1. INTRODUCTION

The Speed-Change Lane (SCL) should have sufficient length to enable a driver to make the appropriate change in speed between the turning roadway and the highway. Moreover, in the case of an acceleration lane, the additional length should permit adjustments in speeds of both through and entering vehicles. Therefore, the entering driver can position the vehicle to a gap in a through-traffic stream and run into the mainstream traffic before the acceleration lane ends [1]. Failing to reach merge speed causes an accident in the main lanes of the freeway and highway. The merge process is a four-step successive process: initial steering control, acceleration, gap search, and merge steering, all of which indicate that these steps work repetitively until a successful merge is completed [2]. The average acceleration rates for free-flow trucks under free-merge conditions are less than the presumed acceleration rates in the Green Book.
accelerations of merging vehicles along the ramp and speed lane changes are not steady [3]. If drivers entering a freeway cannot accelerate to the speed of the traffic stream, then entering drivers will merge with the mainline at a slow speed and may accept an inadequate gap. Moreover, if the freeway is congested, it may be difficult for drivers to find an appropriate gap into which to merge [4]. Researchers and institutes have conducted many observational and experimental studies investigating the required length for the acceleration lane. Two general forms of SCLs are (1) the taper-type and (2) the parallel-type that AASHTO has proposed [1]. A taper-type entrance is merged into the freeway with a long, uniform taper. Studies show a desirable taper rate of approximately 50:1 to 70:1 (longitudinal to lateral) between the acceleration lane’s outer edge and the through-traffic lane’s edge. The gap acceptance length, $L_g$, is also a consideration in the design of taper-type entrances, as illustrated in Figure 1, A [1]. A typical design of a parallel-type entrance is shown in Figure 1, B. A curve with more than 300 m radius with a 60 m length should be provided at the beginning of the lane. If this curve has a short radius, drivers tend to merge onto the freeway without using the acceleration lane. This behavior results in undesirable merging operations. A taper length of approximately 90 m is suitable for design speeds of up to 110 km/h [1].

Figure 1.
Road designing by considering the vehicle’s dynamic behavior provides safety and improves the results. Vehicle dynamics describes the forces acting on the vehicle that result in its motion. Tractive effort and resistance are the two adverse forces determining road vehicles’ performance characteristics [5]. The vehicle’s engine provides the tractive-effort force, and internal friction losses limit these forces. This force is opposed by the forces of air resistance, rolling resistance, grade resistance, and friction resistance [6]. Rakha presented a series of vehicle dynamics models for the acceleration behavior of various trucks and passenger cars. According to the study, the submitted model and model input parameters provide results that are consistent with field observations, presenting errors of less than 10% [7]. The advantages of the vehicle dynamics model is the ability to predict vehicle behavior with readily available input parameters and its flexibility in estimating acceleration rates of both large and small vehicles on varied terrain [8]. On the other hand, various institutes and researchers have examined observational and experimental methods in their studies. The NCHRP 730 observational study results show that on a 0 percent grade, an 85 kg/kW truck can accelerate from 22.5 to 37 km/h within 42.7 m and 57.9 to 62.8 km/h within 39.6 m. For the other design situations with a 0 percent grade and all upgrades, an 85 kg/kW truck cannot meet the design conditions specified in the Green Book, even by applying the upgraded grade adjustment factors [3]. Other observational studies indicate that a minimum SCL length of 374.9 m, including the taper, is desirable for comfortable merging [9]. With experimental research, Harwood used the Truck Speed Profile Model (TSPM) to calculate the minimum acceleration lengths for a 109 kg/kW vehicle to reach the conditions specified in the current design criteria. These minimum acceleration lengths were about 1.8 times greater than the minimum acceleration lengths given in the 2004 Green Book [10]. A potential source for an adjustment factor for entrance terminals is calculating the distance needed to accelerate from one speed to another on different grades through vehicle performance equations. In an experimental research, Fitzpatrick used a spreadsheet to calculate acceleration distances on grades for various vehicle types [11]. Observational studies recommended that acceleration lengths for medium and heavy trucks are approximately 1.3 and 1.6 times greater than the Green Book design guideline. Therefore, for ramps with significant truck traffic, a longer acceleration length or an auxiliary lane should be provided for truck drivers to accelerate to a safe merge speed [12]. One experimental study showed that entrance terminals’ safety is enhanced when 243.8 m or longer acceleration lanes are provided [13]. Researchers at the University of Michigan Transportation Research Institute (UMTRI) argued that the current design guidance was based on passenger car operation and did not consider tractor-trailer trucks’ operating characteristics into account [14]. Researchers at the University of Michigan Transportation Research Institute studied the effect of the geometric design on tractor-trailer truck crashes. Regarding the AASHTO Green Book Design Guide, the researchers point out that the design parameters are based on passenger cars and do not discuss tractor-trailer truck features [14].

As can be seen from previous research, various methods (observational or experimental) based on the Highway Safety Manual (HSM) proposal have been performed. However, the lack of consideration for the truck’s dynamic behavior was the primary motivation for the authors of this article. Therefore, in this study, efforts have been made to provide a solution for correcting the acceleration lane’s geometry by considering the dynamic behavior of trucks in such a way that the driver enters the mainline with the safest mode of acceleration. Moreover, through vehicle dynamics simulation, four different heavy vehicles were simulated. The inputs of software are described in the methodology, and some of the outputs are given in the results section. Data of acceleration lane lengths, obtained by the result of scenarios, were used to develop an equation calculates that the acceleration lane length of these heavy vehicles at given speeds and grades.

2. METHODOLOGY

The method and idea behind this research are to investigate the required length for the acceleration lane at grades of zero, ±3%, and ±5% for heavy vehicles and based on dynamic behavior using TruckSim vehicle dynamic simulation software.

2.1. Road Geometry

A parallel-type design was used for the acceleration lane. A simple horizontal curve was used at the beginning of the roadway, connecting to the acceleration lane and a 90-meter taper. Acceleration lane lengths were equal to the recommended minimum acceleration lengths of the AASHTO Green Book, shown in Table 1. The curve radius at the beginning
of the roadway was selected as the minimum radius proposed by AASHTO for a design speed of 60 km/h. For grades, values of 0, ±3, and ±5 percent were used to analyze the adjusted grade factors shown in Table 2. The friction coefficient factor between the tire and the pavement was assumed to be 0.9.

### 2.2. Driver Behavior

Driver controls in the software have four parts: speed control, brake control, gear-shifting control, and steering control. The truck travels at given speeds. The driver starts to change lane before the taper without braking and enters the mainline of the freeway. Initial speeds of 40, 50, and 60 km/h at the beginning of the acceleration lane and the merge speeds of 74, 88, and 92 km/h were employed at the end of the acceleration lane before starting the taper. In addition, automatic gear-shifting control was used in this study.

### 2.3. Vehicle

The proposed acceleration length of AASHTO is based on experimental studies, and the vehicle’s dynamic characteristics are not considered in the results. Heavy vehicles have a lower acceleration rate than passenger cars for merging into the highway. Therefore, this study tried to investigate the acceleration lane length for heavy trucks by considering the dynamic behavior of different heavy trucks.

Four types of trucks with weight to power ratios of 61, 67, 86, and 108 kg/kW were selected for simulation and their specifications are shown in Table 3. The dimensions of the 108 kg/kW truck are illustrated in Figure 2. The 108 kg/kW truck’s sprung mass is 4455 kg.

After identifying vehicles’ characteristics, road geometry, and driver behavior, the inputs were defined in the TruckSim software. One of the advantages of TruckSim is having the capability to animate the vehicle performance to create a clear perception of simulation for users. TruckSim is universally the preferred tool for analyzing vehicle dynamics, developing active controllers, calculating a truck’s performance characteristics, and engineering next-generation active safety systems. TruckSim provides open-loop and closed-loop driver models with advanced features to help engineers quickly discover a truck’s limitations or its optimal path through complex maneuvers. Parameters, such as geometric roadway, design, inertial properties, and vehicle characteristics, are user-defined. Although vehicle dynamics simulations have long been standard in vehicle design, highway engineers rarely use them in roadway designs [15].

### 2.4. Plots and Data Analysis

After inserting data on road geometry, driver behavior, and vehicle characteristics, the simulation process’s final step is plot definition. The defined plots in this study are the longitudinal acceleration and longitudinal speed versus station. Since outputs are represented as stations in TruckSim software, longitudinal distance or x is calculated by Equation 1. Finally, lin-
ear regression analysis was considered for the simulation's outcome after the simulation process to make them more transparent and valuable in highway design. Therefore, models are based on the vehicle's initial and merge speed, grade, and truck weight to power ratio. Statistical Package for the Social Sciences (SPSS) software was used to analyze the results.

\[ S_i = S_{i-1} + \sqrt{(X_i - X_{i-1})^2 + (Y_i - Y_{i-1})^2} \]  

**Figure 2.** Specifications of 108 kg/kW truck
Table 3. Specifications of trucks

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Tractor</th>
<th>Load</th>
<th>Tractor</th>
<th>Load</th>
<th>Tractor</th>
<th>Load</th>
<th>Tractor</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>61 kg/kW Truck</td>
<td>67 kg/kW Truck</td>
<td>86 kg/kW Truck</td>
<td>108 kg/kW Truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width (mm)</td>
<td>2438</td>
<td>1000</td>
<td>2438</td>
<td>1000</td>
<td>2438</td>
<td>1750</td>
<td>2438</td>
<td>2000</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>3200</td>
<td>1000</td>
<td>3200</td>
<td>1000</td>
<td>3200</td>
<td>1800</td>
<td>3200</td>
<td>2000</td>
</tr>
<tr>
<td>Height of mass center (mm)</td>
<td>1175</td>
<td>1350</td>
<td>1175</td>
<td>1350</td>
<td>1020</td>
<td>2150</td>
<td>1175</td>
<td>2300</td>
</tr>
<tr>
<td>Total Mass (kg)</td>
<td>14165</td>
<td>4000</td>
<td>14165</td>
<td>6000</td>
<td>8525</td>
<td>20000</td>
<td>14165</td>
<td>18340</td>
</tr>
<tr>
<td>Powertrain (kw)</td>
<td>300</td>
<td>-</td>
<td>300</td>
<td>-</td>
<td>330</td>
<td>-</td>
<td>300</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3. Longitudinal speed versus station for 61 kg/kW truck

Figure 4. Longitudinal speed versus station for 108 kg/kW truck
3. RESULTS AND DISCUSSION

3.1. Acceleration lane length

Longitudinal speed versus station of the 61 kg/kW truck is shown in Figure 3. According to Figure 3, the speed controller software results are shown in Diagram 1. In this test, the initial speed was chosen to be 60 km/h, and the merge speed was equal to 74 km/h at level grade. Diagram 2 shows the speed of the vehicle and their responses to acceleration. As shown in Figure 3, curve number 2 at the end of the acceleration lane reached the input merge speed in the software, indicating that the acceleration lane’s length at these initial and merge speeds is sufficient for a truck at 61 kg/kW.

The output of the 108 kg/kW truck is shown in Figure 4. The initial speed was chosen to be 60 km/h, and the merging speed was equal to 74 km/h at level grade. According to Figure 4, Diagram 2 meets with a lag of curve 1, which means that the speed of 108 kg/kW truck does not reach the merge speed during the designed length. In this output, by converting the length shown in Figure 4 to the horizontal distance using Equation 1, it was determined that the heavy vehicle reached 74 km/h after 63 meters at the end of the acceleration lane. As a result, by adding this length to the design length of 205 meters, the minimum length of 268 meters was calculated.

By using the longitudinal speed diagrams versus the station and converting them to the longitudinal distance, the results are presented in Table 4 to Table 8. According to Table 4, when the input speed is 60 km/h and the merge speed is 74 km/h, 61 and 67 kg/kW trucks can accelerate along the design length. In Figure 5, obtained acceleration lane lengths at level grade and the minimum lengths of AASHTO for all trucks are shown.

In Table 5, related to the 3% upgrade, the 108 kg/kW and 86 kg/kW trucks have been unable to achieve the merge speed and have had a poor performance. The 108 kg/kW truck has a poor performance on upgrades, and added length for this truck was too long. For example, at an initial speed of 50 km/h and a merge speed of 74 km/h, the truck reached a distance of 3000 meters to a merge speed of 74 km/h.

Table 4. Acceleration lane length at level grade

<table>
<thead>
<tr>
<th>Design Speed, V (km/h)</th>
<th>Merge Speed, V_a (km/h)</th>
<th>Initial Speed V (km/h)</th>
<th>40</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>74</td>
<td>40</td>
<td>337</td>
<td>334</td>
<td>390</td>
</tr>
<tr>
<td>120</td>
<td>88</td>
<td>50</td>
<td>322</td>
<td>286</td>
<td>325</td>
</tr>
<tr>
<td>130</td>
<td>92</td>
<td>60</td>
<td>407</td>
<td>205</td>
<td>224</td>
</tr>
</tbody>
</table>

Figure 5. Acceleration lane lengths at level grade
In Table 6, on a 3% downgrade, all heavy trucks over 90 meters of taper reached the desired speed when the initial speed of 50 and 60 km/h and the merge speed of 74 km/h were considered. Only 61 and 67 kg/kW trucks could accelerate during taper at an initial speed of 50 km/h and merge speeds of 88 and 92 km/h. The obtained acceleration lane lengths at a 3% downgrade and minimum lengths of AASHTO for all trucks are shown in Figure 6.

Trucks with weight to power ratios of 86 and 108 kg/kW, at a 5% upgrade cannot accelerate to the desired speed (Table 7). Only 61 and 67 kg/kW trucks in this grade accelerated at a merge speed of 74 km/h with a length of 1.8 to 3.9 times greater than the rec-
ommended acceleration lane length of the AASHTO Green Book.

In a 5% downgrade, all trucks could reach the merge speed along the 90 meters taper when the initial speed was assumed to be 60 km/h. Also, all trucks except 108 kg/kW at an initial speed of 40 km/h could accelerate during the taper when the merge speed of 74 km/h was considered (Table 8). The acceleration lane lengths at 5% downgrade and the minimum lengths of AASHTO for all trucks are shown in Figure 7.

The speeds that four types of vehicles reached at the end of the acceleration lane in level grade are presented in Table 9. By considering the acceleration lane length according to the AASHTO Green Book, the speeds reached by trucks in the TruckSim software are shown in Figure 8.
3.2. Acceleration rate analysis

One of the design problems is to assume the constant acceleration rate of vehicles; the TruckSim software can simulate vehicles with variables of the acceleration rates. The output is related to the longitudinal acceleration for the 61 kg/kW truck, shown in Figure 9. As shown in Figure 9, the acceleration rate of the truck is not constant.

Given the unsteady acceleration rate of the vehicle's output, the maximum longitudinal acceleration rate experienced by the vehicle through the acceleration lane is given in Table 10. The 61 kg/kW truck on downgrades had a higher acceleration rate than other vehicles. The acceleration rate at downgrades is about 1.6 times higher than at upgrades. Lower initial speeds have a higher acceleration than other scenar-
### Table 10. Acceleration rates for 61 kg/kW truck at different grades

<table>
<thead>
<tr>
<th>Design Speed (km/h)</th>
<th>Merge Speed (km/h)</th>
<th>Initial Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td>Acceleration Rate for 61 kg/kW Truck at Level Grade (km/h/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>74</td>
<td>3.46</td>
</tr>
<tr>
<td>120</td>
<td>88</td>
<td>3.46</td>
</tr>
<tr>
<td>130</td>
<td>92</td>
<td>3.46</td>
</tr>
<tr>
<td>Acceleration Rate for 61 kg/kW Truck at 3% Upgrade (km/h/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>74</td>
<td>2.59</td>
</tr>
<tr>
<td>120</td>
<td>88</td>
<td>2.59</td>
</tr>
<tr>
<td>130</td>
<td>92</td>
<td>2.59</td>
</tr>
<tr>
<td>Acceleration Rate for 61 kg/kW Truck at 3% Downgrade (km/h/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>74</td>
<td>4.25</td>
</tr>
<tr>
<td>120</td>
<td>88</td>
<td>4.25</td>
</tr>
<tr>
<td>130</td>
<td>92</td>
<td>4.25</td>
</tr>
<tr>
<td>Acceleration Rate for 61 kg/kW Truck at 5% Upgrade (km/h/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>74</td>
<td>2.05</td>
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<tr>
<td>120</td>
<td>88</td>
<td>1.98</td>
</tr>
<tr>
<td>130</td>
<td>92</td>
<td>1.94</td>
</tr>
<tr>
<td>Acceleration Rate for 61 kg/kW Truck at 5% Downgrade (km/h/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>74</td>
<td>4.61</td>
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<tr>
<td>120</td>
<td>88</td>
<td>4.75</td>
</tr>
<tr>
<td>130</td>
<td>92</td>
<td>4.93</td>
</tr>
</tbody>
</table>

**Figure 10.** Acceleration rates for 61 kg/kW truck at different grades
ios. Maximum longitudinal acceleration rates are shown in Figure 10.

### 3.3. Statistical Analysis
Regression models are a valuable tool for describing the relations between different variables. These models are widely used for descriptions, estimations, predictions, and control. In general, a multiple linear regression model can be considered as follows:

\[
Y = a_0 + a_1X_1 + \cdots + a_kX_k + \varepsilon
\]  
(2)

Where \( Y \) is the response variable and \( X_1 \ldots X_k \) is an independent variable. Also, the values \( a_1 \ldots a_k \) are regression coefficients, and \( \varepsilon \) is known as residual.

In the present study, four variables were considered as the independent variables, including I.S.: Initial speed (km/h), M.S.: Merge speed (km/h), W.P.: Weight to power ratio (kg/kW), and G: Grade (%). Also, \( A_{clength} \): Acceleration lane length (m) as the response variable. By using the Equation 2, the following multiple regression model with \( R^2 = 0.742 \) to the data was fitted:

\[
A_{clength} = 10486.422 \ G + 0.6174 \ WP + 205.701 \ (M.S) / (I.S) + 2510.367 \ \log (M.S) - 4631.748
\]  
(3)

The validity of some assumptions in the regression model should be checked. If they are adequate, the regression model is valid, and other statistical inferences such as prediction and control can be made. The basic assumptions in regression analysis are as follows:

1. Residuals are normally distributed; 2. Residuals are uncorrelated; 3. Residuals have the constant variance; 4. Independent variables are uncorrelated. In the following, all of these assumptions are checked:

1. Normality of residuals: A histogram and PP plot can be used for the graphical checking of this assumption. Figure 11 gives the histogram and PP plot for the regression model in Equation 3. This figure can verify the normality of residuals. Another theoretical way to check the normality of the residuals is the Kolmogorov-Smirnov test. Since the “p-value” is 0.056, which is more than 0.05, the normality of the residuals is accepted.

2. Uncorrelated residuals: The Durbin-Watson statistic can be used to check this assumption. This assumption is verified when the Durbin-Watson statistics are placed within the range 1 to 2. For Equation 3, this assumption is acceptable because the Durbin-Watson statistic is 1.283.

3. Homoscedasticity (same variance) of residuals: The Pagan-Godfrey test is used to check of homoscedasticity for the variance of residuals. For this aim, another regression model should be fitted between the square of residuals as a response variable and the independent variables of the original model. When \( nR^2 < \chi^2_{\nu} \), this assumption is accepted, where \( n \) is the number of observations, \( \nu \) is the degree of freedom for the model, \( \chi^2_{\nu} \) is the value of the chi-square distribution, and \( R^2 \) is \( R^2 \) of this model. In Equation 3, as \( 132 \times 0.277 < 4 \times 9.49 \), we accept this assumption.

4. Uncorrelated independent variables: the non-correlation of the independent variables should be
checked by $T=1-R^2$, tolerance measure, or Variance Inflation Factor (VIF = $\frac{1}{T}$) where $T>0.1$ ($VIF<10$). According to Table 11, we accept this assumption.

4. VALIDATION OF SIMULATION SOFTWARE

TruckSim software predicts vehicle performance in response to driver control inputs such as steering, throttle, brake, clutch, and shifting in a given environment, including road geometry, coefficient of friction, and wind. Therefore, it is possible to study changes in vehicle behavior and change any of the vehicle parameters, control inputs, or driving environment, as well as the possibility of adding control systems such as ABS, traction control, and stability control to the vehicle and using them to expand the control algorithm.

An investigation was conducted in China to compare real data with a simulation model. The tractor-semi-trailer was controlled by a driver with more than ten years of experience. The VBOX and gyroscope recorded the speed and lateral acceleration. In conclusion, the dynamic responses of the simulation model were in agreement with those of field tests, indicating that the driver-vehicle-road dynamic simulation model was sufficiently accurate for the tractor-semi-trailer [16].

4.1. Acceleration lane length

The acceleration lane length of the 108 kg/kW truck at level grade is compared with other studies. For a more accurate comparison with previous studies, given the AASHTO’s Green Book and NCHRP report 505, an initial speed of 35 km/h was considered for a 40 km/h entrance curve design. The results of the TruckSim software output are shown at an initial speed of 35 km/h and merge speeds of 74 and 88 km/h (Table 12).

According to Table 12, acceleration lane lengths for 108 kg/kW of these two tests differed by 1% compared to those found in NCHRP Report 505. In the NCHRP 505 report, the Truck Speed Profile Model (TSPM) was used, in which the acceleration lane length was 1.8 times greater than the recommended length in AASHTO Green Book.

4.2. Acceleration rate analysis

Table 13 summarizes the compared acceleration rate in this study and in the AASHTO green book. It should be noted that the acceleration rates report...
ed in this study are the highest accelerations that vehicles experience during the acceleration lane. Also, the values obtained from the AASHTO Green Book results are based on the initial speed, merge speed, and acceleration lane length, which assumes that acceleration rate values are constant and based on kinematic equations. The initial design speed for 40, 50, and 60 km/h were considered 35, 42, and 51 km/h, respectively. A more accurate comparison is shown in Table 13. The results of the research are also presented with the mentioned initial speeds. The acceleration rates reported in this study are affected by vehicle performance, which has an internal resistance, such as internal friction and gradient resistance. In an observational study for an initial speed of 51 to a merge speed of 74 km/h (NCHRP report 730), the average acceleration rate was calculated at about 1.75 km/h/s. In this study, the acceleration rate for a 109 kg/kW truck reaches about 1.58 km/h/s.

4.3. Vehicles’ weight to power ratios

The comparison of NCHRP report 505 and the results obtained in this study are shown in Table 14. In this study, at the initial speed of 35 km/h and the merge speed of 74 km/h, the heaviest vehicle that could accelerate was the 67 kg/kW truck. Table 15 compares the highway research program results at the 2% upgrade and this study at the 3% upgrade. As shown in Table 15, in the 3% upgrade, the lightest truck in this research (61 kg/kW) could not accelerate at the recommended length of AASHTO’s Green Book except in the 51 to 74 km/h test by adding a 90-meter taper. In NCHRP report 505, a truck with a maximum weight to power ratio of 52 kg/kW at a 2% upgrade can reach the merge speed at the recommended length of AASHTO’s Green Book. The difference between this study and the NCHRP505 studies is due to considering the vehicle’s internal deterrent forces in the model.

5. CONCLUSIONS

In some cases, accidents have occurred at the entrance ramps, in which heavy vehicles merge into the main freeway from the acceleration lane. Therefore, in this study, different types of trucks were simulated, and the dynamic behavior of vehicles was examined using TruckSim software. The final results are as follows:

- Truck with 61 kg/kW: The minimum acceleration lengths after using the grade factor of 5% downgrade in the AASHTO Green Book are decent for
this vehicle. The given lengths are sufficient for a 3% downgrade except for the 40 to 92 km/h test. In this simulation, the minimum length was 434, while the Green Book recommended 318 m in this case. The outputs of minimum lengths at a 3% upgrade were 1.27 to 1.88 times greater than the proposed lengths of the Green Book except at the merge speed of 74 km/h and the initial speed of 50 and 60 km/h; the reference lengths were adequate. At level grade, with a running speed of 40 km/h and the merge speeds of 88 and 92 km/h, the AASHTO lengths should be increased by 20 to 40%.

• Truck with 67 kg/kW: Lengths were desirable in all the cases except the 40 to 92 km/h test at a 5% downgrade. Except for the 40 to 88 and 92 km/h cases, the truck could accelerate to the merge speeds at a 3% downgrade. The truck could reach the merge speed of 74 km/h when the primary speed was 60 km/h with a 3% upgrade. At the initial speeds of 40 and 50 km/h and the merge speeds of 74 and 88 km/h, the lengths are 1.27 to 2.15 times greater than the reference lengths at a 3% upgrade. The reference acceleration lengths were desirable for all the scenarios at level grade except the 40 and 50 km/h to 88 and 92 km/h. In these cases, lengths should be increased by 27 to 39%.

• Truck with 86 kg/kW: It can get the merge speed at a 5% downgrade except at the 40 to 92 km/h test. In this case, the proper length should be about 380 m instead of 265 m. The Green Book lengths should be added by 37 to 50 percent in a 3% downgrade at the 40 and 50 km/h to 88 and 92 km/h; in other scenarios, the lengths are appropriate. The truck could not meet the given merge speeds at a 3% upgrade in any tests. In the running speeds of 50 and 60 km/h, the merge speed of 74 km/h in level grade lengths was sufficient for accelerating. However, in other tests, lengths were 1.36 to 1.6 times greater than the Green Book lengths.

• Truck with 108 kg/kW: This heavy vehicle could not gain the merge speed in a 3% upgrade. The minimum lengths were 1.23 to 2.05 times greater than the reference at level grade, except for the 60 to 74 km/h test. Furthermore, at a starting speed of 60 km/h, they can reach the merge speeds at a 5% downgrade, and at a merge speed of 74 km/h, the given lengths were appropriate for initial speeds of 40 and 50 km/h. At the two examinations of 50 and 60 to 74 km/h, the truck could accelerate to merge speed at a 3% downgrade. In other cases, at a 3% downgrade, the proposed lengths should be added by 43 to 74 percent.

• None of the trucks could reach the merge speeds at a 5% upgrade in all the scenarios.

Note: In all the cases in which the Green Book lengths were sufficient, the 90 m taper was considered.

The acceleration rate suggested in the AASHTO Green Book is based on physical relationships. The initial speeds mentioned in the AASHTO Green Book are less than the design speed. These speeds may vary with what happens in reality and when the vehicles enter the acceleration lane at higher speeds. Hence, the initial speed and merge speed need to be reviewed. In this research, sight distance is not considered. However, whether the acceleration lane lengths are sufficient or not in ramps with limited sight distance should be controlled.

The authors declare that they have no conflicts of interest.

REFERENCES


