Truck acceleration behavior study and acceleration lane length recommendations for metered on-ramps

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A R T I C L E   I N F O

A B S T R A C T

This paper investigated the actual truck acceleration capability at metered on-ramps. Truck acceleration performance data were collected through a video-based data collection method. A piecewise constant acceleration model was employed to capture truck acceleration characteristics. It was found that the existing acceleration length will affect truck drivers' acceleration behavior. At the taper type ramp that has limited acceleration distance, acceleration profile indicated a decreasing trend with distance. While for the ramp with an auxiliary lane that has sufficient acceleration distance, it was found that the acceleration behavior is to have a high acceleration rate in the beginning, then acceleration rate decrease with speed increase, and high acceleration rate again as drivers approach the merging area. Field data show that the truck acceleration performance data documented in the ITE's (Institute of Transportation Engineers) "*Traffic Engineering Handbook*" are much lower than the field collected data. Also, based on the regression analysis of speed versus distance profiles, it was found that the AASHTO's (American Association of State Highway and Transportation Officials) Green Book acceleration length design guidance is insufficient to accommodate trucks at metered on-ramps. The required acceleration lengths for medium and heavy trucks are approximately 1.3 and 1.6 times of the Green Book design guideline, respectively.

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Introduction

Currently, the 2011 American Association of State Highway and Transportation Officials (AASHTO) Green Book, "*A Policy on Geometric Design of Highways and Streets*" (AASHTO, 2011) is employed by most state DOTs in the U.S. for metered on-ramp acceleration lane length design. Nevertheless, it was found that the acceleration lane length values documented in the 2011 AASHTO Green Book closely match the values in the 1965 AASHTO Blue Book, "*A Policy on Geometric Design of Rural Highways*" (AASHTO, 1965). Since the acceleration lengths documented in the 1965 AASHTO Blue Book were developed based on passenger car acceleration data produced from a 1938 Bureau of Public Roads study titled "*Speed-Change Rates of Passenger Vehicles*" (Loutzenheiser et al., 1938), the recommended acceleration lengths in the Green Book are designed to accommodate passenger cars, which might be too short for heavy vehicles with poorer performance characteristics, such as tractor-trailer trucks.

The impacts of truck acceleration capability on freeway on-ramp acceleration lane length design have caused transportation engineers' concern since the 1950s (Deen, 1954). A number of studies have been conducted in attempts of investigating the truck speed and acceleration profiles (Rakha et al., 2001; Rakha and Lucic, 2002; Gattis et al., 2010) and updating freeway on-ramp acceleration length design for trucks (Fancher, 1983; Harwood et al., 2003; Gatties et al., 2008). However, there is no specific document to date that provides truck acceleration performance data for acceleration length design at metered on-ramps. When an on-ramp is metered, approaching vehicles have to stop at the ramp meter signal before accelerating again and merging to the freeway mainline traffic flow. Such meter-to-merge operation poses great challenges to trucks since trucks usually have lower acceleration capability than passenger cars and thus require a longer acceleration distance to catch up with the freeway mainline speed. Insufficient acceleration lane length could have significant highway performance and safety implications. Trucks unable to accelerate to freeway mainline speeds will cause delays at the interchange as well as increase the potential for collisions. Therefore, actual truck acceleration performance data are especially critical for acceleration length design at metered on-ramps where substantial truck volumes exist.

The purpose of this paper is to investigate the actual truck acceleration performance data at existing ramp-metering locations. The intent of the findings is to better accommodate the acceleration characteristics used by truck drivers in a real world setting, which would eventually be used for determining acceleration lane length at new proposed ramp metering sites or retrofitting of existing unmetered ramps with high truck volume. The remainder of the paper is organized as follows: firstly, a brief literature review to summarize the existing truck acceleration studies; then, framework of the piecewise constant acceleration model for modeling acceleration characteristics; after that, data collection at typical ramp-metering sites and the data processing approach; then, truck acceleration profile analyses are presented; and finally, major findings and limitations of this study.

Literature review

In the 1950s, Deen (1957) investigated the acceleration behavior of heavy commercial vehicles and made recommendations regarding acceleration lane length design for heavy vehicles. Based on the field collected actual acceleration performance data of loaded sample vehicles, the author concluded that the acceleration lane lengths presented in the 1954 AASHTO Blue Book (AASHTO, 1954) were adequate only for single unit trucks at design speeds of 50 mph or less and were adequate for semitrailer trucks at design speed of 30 mph or less. Additionally, the author pointed out that the design of acceleration lanes should accommodate heavy commercial vehicles to accelerate to the desired freeway mainline speed.

The NCHRP (National Cooperative Highway Research Program) Report 505 "*Review of Truck Characteristics as Factors in Roadway Design*" (Harwood et al., 2003) discussed the role of truck characteristics on roadway designs. The main purpose of that research project was to examine whether the geometric design criteria presented in the Green Book could reasonably accommodate the dimensions and performance characteristics of trucks. Based on a 180 lb/hp truck and similar conditions used in the Green Book, it was found that the minimum acceleration lane lengths were about 1.8 times greater than the minimum acceleration lane lengths provided in the Green Book. A similar study made by Gattis et al. (2008) examined attributes such as weight and speed associated with tractor-trailer trucks accelerating on freeway on-ramps. Mathematical models were developed to predict average and 10th percentile speeds of tractor-trailer trucks on slight upgrades, downgrades and level conditions. The researchers then proposed calculated acceleration lane lengths at freeway on-ramps using predicted average truck speeds from the developed model. It was found that the obtained acceleration lengths are substantially longer than those proposed in the Green Book.
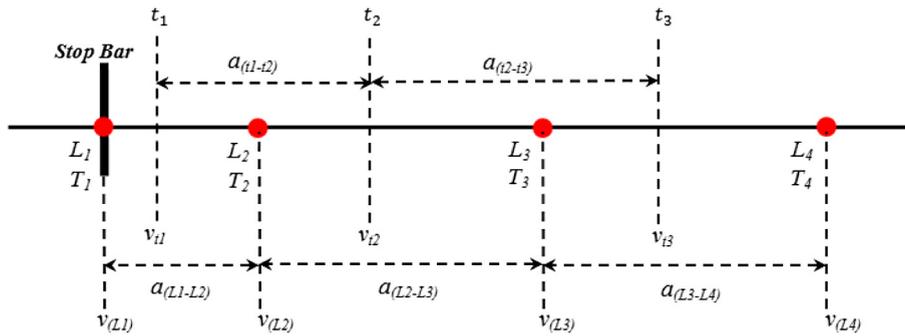
Another source for truck acceleration performance data is the ITE's (Institute of Transportation Engineers) "*Traffic Engineering Handbook*" (Pline, 1999). This handbook provides tables and charts that describe the speed versus distance relationships during maximum acceleration rates for tractor-semitrailer trucks with various weight-to-power ratios, as reproduce in Table 1. However, it is necessary to clarify that the truck acceleration data presented in the ITE Traffic Engineering Handbook were developed based on the 1970 SAE's (Society of Automotive Engineers) study (Hutton, 1970), which seems to be outdated in describing the current driving pattern and required acceleration lengths. Also, the maximum accelerations are not adequate to determine the proper acceleration lengths required on the freeway because the acceleration behavior of vehicles depends not only on vehicle capabilities but also on driver behavior. In reality, drivers usually accelerate at normal acceleration rates, which is lower than the maximum capability.

Nevertheless, all the aforementioned truck acceleration performance studies were focused on un-metered ramps, without consideration of the potential impacts of ramp metering on drivers' acceleration behavior. In reality, acceleration capability of different vehicle types vary and are usually influenced by prevailing traffic conditions and road geometric features. When drivers realize there is limited distance ahead for acceleration, they are more likely to accelerate at a higher rate to quickly pick up the freeway mainline speed. A previous acceleration characteristic study for metered on-ramps found that existing acceleration lane lengths will affect drivers' acceleration behavior; ramps with a shorter existing acceleration lane tend to produce higher acceleration rates (Yang et al., 2015). With consideration of the potential impacts of ramp metering on drivers' acceleration behavior, existing truck acceleration studies may not be applicable for metered on-ramp acceleration length design. Therefore, it is of significant importance to investigate the actual truck acceleration capability at existing metered on-ramps to determine the sufficient acceleration length that could accommodate truck drivers to accelerate to a desired merge speed.

Table 1
Typical maximum acceleration rates for tractor-semitrailer combination trucks documented in the ITE traffic engineering handbook (Pline, 1999).

Vehicle type	Weight-to-power ratio (lb/hp)	Typical maximum acceleration rate on level road (ft/s^2)				
		0–10 mph	0–20 mph	0–30 mph	0–40 mph	0–50 mph
a. Maximum acceleration from standing start						
Tractor-semitrailer	100	2.9	2.3	2.2	2.0	1.6
	200	1.8	1.6	1.5	1.2	1.0
	300	1.3	1.3	1.2	1.1	0.6
	400	1.3	1.2	1.1	0.7	NA

Vehicle type	Weight-to-power ratio (lb/hp)	Typical maximum acceleration rate on level road (ft/s^2)			
		20–30 mph	30–40 mph	40–50 mph	50–60 mph
b. Maximum Acceleration for 10 mph Increments					
Tractor-semitrailer	100	2.1	1.5	1.0	0.6
	200	1.3	0.8	0.5	0.4
	300	1.0	0.6	0.3	NA
	400	0.9	0.4	NA	NA

Fig. 1. Parameters and procedure for piecewise-constant acceleration data extraction.

Piecewise-constant acceleration model

In this paper, it is assumed vehicles make a uniformly accelerated motion within each short time or space interval. A piecewise-constant acceleration model is employed to analyze vehicle acceleration characteristics at metered on-ramps. As illustrated in Fig. 1, C_i means the ith reference cone and L_i is the location of the ith reference cone from the ramp meter stop bar, which is pre-determined prior to placing the cone. T_i is the time point of a vehicle passing the reference cone C_i, which is extracted from the video camera. The average speed between adjacent cones of C_i and C_{i+1} is calculated by the following equation:

$$V_{i \sim i+1} = \frac{L_{i+1} - L_i}{T_{i+1} - T_i} \qquad (1)$$

Based on the assumption that a vehicle has a fixed acceleration rate within a short space or time interval and according to the basis kinematic theory, a vehicle's speed arrives at this average speed at the middle-time point t_i of the ith segment.

$$\text{where } t_i = T_i + \frac{T_{i+1} - T_i}{2} \qquad (2)$$

Therefore, the real-time speed v_{ti} at the middle-time point of each segment t_i can be estimated using the average speed, i.e., $v_{ti} = V_{i \sim i+1}$.

Time interval $(t_1 \sim t_2)$ can also be written as: $(T_3 - T_1)/2$; during this time interval, speed increases from v_{t1} to v_{t2}; accordingly, average acceleration rate of this period could be calculated as:

$$a_{t_1 \sim t_2} = \frac{v_2 - v_1}{t_2 - t_1} \qquad (3)$$

Knowing $V_{i \sim i+1}$, $a_{t_i \sim t_{i+1}}$ and T_i, spot speed at each cone location could be calculated using equation:

$$v_{i+1} = v_{ti} + a_{i \sim i+1} \times \frac{(T_{i+1} - T_i)}{2} \qquad (4)$$

Finally, the average acceleration rate of each interval is calculated according to the kinematic equation:

$$a_{i\sim i+1} = \frac{v_{i+1}^2 - v_i^2}{2(L_{i+1} - L_i)} \tag{5}$$

Data collection and processing

Vehicle classification

Based on the field observation at California sites and according to FHWA vehicle classification standard (FHWA, 2015), trucks in this paper are categorized into three types: light, medium, and heavy. Description and graphic examples of each truck type are listed in Table 2.

Data collection

Truck acceleration performance data under actual conditions were collected at two existing metered on-ramps in the San Francisco Bay Area, California. The Industrial Pkwy to NB 880 ramp-metering site has an auxiliary lane; therefore, truck drivers are provided with sufficient space for acceleration. In comparison, the Mowry Ave to NB 880 ramp-metering site is a taper type on-ramp with a limited existing acceleration length. Geometric and traffic features of the two candidate sites are listed in Table 3.

In this research, vehicle time and location information were collected through videos from parallel cameras. Speed and acceleration data were calculated based on the proposed piecewise-constant acceleration model. Trucks were classified manually based on the aforementioned criteria in Table 2. Although this method calls for great laborious work, it can minimize both the vehicle classification and the speed measurement errors caused by random factors; also, it has the ability of tracking the entire trajectory of an individual vehicle.

Traffic sign cones were placed along a metered ramp as reference points from the ramp meter stop bar with a known distance between adjacent cones. A video camera was set up behind each cone to record the time point of a vehicle passing this designated reference point. The layout of reference cones and cameras are demonstrated in Fig. 2; eight cameras were placed along the acceleration lane of the study ramp metering sites and covered a total distance of 500 feet downstream from the stop bar.

Acceleration data processing

With the video clips captured by cameras along a metered ramp, data processing is conducted to extract speed information for each individual sample. The data extraction starts with time synchronization of videos recorded by different cameras. Each camera recorded the stopwatch time and the time point of the sample vehicle that passes the reference cone in the camera view. The time offsets between the stopwatch time and video time of two consecutive cameras are calculated and then the relative offsets are calculated and used for the extraction of travel times between cones. Description of each captured vehicle is documented, including vehicle type, model, and color. By knowing each vehicle's description, the records of the same vehicle in different cameras can be identified, so that the entire trajectories of a vehicle, including time and location information, along the acceleration lane can be depicted.
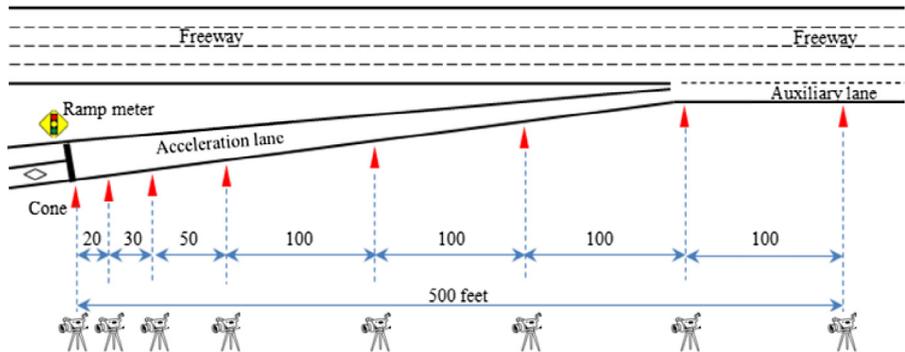
Table 2
Truck type defined in this study.

| Truck type defined in this study	FHWA vehicle classification	Vehicle description	Typical model
Light truck	Class 5	Single unit 2-axle trucks	
Medium truck	Class 6 & 7	Single unit, 3 or more axles trucks	
Heavy truck	Class 8 & 9	Single trailer, 3, 4, 5 axles trucks	

Table 3
Geometric features and traffic conditions of data collection sites.

Criteria	Industrial Pkwy to NB 880	EB Mowry Ave. to NB 880
Merging type	Auxiliary lane	Taper
Existing length* (ft.)	395	390
On-ramp lane	1 + HOV	1 + HOV
Grade	Flat	Flat
Freeway flow	Uncongested	Uncongested
On-ramp demand	Medium	Low
Sample size	174	55

* Existing acceleration length is the distance from stop bar to the gore; after the gore vehicles can merge into the freeway mainline.

a. Industrial Pkwy to NB 880 auxiliary lane ramp
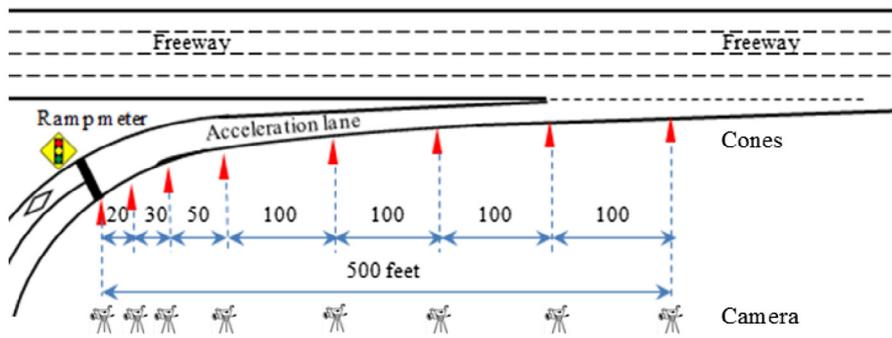
b. EB Mowry Ave to NB 880 taper ramp

Fig. 2. Schematic diagram of reference cone and camera layout.

Table 4
Synchronized time and location information.

Vehicle ID	Color	Type	Model	Time point pass each cone location							
				A	B	C	D	E	F	G	H
1	White	Light	Ford	00:00.00	00:02.77	00:04.99	00:07.35	00:10.71	00:13.45	00:15.92	00:18.15
2	Orange	Heavy	Volvo	00:00.00	00:02.21	00:04.85	00:08.18	00:13.20	00:17.08	00:20.58	00:23.85
3	Gray	Medium	–	00:00.00	00:03.59	00:06.29	00:09.37	00:13.80	00:17.16	00:19.97	00:22.34
4	White	Heavy	Volvo	00:00.00	00:01.86	00:03.73	00:05.95	00:09.11	00:11.86	00:14.31	00:16.48
5	White	Medium	–	00:00.00	00:01.97	00:03.66	00:05.74	00:08.84	00:11.41	00:13.72	00:15.85

With knowing the actual time points of each vehicle passing the reference cones and the relative offsets between adjacent cones, it is possible to synchronize all time points to draw a time series for each individual sample. Assume a time series starts at location zero (i.e., the stop bar) and time zero, then the time point a sample vehicle arrives at each reference cone could be depicted, as demonstrated in Table 4. Accordingly, travel time between adjacent cones can be calculated as $T_{i+1} - T_i$, where T_i is the time point of a vehicle passing the reference cone C_i.

By knowing the location and time information of each sample vehicle, the spot speed at the predetermined cone locations and the average acceleration rate within each interval could be calculated through the proposed piecewise constant acceleration model.
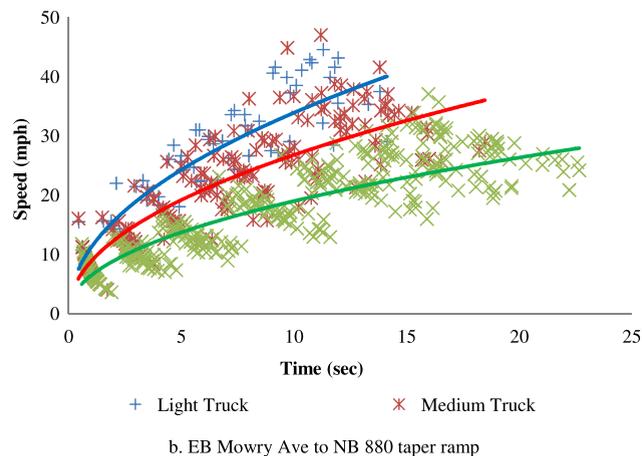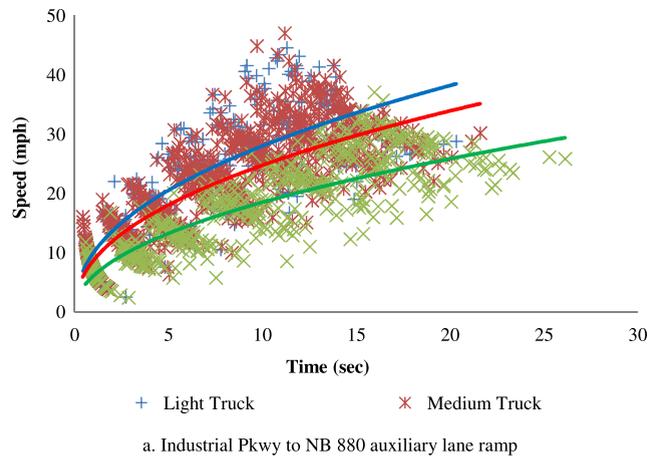
Truck acceleration profiles

Speed versus time profile

Using the extracted vehicle time versus location information and based on the proposed piecewise constant acceleration model, the spot speeds of individual vehicles at the predetermined cone locations were calculated. Accordingly, the speed versus time profile of each truck type was generated, as illustrated in Fig. 3. As expected, light trucks can accelerate to a higher speed in a given time frame. Statistics results indicate that on average, light truck drivers can accelerate from the stop condition to approximately 37 mph in 500 feet. In comparison, medium and heavy truck drivers can accelerate to approximately 34 mph and 31 mph in 500 feet, respectively.

### Acceleration profiles of different truck types

For each individual sample, the extracted location versus time information was eventually used to generate the acceleration versus location (or time) profile. For demonstration purposes, the average acceleration values of each truck type were

a. Industrial Pkwy to NB 880 auxiliary lane ramp

b. EB Mowry Ave to NB 880 taper ramp

Fig. 3. Speed versus time scatter plots and profiles of three truck types.
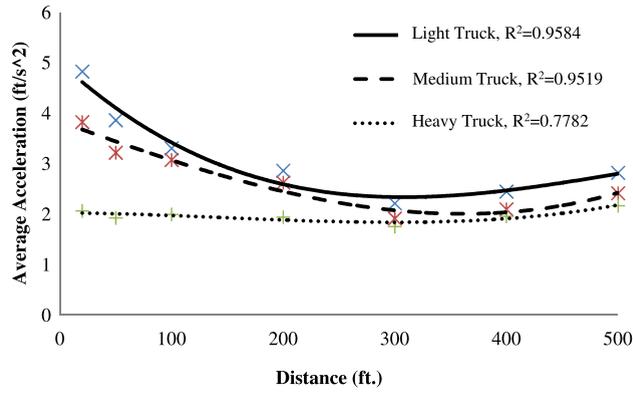
a. Industrial Pkwy to NB 880 auxiliary lane ramp
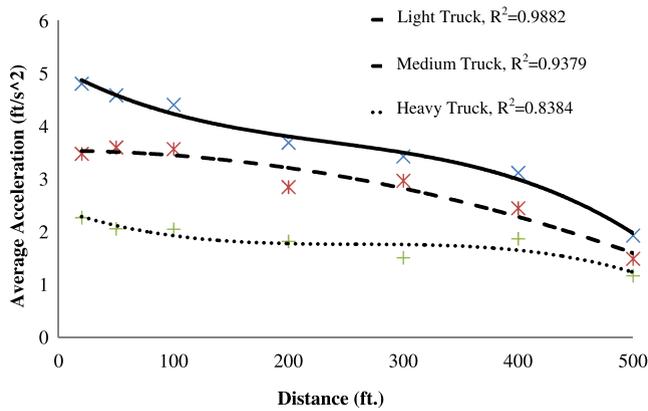
b. EB Mowry Ave to NB 880 taper ramp

Fig. 4. Average acceleration versus distance profiles of three truck types.

used. Polynomial regression analysis of the field collected acceleration data was employed to generate acceleration versus distance profiles at the two metered on-ramps, as illustrated in Fig. 4.

Results show that for the auxiliary lane type ramp that has a longer potential acceleration length, the acceleration versus distance profiles indicates that the acceleration behavior is a high acceleration rate in the beginning. Then, the acceleration rate decreases as speed increases, but the acceleration rate increases again as drivers approach the merging area. In comparison, acceleration behavior at the taper type ramp indicates an exponential decreasing trend with speed increase.

Truck acceleration rates

The estimated piecewise-constant average acceleration rates of the three truck types were summarized in Table 5. In addition, to better illustrate the actual acceleration capability of different trucks, the average acceleration rate from the stop bar to 500 feet downstream (i.e., assume a constant acceleration rate during the entire accelerating period) was calculated, including the mean, the 15th, 50th and the 85th percentile acceleration performance data, as listed in Table 5.

Table 5
Truck acceleration performance data.

Truck type	Sample size	Piecewise-constant average acceleration rates (ft/s^2)							0–500 ft. Average acceleration rate (ft/s^2)				
		a_{0-20}	a_{20-50}	a_{50-100}	$a_{100-200}$	$a_{200-300}$	$a_{300-400}$	$a_{400-500}$	Mean	S.D.	15 th %	50 th %	85 th %
Light	44	4.79	4.03	3.57	3.05	2.49	2.59	2.59	2.93	0.85	1.92	2.84	3.77
Medium	114	3.78	3.31	3.17	2.67	2.13	2.17	2.24	2.51	0.68	1.85	2.44	3.23
Heavy	71	2.12	1.97	2.04	1.91	1.91	1.94	1.86	1.93	0.42	1.56	1.96	2.24

Note: S.D. is standard deviation of the mean acceleration rate of each group; 15th % and 85th % represent for the 15th percentile and 85th percentile acceleration rate of each group.

The ITE Traffic Engineering Handbook (Pline, 1999) documented the maximum acceleration rate of tractor-semitrailer trucks with various weight-to-power ratios. Based on the similar reached speed (0–30 mph), the estimated heavy truck acceleration performance data were compared to the ITE values. In this study, the 85th percentile average acceleration rate of heavy trucks is 2.24 ft/s^2. The ITE Traffic Engineering Handbook recommended the maximum acceleration rate for tractor-semitrailer truck with 100, 200, 300, and 400 lb/hp weight-to-power ratios to be 2.2, 1.5, 1.2, and 1.1 ft/s^2, respectively. It can be seen that field collected acceleration performance data, even just using the 85th percentile data, are still much higher than that documented in the ITE Traffic Engineering Handbook. This indicates that the ITE truck acceleration performance data, which were developed based on a truck acceleration study performed in 1970, seems to be out-of-date for modern vehicles.

Truck acceleration lengths recommendations

Distance-speed regression model

Spot speeds of each individual vehicle at the pre-determined locations were extracted from the field videos. For each truck type, the 15th percentile, 50th percentile, and 85th percentile spot speeds at each cone location were identified. The 15th percentile speed means that 15 percent of speeds are lower than this speed and the 85th percentile speed means 85 percent of speeds are lower than this speed. Fig. 5 illustrates the profiles of 15th, 50th, and 85th percentile speed versus distance of medium trucks, which were plotted with 114 individual samples collected at the two metered on-ramp.

Based on the field observed speed versus distance profiles of Fig. 5, regression analysis method was employed to generate the distance versus speed equations, since such equations could better describe the required acceleration lengths for a given speed. A previous study found that the power function model would best capture the realistic distance versus speed profile (Yang, et al., 2016), and thus was employed by this study for truck acceleration length prediction. The 85th percentile, 50th percentile and 15th percentile distance versus speed regression models for medium trucks at the study ramp metering sites can be described by the following power functions and also demonstrated in Fig. 6.

$$\begin{cases} L_{85th\ Percentile} = 0.1314 \times v^{2.4367}, & R^2 = 0.9977 \\ L_{50th\ Percentile} = 0.0452 \times v^{2.6403}, & R^2 = 0.9995 \\ L_{15th\ Percentile} = 0.0172 \times v^{2.8208}, & R^2 = 0.9985 \end{cases} \tag{6}$$

The generated speed-distance relationships can be used as a recommendation of acceleration length design for ramp metering sites with substantial heavy truck volume. For example, if knowing the merging speed is 40 mph, then the estimated medium acceleration length would be 790 feet and the allowable acceleration length can be in the range of 570 feet and 1050 feet. A summary of the 85th percentile and 50th percentile predicted acceleration lengths for various merging speeds are listed in Table 6.

Recommendations compare with Green Book

To accommodate the majority of drivers to accelerate to a safe merging speed, this paper recommends using the 85th percentile distance as the minimum acceleration lane length design value. Comparisons between the recommended lengths and the Green Book design guideline (AASHTO, 2011) are presented in Fig. 7.

Results show that the recommended acceleration lengths for both medium and heavy trucks are substantially longer than those proposed by the Green Book, which indicates that the AASHTO acceleration length design guideline is insufficient for trucks. In general, the recommended acceleration lengths for medium and heavy trucks are approximately 1.3 and 1.6 times of the Green Book design guideline, respectively.
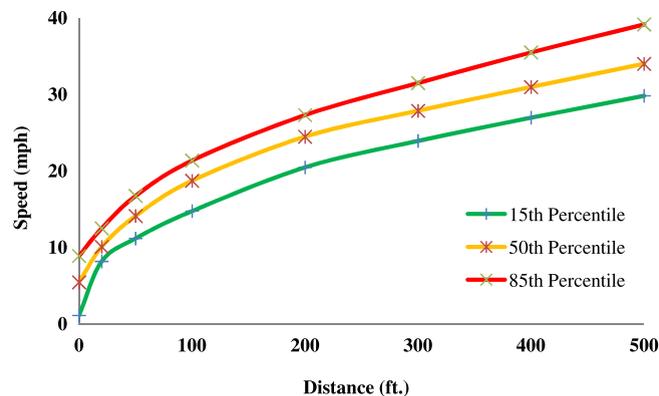

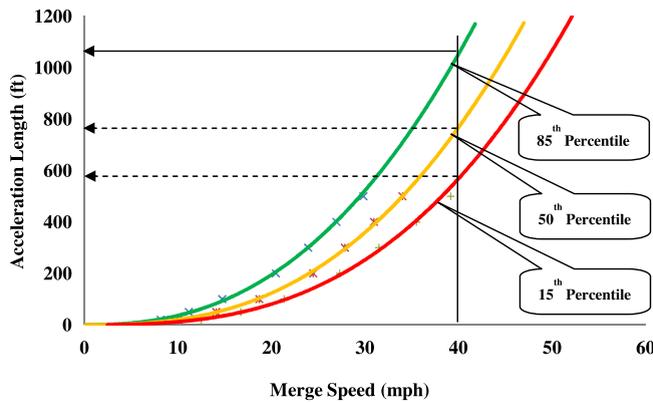Fig. 5. Field observed percentile speed versus distance profiles of medium trucks.

Fig. 6. The distance versus speed regression model for acceleration length prediction.

Table 6
Predicted acceleration lengths for trucks under different merging speeds.

| Truck type	Sample size	Distance versus speed regression model	R^2	Predicted acceleration length (ft.) to reach merge speed of						
				30 mph	35 mph	40 mph	45 mph	50 mph	55 mph	60 mph
Medium Truck	114	$L_{85th\%} = 0.1314v^{2.4367}$	0.9977	525	760	1050	1400	1815	2290	2830
		$L_{50th\%} = 0.0452v^{2.6489}$	0.9995	370	555	790	1,080	1,430	1,840	2,320
		$L_{15th\%} = 0.0172v^{2.8208}$	0.9985	255	390	570	790	1065	1395	1785
Heavy truck	71	$L_{85th\%} = 0.3001v^{2.2740}$	0.9961	685	975	1320	1725	2190	2720	3320
		$L_{50th\%} = 0.1321v^{2.4261}$	0.9962	505	735	1020	1355	1750	2205	2720
		$L_{15th\%} = 0.0709v^{2.5479}$	0.9955	410	610	855	1155	1510	1925	2405
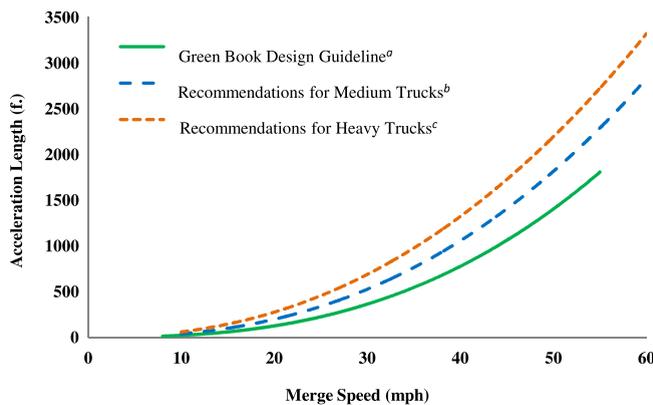
Fig. 7. Comparison of the recommended truck acceleration lengths with Green Book design guideline.

Concluding remarks

Ramp metering has more significant influences to trucks than passenger cars since trucks usually have poorer acceleration capability and hence call for a longer acceleration distance to accelerate to the desired merge speed. In reality, the acceleration capability of different vehicle types varies and is usually influenced by prevailing traffic and road geometric features. Therefore, acceleration performance data should be based on large field data collected at ramp-metering sites with different geometric configurations. This paper aims to investigate the actual acceleration capability of trucks starting at metered on-ramps. Major findings of this study are listed as follows:

- Acceleration versus distance profiles of various ramp geometric configurations differ. In general, the acceleration profile of taper merging ramps indicates a decreasing trend with distance. For ramps with an auxiliary lane that have sufficient acceleration distance, the entire accelerating process could be divided into two stages: in the first stage, acceleration rates decrease as the speed increases; and then, when vehicles are approaching the merging area, drivers are more likely to accelerate at higher rates to catch up with the freeway mainline speed and merge into the freeway.

- Field data show that on average, light, medium and heavy truck drivers can accelerate from speed zero to approximately 37 mph, 34 mph and 31 mph in 500 feet, respectively. The median acceleration rates of light, medium, and heavy trucks at the study metered on-ramps are approximately 2.84 ft/s², 2.44 ft/s², and 1.96 ft/s², respectively.
- The Green Book acceleration length design guideline cannot accommodate truck drivers to accelerate to the desired speed. It was found that the required acceleration lengths for medium and heavy trucks are approximately 1.3 and 1.6 times of the Green Book design guideline, respectively. For metered on-ramps with substantial truck demand, a longer acceleration length, or better, an auxiliary lane, should be provided to accommodate the majority of truck drivers accelerate to a safe merge speed.

This paper presents a qualitative analysis of the truck acceleration profile at two metered on-ramps in a single metropolitan area. For other areas where the ramp metering operation characteristics, geometric features, and driver behavior may differ from the study sites, it is recommended to carry out a similar study using the proposed data collection and processing procedure. It is necessary to clarify that the truck acceleration data were collected based on real-world conditions without knowing whether an observed truck was loaded or unloaded. Also, the results presented in this paper were based on ideal geometric and weather conditions (flat ramps with good sight distance). Future works need to investigate the potential impacts of road geometric features and traffic flow conditions on drivers' acceleration characteristics, such as grade, visibility, friction, weather, on-ramp volume, and freeway running speed, to develop adjust factors for various geometric and traffic scenarios. Additionally, this study was limited to the first 500 feet downstream of the ramp meter stop bar. To generate more accurate results, future studies should be able to cover a longer distance where the majority of vehicles could merge into the freeway mainline.

Acknowledgements

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