travelling on a section with a slope, the slope percentage will only change its maximum acceleration. The calculation of the vehicle velocity uses the same calculation for when the vehicle is on a horizontal surface. Therefore, the slope percentages will not change the vehicle speed. In other words, AIMSUN is just a program that applies the microscopic traffic simulation in a mathematical way, and cannot replace field tests.

Moreover, the behavior of a lead vehicle at intersections with traffic signals was investigated. When approaching a red light, a linear regression was drawn between lead vehicle deceleration distance and the vehicle's original speed; i.e., the speed deceleration before deceleration. However, the data also showed a more random distribution when approaching a green light. The study showed that the higher the roadway speed, the higher the percentage of lead vehicles that slowed down. More lead vehicles would reduce their speed when they travel on the higher speed roadways when approaching an intersection with a green light.

Finally, how the change in speed at a curve for all vehicles caused by the change in speed of the lead vehicles was studied using field data. An API was developed to manually carry out this plan in the simulation. The findings show that if the speed of all of the lead vehicles is affected by curvature, i.e., resulted in a reduction in speed, all of the vehicles in the entire network would be affected in the same manner regardless of the volume and speed limit.

It is suggested that a more realistic speed distribution of lead vehicles responding to the external environment, e.g., curvature or grade, should be used in the simulation. Data collection on various driver populations with different behavior or age groups is absolutely necessary to enhance the accuracy of the simulation.

Acknowledgement

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