Start-Up Accelerations of Heavy Trucks on Grades

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ABSTRACT

The acceleration performance of heavy trucks starting on grades represents an important boundary consideration in highway design. Trucks generally possess the lowest levels of acceleration performance. This, in combination with their length, makes them the highway vehicle class that requires the greatest time to proceed across intersections. Especially at railroad-highway grade crossings, truck performance establishes bounds on the timing requirements for warning devices. Guidelines on truck acceleration performance on level grades have been established in the past for use in highway design. However, the new size and weight allowances warrant review of these guidelines and present the opportunity to consider the influence of grade on performance. The performance bounds for truck acceleration depend on both the truck properties and the driving techniques used by the driver. The application of some "rules of thumb" for driving and knowledge of truck power train design provide a basis for a first-order estimate of the start-up performance range expected on various grades. The analysis is applied to the problem of clearance times at rail-highway grade crossings where regulations mandate travel in the start-up gear and the time-distance relationships are thus determined by the gear required for starting on the grade. The analysis finds that attainable speed decreases with increasing grade and affects the clearance times that should be allowed.

The acceleration performance of heavy trucks represents an important boundary consideration in highway design. Trucks generally possess the lowest levels of acceleration performance, which, in combination with their length, makes them the highway vehicle class most likely to impede other traffic. Truck acceleration performance affects highway design in a number of areas:

1. Need for climbing lanes on long upgrades,
2. Lengths of acceleration lanes at traffic merge areas,
3. Sight distance and signal timing at traffic intersections, and
4. Clearance times at rail-highway crossings.

A truck's ability to accelerate from a full stop and clear an intersection is the key interest in the last two categories. Yet, in many situations, the truck cannot accelerate continuously; it is constrained by regulations or grade conditions to traverse the intersection at the limiting speed of the starting gear.

For example, federal, state, and Bureau of Motor Carrier Safety (BMCS) regulations require vehicles transporting passengers and hazardous materials to stop at rail-highway grade crossings regardless of the type of warning device present. The regulations then require the vehicle to proceed through the crossing in a gear that allows the vehicle to complete the crossing without a change of gears. This practice results in the vehicle negotiating the crossing at the speed limit of the starting gear, thus increasing exposure time in the hazard zone.

Similar situations may arise at an upgrade intersection where the truck must stop. The low gear required for starting on steep grades does not allow the attainment of sufficient speed to permit a shift to a higher gear to be accomplished without the vehicle again slowing to a stop. Thus the driver must proceed in the starting gear to a point where the grade diminishes. Though infrequent, these conditions create hazards by obstructing traffic and presenting longer exposure times in intersections.

Predicting truck clearance times in intersections requires an understanding of the mechanics of the start-up process and how it is influenced by grade. The objective of this paper is to present an analysis of these mechanics and apply the methods to the problem of predicting truck clearance times at rail-highway grade crossings. The analysis is limited to heavy highway trucks typified by the 80,000-lb tractor-semitrailer.

MECHANICS OF TRUCK START-UP

The start-up acceleration process for heavy highway vehicles involves two phases of operation--the start-up mode in which the clutch is being engaged and the full-throttle acceleration mode from the point of full clutch engagement until maximum engine speed is reached in that gear. In normal situations, a gear shift would occur and the truck would continue to accelerate. However, at rail crossings or upgrade intersections it may be necessary for the vehicle to proceed in the start-up gear while it clears the crossing or intersection. For heavy highway vehicles, predominantly powered by diesel engines, the maximum speed is controlled by the gear selected and the governed speed of the engine. Unlike passenger automobiles, heavy trucks are routinely driven with the engine at or near its maximum governed speed.

The start-up mode involves the least time and distance; therefore, it has little direct influence on the time required to traverse an intersection. Indirectly, the practices that are used may have significance in that the selection of the gear in which the vehicle is started affects travel speed through the crossing. The low gear ratios on tractor-trailers may include "deep reduction gears" intended for use in terminal operations or when the

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vehicle is off the road. The choice of the lowest gear may limit the vehicle to an unnecessarily low speed for the duration of the travel, and the gear chosen may be so low as to be an unreasonable choice by the driver.

In the acceleration phase the full torque output of the engine is applied to accelerating the rotating components as well as the vehicle itself. Characteristically, in the lower gears, the effective inertia of the rotating components may be as large as, or larger than, the translation inertia of the vehicle. The effective inertia of the rotating components is dependent on the square of the gear ratio; thus selection of an unnecessarily low gear will adversely affect the acceleration phase of the travel.

Finally, during travel at top speed in low gear, which represents the majority of the time required for clearing the crossing, the specific choice of gear, and the associated top speed, will directly influence the time consumed.

Selection of Starting Gear

Little quantitative information is available to aid in identifying the normal practices of drivers in selecting a gear and actuating the clutch from a full stop in tractor-trailer vehicles. At best the practices that would be used by a conscientious driver can be described as releasing the clutch while the engine is at, or near, idle speed without allowing the engine to stall then fully applying the throttle while the vehicle is accelerated. Klokkenga (1) suggests that the gear selected for start-up should be the highest gear (lowest numerical ratio) for which the steady-state gradability of the vehicle exceeds the local grade by 12 percent. According to knowledgeable engineers in companies that are manufacturers of heavy-truck clutch and transmission components, a good rule of thumb for engine output torque during start-up is 500 ft-lb. The gear selected must be of a high enough ratio to allow complete engagement within a period of 1 to 2 sec without pulling the engine to a speed of much less than 500 revolutions per minute (rpm). In general, this requirement is in consonance with the 12 percent reserve suggested by Klokkenga.

The gearing of the transmission is not the only reduction in the driveline; there is also gearing in the rear axle. In addition, the maximum speed of the engine, which is fixed by the governor, will directly affect the maximum speed possible in a gear. Although these factors appear to present additional variables of choice in the analysis, rules of thumb can again be applied to help rationalize a selection. The rationale derives from the fact that the overall gearing in the majority of trucks is selected in conjunction with the governed speed of the engine and the tire size to produce a maximum speed of about 60 to 65 mph. Rarely would the selection yield a maximum speed of 55 mph or less. Accordingly, gearing for much higher speeds is not common except in some of the specialty (owner-operator) trucks used in the West. Inasmuch as the top speed is normally associated with direct drive in the transmission (a 1:1 input-to-output speed ratio), the maximum speed possible in the other gears of the transmission can be readily estimated by dividing 60 mph by the numerical ratio. For example, a low gear ratio of 10:1 will have a top speed of 60/10 or 6 mph. Ratios for the lowest gears commonly used in tractor-trailers range from 7.5:1 to 15:1. Maximum speeds for these two ratios are, respectively, 8 and 4 mph.

The gear ratio necessary to start up on different grades while satisfying the previously mentioned criteria can be determined by writing Newton's second law for the truck. Neglecting aerodynamic drag because of the low speed, the governing equation is

$$F_x = W\,(a/g + G + C_r) \tag{1}$$

where

F_x = tractive force at the ground from the drive wheels,
a = vehicle acceleration,
g = gravitational acceleration,
G = grade, and
C_r = coefficient of rolling resistance.

The drive force comes from the engine and can be related to engine torque by

$$F_x = TN_tN_rn_tn_r/R \tag{2}$$

where

T = engine torque,
N_t, N_r = transmission and rear axle gear ratios,
n_t, n_r = transmission and rear axle drive efficiencies, and
R = radius of drive wheels.

In clutch engagement the transmission gear ratio selected for Equation 2 must be high enough that the acceleration in Equation 1 is sufficient to achieve a vehicle speed that synchronizes with the engine idle speed (nominally 500 rpm) in a period of about 1 to 2 sec. The parameters N_r/R in Equation 2 simply relate engine speed and forward speed in direct drive (high gear). Substituting ϕ_m/V_m for these parameters and combining the equations yields a quadratic equation for the transmission ratio required by the start-up conditions:

$$N_t^2 - \{[W(G + C_r)V_m]/Tn_tn_r\phi_m\}N_t - (WV_m^2\phi_s/\phi_m^2t_sgTn_tn_r) = 0 \tag{3}$$

where

t_s = time for clutch engagement,
ϕ_s = engine speed at synchronization,
ϕ_m = maximum governed engine speed, and
V_m = maximum governed vehicle speed with $N_t = 1$.

This equation can then be solved to find the "best" ratio for the start-up gear at any grade condition. Figure 1 shows the solution as a function of grade with positive values for upgrade conditions and negative values for downgrades. Solutions for both a 1- and a 2-sec clutch engagement time are shown. For this plot a maximum vehicle weight of 80,000 lb has been assumed, and the other parameter choices are as listed in Table 1.

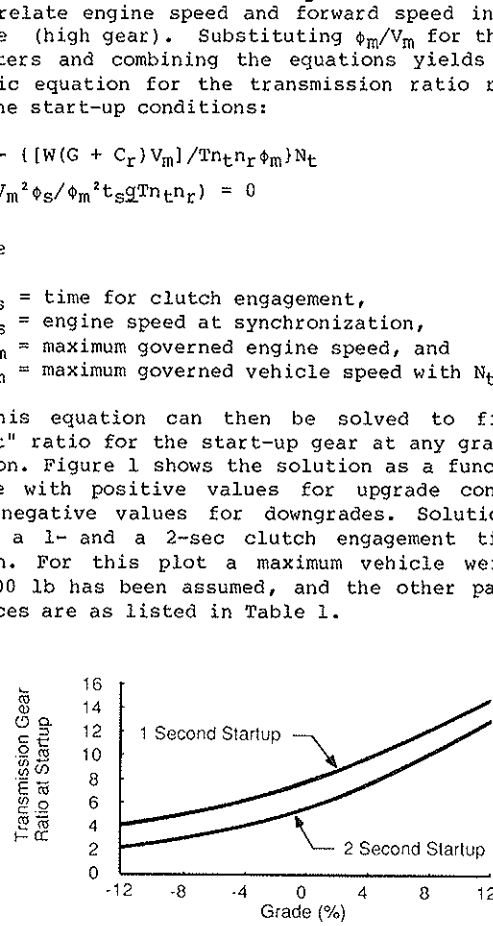

FIGURE 1 Start-up gear ratio predictions for various grades.

TABLE 1 Parameters for Calculation of Start-Up Gear

Symbol	Meaning	Value
W	Gross vehicle weight	80,000 lb
C_r	Coefficient of tire rolling resistance	0.0041
V_m	Maximum speed in direct drive	60 mph
T	Engine torque during start-up	500 ft-lb
n_t	Transmission efficiency	0.90
n_r	Rear axle efficiency	0.85
ϕ_m	Maximum engine speed	2000 rpm
ϕ_s	Engine speed at full engagement	500 rpm
g	Gravitational constant	32.2 ft/sec^2
t_s	Time of clutch slip during engagement	1, 2 sec

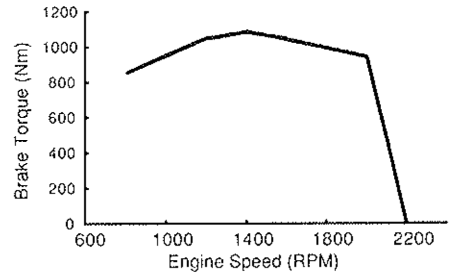

FIGURE 3 Torque characteristics of a typical truck diesel engine.

These predictions of the starting gear ratio align well with real practice and support the constraint assumptions from which they are derived. For the most common upgrade conditions, normally limited to the 0 to 6 percent range on main highways, Figure 1 indicates that the gear of choice would not have to exceed a ratio of 9:1. The first gear on many modern trucks intended for highway use has a ratio of 7.5 to 8. Thus they can readily start up with only 1 to 2 sec of clutch slip on grades of up to 4 percent and with only slightly greater abuse on grades of up to 6 percent. On steeper grades a lower gear is used if available or, if a lower gear is not available, the driver may typically try to avoid coming to a full stop.

On downgrades the gear ratios drop well below the 7.5 to 8 range available in first gear. This simply reflects the reality that under these circumstances the vehicle can be started in a higher gear (lower numerical ratio).

On the assumption that the maximum road speed is 60 mph, the maximum speed in the start-up gear can be determined. The value is simply 60 divided by the numerical ratio. By defining the best start-up gear ratio as that required for the 1-sec clutch engagement, the maximum speed in the start-up gear can be predicted for upgrade conditions as shown in Figure 2. For level conditions the speed is approximately 8 mph but may drop as low as 4 mph on steep grades

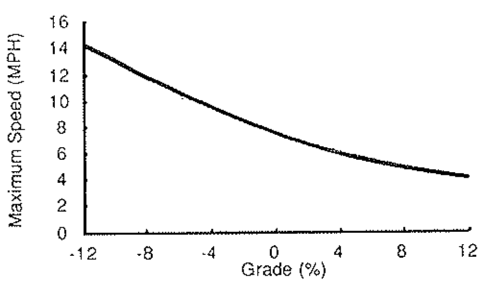

FIGURE 2 Maximum speeds in the start-up gear required for 1-sec clutch engagement.

where the highest available reductions (a 15:1 first gear) would be used.

Full-Throttle Acceleration

When clutch engagement is complete, routine driving practice with a heavy truck involves full-throttle acceleration up to maximum engine speed. At that point the governor will cut back on the amount of fuel supplied to prevent the engine from going above its rated speed. These characteristics for a typical diesel engine (1) are shown in Figure 3. Note that over most of the operating speed range (600 to 2000 rpm) this engine's characteristics are close to those of a constant torque model. Some other modern diesel engines have a "torque rise" with decreasing speed that is nearly equivalent to constant power.

To precisely calculate acceleration during this period of full-throttle application, more comprehensive equations, which take into account the rotating inertias of the drive system, must be written. Instead of taking this laborious route, a computer simulation available at the University of Michigan Transportation Research Institute (UMTRI) has been used to study this phase of truck acceleration.

Among the computer programs developed over the years at UMTRI for simulating various aspects of heavy-truck performance is a Truck Acceleration Performance program that operates on the IBM-PC desktop computer (2). The program calculates, as a function of time, the speed of a truck encountering arbitrary grades at full throttle. A typical application is to calculate the change in speed as a truck encounters a grade in the road and thus to generate a speed-distance or speed-time profile. Time-based integration is performed using the mathematical equations that include the drag effects on the vehicle from tire rolling resistance, aerodynamic drag, and grade. Tractive force from the engine is calculated as a function of its torque output, gear ratios, driveline efficiencies, tire radius, and other appropriate factors. Algorithms are included that select the highest possible gear at all times, determine appropriate shift points, and account for the loss of engine effort during the shift periods.

The program was used to calculate truck accelerations during a start-up maneuver as discussed in the preceding section. Specifically, when started from zero speed, an engine torque value of 500 ft-lb is applied to the driveline until such time as the vehicle speed increases to match a 500 rpm engine speed. Thereafter, a wide-open throttle condition that allows the vehicle to accelerate to the governed speed of the engine is assumed. For these calculations the engine was assumed to be a constant torque source equivalent to 300 hp at a governed speed of 2100 rpm (typical values for a tractor-trailer of the assumed type). The tires were assumed to be of the radial type with a rolling coefficient obtained from SAE recommendations. For these low speeds the aerodynamic parameters are not important and were simply set at typical values for van-type trailers. The gross combination weight was 80,000 lb.

Start-up simulations were conducted using the first gear ratios indicated in Figure 1 for the 1-sec clutch engagement time on different grade conditions. When maximum speed has been reached in a gear, in the case in which the driver cannot shift, the time-distance values beyond this point can be readily calculated from

$$dX = V_{max}dt \quad (4)$$

where

dX = incremental distance traveled,
V_{max} = maximum velocity in that gear, and
dt = incremental time consumed.

The calculated time-distance plots for grades of from 0 to 10 percent are shown in Figure 4. The initial start-up and acceleration phase occurs at the far left of the figure (covering no more than the first 25 ft). In this region performance varies little with grade. However, because of the different limiting speeds on each grade, the performance curves begin to diverge significantly when maximum speed has been reached. Note that the distance traveled during start-up and acceleration is relatively small, from 6 to 20 ft, which is only a fraction of the length of the truck. The majority of the travel distance (and time) required to cross and clear an intersection is covered while the truck is running at constant speed, and the primary variable controlling this performance is the ratio of the start-up gear. Thus the exact shape of the curves in the initial phase of acceleration is of little significance. The constant-speed region of the time-distance curves represents the area of primary interest.

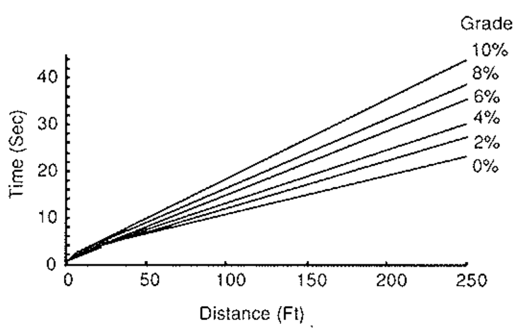

FIGURE 4 Time-distance plots calculated for various grades.

If the time-distance lines are extrapolated back to zero distance, they all intercept the time axis at approximately 3 sec or less. Consequently truck performance can be easily characterized by

$$\text{Time (sec)} = \text{Distance}/V_{m1} + 3 \text{ (sec)} \quad (5)$$

where V_{m1} is the maximum speed in the start-up gear as shown in Figure 2. The reasonableness of the time constraint on clutch engagement can be seen more directly by considering what happens if only one gear ratio is used on all grades. Simulated starts were performed using only a 12:1 low gear ratio on 0, 5, 10, and 13 percent grades. The results are shown in Figure 5. The initial curve in each of the plotted lines represents the clutch engagement segment along with acceleration to maximum engine speed. For 0 and 5 percent grades, the clutch is engaged within the first few seconds of the start-up process. Note that this cannot be seen readily on the plots but is obtained from the calculations in the computer simulation. Therefore the 12:1 ratio is a reasonable gear selection for starting on those grades. At the extreme of the 13 percent grade, the clutch must slip for more than 5 sec, which would be considered a very severe start for the vehicle. Thus a still lower gear would be selected by an experienced driver if it were available. Many truck transmissions do not have a gear

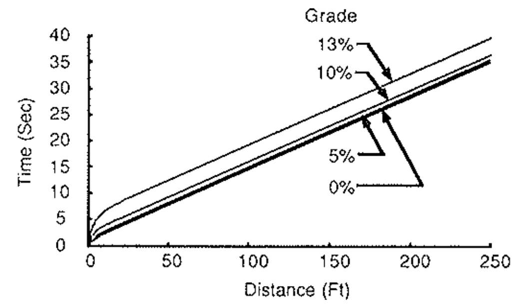

FIGURE 5 Simulated start-up with a 12 to 1 gear ratio on various grades.

lower than the 12:1 ratio, in part because a 13 percent grade situation is infrequent. However, if such a grade were encountered, most drivers would compensate either by stopping at a different point, where the grade was less severe, or by not coming to a complete stop in order to avoid having to overwork the clutch.

PREDICTIONS OF RAIL-HIGHWAY CLEARANCE TIMES

A practical application of this analysis lies in estimating the clearance times for various tractor-trailer combinations under differing grade conditions at rail-highway grade crossings. This issue was brought up in a recent project conducted by Goodell-Grivas, Inc., "Consequences of Mandatory Stops at Railroad-Highway Crossings" (3). At such crossings the vehicle is required to stop before the crossing and then proceed in a low gear until the crossing is cleared. The highway between and in the near vicinity of the tracks, as shown in Figure 6, represents a hazard zone where collision with a train is a risk. The time interval from vehicle

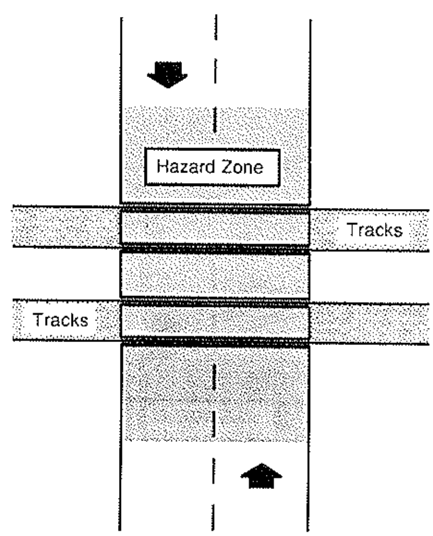

FIGURE 6 Hazard zone at a rail-highway grade crossing.

start-up until the rear of the unit clears the hazard zone is therefore a key variable in properly timing warning devices and establishing necessary sight distances.

By using Equation 4 the problem of estimating clearance times is reduced to a decision about what

TABLE 2 Clearance Time (sec) for 65-ft Tractor-Semitrailer

	Length of Hazard Zone (ft)								
Grade (%)	35	45	55	65	75	85	95	105	115
0-2	11.5	12.4	13.2	14.1	14.9	15.8	16.6	17.5	18.3
3-5	14.4	15.5	16.6	17.7	18.9	20.0	21.2	22.3	23.5
6-10	16.6	18.0	19.4	20.7	22.1	23.5	24.8	26.2	27.5
11-13	20.0	21.8	23.5	25.2	26.9	28.6	30.3	32.0	33.7

TABLE 3 Clearance Time (sec) for 70-ft Doubles

	Length of Hazard Zone (ft)								
Grade (%)	35	45	55	65	75	85	95	105	115
0-2	11.9	12.8	13.6	14.5	15.4	16.2	17.1	17.9	18.8
3-5	14.9	16.1	17.2	18.3	19.5	20.6	21.8	22.9	24.0
6-10	17.3	18.7	20.0	21.4	22.8	24.1	25.5	26.9	28.2
11-13	20.9	22.6	24.3	26.0	27.7	29.4	31.1	32.8	34.5

TABLE 4 Clearance Time (sec) for 115-ft Triples

	Length of Hazard Zone (ft)								
Grade (%)	35	45	55	65	75	85	95	105	115
0-2	15.8	16.6	17.5	18.3	19.2	20.0	20.9	21.8	22.6
3-5	20.0	21.2	22.3	23.5	24.6	25.7	26.9	28.0	29.1
6-10	23.5	24.8	26.2	27.5	28.9	30.3	31.6	33.0	34.4
11-13	28.6	30.3	32.0	33.7	35.4	37.1	38.8	40.5	42.2

constitutes a reasonable value for the maximum speed in the start-up gear. From Figure 4 is it evident that clearance times can vary over a substantial range depending on the starting gear selected. On shallow grades any of the gears could be selected depending on driver choice. On steeper grades there are fewer choices for a reasonable gear. Hence it is only possible to estimate a range of clearance times that reflects the variations in driver practices.

The times required for semitrailers, doubles, and triples were estimated for the Goodell-Grivas study using an analysis similar to that presented here. Assuming 80,000-lb gross vehicle weights and a 300-hp engine, the clearance times for the three vehicle combinations given in Tables 2, 3, and 4 were obtained. It should be noted that overall vehicle length is the only distinction among semitrailers, doubles, and triples that is relevant to this analysis. That is, the acceleration and speeds achieved by the vehicles are not affected by the configuration because they are all assumed to be at maximum gross weight. It should also be noted that the power reserve of the engine is adequate in every grade condition to reach governed speed. Although in reality the maximum speeds possible will be slightly reduced on higher grades (perhaps by a factor of a few percent) because of engine governor characteristics, this effect was neglected in the analysis.

The shortest times for each of the grade ranges in the tables can be interpreted as reasonable estimates for typical vehicles and driver practices on the indicated grade.

The longest times, listed for grades of from 11 to 13 percent, not only apply to rail-highway crossings with those grade conditions, they may also be interpreted as the prevailing clearance times for that portion of the truck population with gear ratios of approximately 15:1 available (and presuming the drivers proceed through the crossing in the lowest gear).

Clearance times that are best to use in any particular application, of course, should be selected with knowledge of the consequences. The maximum times shown in the tables (for the 11 to 13 percent grades) are suggested as the most conservative choice, regardless of the grade at a crossing, for design of warning devices. Though the choice will be conservative in comparison with the performance of a majority of the tractor-trailers encountering any given rail crossing, it will accommodate the slower vehicles that exist within the overall truck population.

COMPARISON WITH EXPERIMENTAL DATA

Data were collected at three locations in Michigan for comparison with the predictions. All of the locations were at zero grade because of the difficulty of finding crossings that were on roadway grades. Observations of time versus distance were made of a total of 77 tractor-trailers that came to a complete stop before the crossing. There was no knowledge of which vehicles were empty or loaded or of gross vehicle weight. In addition, no doubles or triples were included in the sample.

The data are compared with the predictions for tractor-semitrailers on the 0 to 2 percent grade in Figure 7. The experimental data are quite scattered, reflecting the difference capabilities of each vehicle and the different practices of each driver. The majority of the experimental points properly fall below the prediction, which is an estimate of the upper bound on the clearance times. The points below the prediction line represent vehicles loaded to less than the maximum permitted weight assumed in the calculations or started from higher gears, or both. Lower weight allows better performance and thus shorter clearance times. The points that fall above the prediction line would represent trucks started in gears that are lower than necessary or drivers who are more casual in their start-up practices.

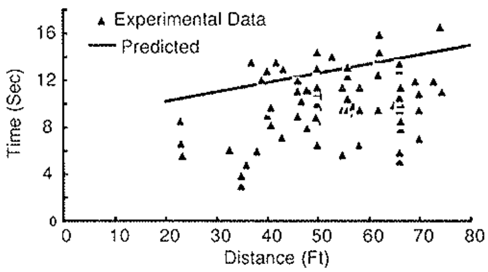

FIGURE 7 Comparison of experimental and predicted time-distance relationships on a level grade with tractor-semitrailers.

CONCLUSION

The agreement seen in Figure 7 indicates that nominal predictions of truck start-up performance can be made from the analysis presented. Because trucks and driver practices differ, the performance is variable. However, the predictions from the analysis capture approximately 90 percent of the vehicles and at that level provide a reasonable estimate of maximum clearance times required. Experimental data were only available for level grade crossings, so the accuracy of the predictions for steeper grades cannot be assessed.

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California Design Practice for Large Trucks

EARL ROGERS

ABSTRACT

Highway design engineers have long been concerned about the wide offtracking characteristics of large trucks. With the enactment of the Surface Transportation Assistance Act (STAA) of 1982, a truck longer and wider than ever before was allowed on the Interstate and qualifying primary system known as the designated system. Following the passage of the 1982 STAA, the California State Legislature changed state laws to comply with federal truck regulations on the designated system. The new state law prescribes access to the system. Service access and terminal access are separately defined. The former is handled by the State Department of Transportation. Local agencies are responsible for the latter. California has adopted an Interstate design vehicle based on dimensions spelled out in the 1982 STAA. A computer program is now available for generating offtracking plots. As a tool for highway design engineers a set of truck-turn templates has been prepared. Design practice is evolving. Current practice requires highway designers to use the Interstate truck-turn templates on all new or upgraded interchange projects. Some exceptions to the current practice are allowed. On 3R projects at designated service access points large trucks are accommodated if the work can be done at reasonable cost with no extra right-of-way. The answer to who bears the cost of retrofitting interchanges and upgrading local roads for terminal access is also evolving. The most likely arrangement will probably be shared cost with both public and private funding.

Highway design engineers have long been concerned about the offtracking characteristics of large trucks. With the enactment of the Surface Transportation Assistance Act (STAA) of 1982, a truck longer and wider than ever before was allowed on the Interstate and qualifying primary system known as the designated system.

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California has traditionally controlled offtracking by limiting the maximum kingpin-to-rear axle dimension. Currently, California law places a 38-ft limit on the kingpin dimension except on the desig-