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Methods for Predicting Truck Speed Loss on Grades

Executive Summary

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16. Abstract

Truck speed loss on grades reduces highway capacity and increases the risk of accidents. The rational design of a truck climbing lane as a solution to this problem requires means for predicting truck speed changes on grades.

Experimental measurements of the speed loss of trucks operating on highways were conducted at 20 sites throughout the country. These data were analyzed to compare performance to present guidelines for highway design embodied in the AASHTO Policy on Geometric Design of Highways and Streets. The performance of the straight truck and tractor-trailer population is notably better than that reflected in the AASHTO publication.

Methods were developed for modeling the hill-climbing performance of the four major truck classes at the 12.5 and 50 percentile population level using empirically determined weight-to-power values. Speed-distance plots are provided for each class on constant grades, along with a simple computer program for calculating speed versus distance on arbitrary grades defined by the user. These speed-loss models are recommended as alternatives to the AASHTO standard for highways carrying primarily straight trucks and tractor-trailers.

Trucks pulling trailers, and doubles and triples are the truck classes with lowest hill-climbing performance. For the limited data obtained, the AASHTO model appears to provide a reasonable performance prediction for the 12.5 percentile population.

Methods for estimating performance at the 12.5 percentile level for mixed truck populations are presented. The need of a rationale for making design decisions with mixed truck populations is recognized, and suggested as a future research topic.

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INTRODUCTION

Background

This document is the final report for the FHWA study, "Truck Tractive Power Criteria," Contract Number DTFH61-83-C-00046, performed over the period July 1983 to October 1985. The study focuses on the problem of predicting the speed loss of trucks encountering grades on our nation's highways.

For purposes of this project, the term "truck" refers to any combination of single- or multi-unit vehicles having at least one axle with dual wheels. Vehicles of this type normally have a gross vehicle weight rating (GVW) of 10,000 lb or more, and are thus separated from the much larger population of light trucks (pickups), which are similar in hill-climbing performance to passenger cars. The trucks considered in the project then range from the smaller 2-axle straight trucks with GVW ratings over 10,000 lb, to tractor-semitrailers, and doubles or triples combinations with GVW ratings to the maximum allowable on the highways.

Trucks characteristically exhibit the lowest level of hill-climbing performance of all vehicles using the nation's highways. Thus, at uphill grades of sufficient length and steepness their speed loss may be great enough that they impede the traffic flow, reducing the capacity of the highway to carry traffic, and creating possible hazards to other vehicles. To counteract these influences, climbing lanes may be added along the uphill grade section. The additional construction and maintenance costs, however, warrant careful consideration with regard to when climbing lanes are needed, and over what portion of the grade.

To aid highway designers in making decisions on this and other matters, the American Association of State Highway and Transportation Officials (AASHTO) publishes a Policy on Geometric Design of Highways and Streets. The Policy addresses the issue of truck uphill performance and the need for climbing lanes. In brief, a truck's weight-to-power (W/P) ratio is considered to be the most important characteristic affecting hill-climbing performance, with a value of 300 lb/hp taken as the representative W/P value for design purposes. Plots of speed versus distance on constant grades are presented for a typical truck of 300 lb/hp as a tool for the highway engineer to estimate truck speed losses on a proposed design. Studies are referenced that indicate that truck accident frequency increases with differential in speed, thus climbing lanes are advantageous when excessive speed differentials are anticipated. A speed difference of 10 mi/h (16 km/h) is suggested as a limit at which point a given grade is of the "critical" length justifying consideration for a climbing lane.

The decision to add a climbing lane carries with it an economic penalty, and in many cases complicates the overall design. For determination of where on the grade the climbing lane must start, the characterization of truck performance is very critical. The basis for characterizing truck performance by a W/P of 300 lb/hp derives from a number of past studies ranging in time from 1945 to 1978. Yet, there is need for a more comprehensive study examining truck hill-climbing performance in a more general way--considering the possible differences in geography, road type, and, particularly, the temporal changes in truck properties.

Objectives

This study addressed the broad issue of how truck hill-climbing performance could be best characterized, and what methods could or should be applied by the highway engineer to quantitatively estimate truck speed losses for a particular design. The individual objectives may be stated as follows:

1) To determine how to model or characterize hill-climbing performance in a way that is most useful for the highway design process.

2) To determine the primary variables affecting hill-climbing performance that may be specific to a site (i.e., truck class, grade, speed, road classification, and location).

3) To develop guidelines and/or procedures for the highway engineer that can be used to quantitatively estimate hill-climbing performance of the general truck population at a site, taking into account the above variables.

FINDINGS

Experimental measurements of the climbing performance of over 4,000 trucks were made throughout the country. From 20 sites distributed both in the East and West, the speed loss of trucks was measured on grades from 2 to 6 percent, along with descriptive data about the trucks. Individual trucks were tracked through the grades, and at some sites additional data on weight and power were obtained while they were stopped at nearby weigh stations.

The observed truck performance always took the form of a distribution which is nearly linear in the range from about the 12.5 to the 50 percentile level. At the high percentile levels the distribution may be skewed by heavy representation of trucks with higher performance levels, perhaps because of light loading. The 12.5 and 50 percentile levels were selected as means to characterize the population distribution, capitalizing on the linearity as means to estimate performance at other percentile levels.

Final Climbing Speeds

On constant grades of sufficient length a truck will decelerate to a steady speed, often called the "final climbing" speed. Final climbing speed is significant both because of its influence on highway capacity, and because of what it tells about truck performance capabilities. At this operating condition, shifting is no longer required and the speed achieved represents a balance between engine tractive effort and the drag forces acting on the truck. On steep grades the primary drag is that due to grade which can be determined independently by measurement of the grade angle. This contrasts with measurements during the deceleration phase at the beginning of grade where deceleration levels must also be determined to quantify performance.

Final climbing speeds varied with grade and with truck class. Although the data from the different sites exhibit scatter because of random differences between trucks and site conditions, the values used by AASHTO closely bound the 12.5 percentile climbing speeds for trucks with trailers and doubles. The bound for straight trucks and tractor-trailers at the 12.5 percentile level is generally 2 to 4 mi/h (3 to 6 km/h) above the AASHTO estimate.

Deceleration at Speed

Truck decelerations at high speed on a grade are of primary importance in determining where a climbing lane should start. To characterize the trucks by a direct measure of performance at high speed, a weight-to-power value, W/P_3, is formulated. The P_3 symbol denotes the power available to accelerate the truck and/or overcome grade at speed. Thus, it is the drive power at the wheels less the aerodynamic and rolling resistance drag forces.

The W/P_3 values may be determined from the observations of deceleration and speed by noting the change in speed between two points on a known grade, and the average speed. The experimental measurements yielded two values in the entry portion of the grade, plus an additional value from the final climbing speed.

The data from all trucks on all sites were reduced to W/P_3 values and examined to identify dependence on truck or road class. No dependence on grade was indicated. An estimate of the equivalent W/P_3 values for the "typical truck" in the AASHTO guide was derived from the equations for characterizing the truck, as a point for comparison.

The performance of straight trucks and tractor-trailers is notably better than that predicted by the AASHTO model. Data for trucks with trailers and doubles is less conclusive because of the limited sample size, but falls closer to the AASHTO model.

Performance Characterization

In light of the disparity between the AASHTO predictions and the performance observed with modern trucks, alternative means of characterization were devised. The assumption that P_3/W is linear with speed allows a representation that can be readily matched to experimental data, and greatly simplifies the calculation of speed losses on arbitrary grades. The P_3/W function is determined by selecting the reciprocal, W/P_3 value, for speeds of 25 and 50 mi/h (40 and 80 km/h) that bound the experimental data points.

Performance limits for the 12.5 and 50 percentile of each truck class on each road class were selected. To validate the characterization, spatial decelerations (speed loss per unit distance traveled) were extracted from the experimental data for tractor-trailers on nominal grade levels of 3, 4, 5, and 6 percent. The P_3/W function selected for tractor-trailers bounds the experimental observations much more closely than that derived from the AASHTO speed-distance curves. Thus, use of the P_3/W function provides much more precise prediction of speed losses on a grade.

The overall performance of straight trucks and tractor-trailers are closely equivalent. Straight trucks on Eastern interstates and on primary roads show slightly better performance, but can be lumped with tractor-trailers to simplify prediction of speed-distance behavior for these two truck classes. Trucks with trailers and doubles exhibit lower performance in hill-climbing, much closer to the current AASHTO predictions. Because of the small sample size encountered in the experimental tests, precise characterization is not possible.

Using the empirically-based P_3/W functions, new speed-distance curves are computed for each truck class and road class. The empirical constants and a simple Basic-language computer program are provided to allow computation of speed-distance curves for any arbitrary grade.

Where a mixed population of truck traffic is anticipated, the prediction of performance at a given percentile level is more complicated. The inclusion of trucks in the lower performance classes (trucks with trailers or doubles) requires separate analysis to establish the performance of the mixed population. Methods for analysis are given.

From measurements at the weigh stations, it is possible to compare the performance in hill-climbing to that predicted from knowledge of the actual weight-to-power ratio. The comparisons indicated that drivers of straight trucks use nominally 45 percent of the "rated" engine power, with up to 80 percent used by drivers of tractor-trailers. The actual weight-to-power values for the trucks observed in this study are lower than those extracted from the Truck Inventory in Use surveys conducted periodically by the Department of Commerce.

CONCLUSIONS AND RECOMMENDATIONS

The main objective in this project was to obtain experimental measurements of the hill-climbing performance of modern trucks, and develop methods for predicting speed loss of the general truck population on arbitrary grades. The data and methods have significance as potential aids in the decision-making process with regard to the need for, and design of, truck climbing lanes. The work has resulted in some significant conclusions with regard to truck performance prediction:

1) The AASHTO curves for speed versus distance on different grades are conservative estimates of truck performance, nominally equivalent to the 12.5 percentile of the lower performing truck classes (trucks with trailers, and doubles). The performance limits for 12.5 percentile straight trucks and tractor-trailers are somewhat higher than the AASHTO values. For these vehicles the final climbing speeds are 2 to 4 mi/h (3 to 6 km/h) higher. The rate of speed loss on grades (spatial decelerations) observed for straight trucks and tractor-trailers was lower than that of the AASHTO speed-distance curves. Thus, the "critical length of grade" indicated in the AASHTO guide is shorter than warranted for these vehicles. On a 6 percent grade the "critical length" based on AASHTO is approximately 100 feet shorter than necessary. On a 3 percent grade it is about 700 feet shorter.

2) Measurable differences in performance were observed among certain truck classes, road classes, and geographic locations. Tractor-trailers exhibited consistent performance throughout the country on both interstate and primary roads. Straight trucks had slightly better performance on primary roads, and on interstates in the West. Trucks pulling trailers and doubles are significantly lower in performance than trucks and tractor-trailers.

3) A simplified means of predicting truck hill-climbing performance was developed based on characterization of the available power for accelerating and overcoming grade (denoted by the symbol "P_3"). The ratio of available power to weight (P_3/W) is speed

dependent, but provides an easy means for calculating truck speed profiles on arbitrary grades. Appropriate P_3/W ratios, representative of the 12.5 and 50 percentile of most vehicle classes, were determined from the experimental data acquired in the project.

4) The recognition that performance variations exist within vehicle classes, and between vehicle classes, brings to focus a need for more comprehensive methods for decision making on climbing lane design. Minimizing the frequency of trucks operating below a critical speed on the highway network is suggested as the goal in a decision model. The performance of the 12.5 percentile truck in a population has been suggested as a benchmark for conservatively estimating critical length of grade. Methods for determining performance of the 12.5 percentile vehicle in a mixed population of truck classes are provided.

Although the project was successful at answering many of the questions posed at the outset, and clarifying many of the issues involved, it has become obvious that there are many areas of need for data and methodology by which to refine the climbing lane design process. Extensive data were obtained on tractor-trailer vehicles and reasonable samples were obtained for straight trucks. The homogeneity observed with tractor-trailer vehicles suggests that their characterization is well founded. The more limited data on trucks, and the differences observed on interstate and primary highways would argue that more experimental data should be acquired to refine the estimates of their performance limits. In the meantime, it is recommended that the speed-distance relationships for the 12.5 percentile vehicle given in figure 22a of the main report be used for prediction of straight truck and tractor-trailer performance. This figure should be considered as an alternative to the AASHTO speed-distance curves on roads limited to truck traffic of these two classes.

The data on straight trucks pulling trailers, and doubles and triples are so limited that the performance limits determined here should be taken only as estimates of the population as a whole. More experimental data on these particular vehicle classes are warranted before performance limits can be confidently assessed. The speed loss on grade for the 12.5 percentile of both of these vehicle classes appears comparable to that in the current AASHTO guide. Thus, AASHTO speed-distance curves are still appropriate for characterizing these vehicles, pending more experimental data to improve predictions of their performance. For optimal design, the AASHTO guidelines should not be applied casually to highways simply because truck traffic of these vehicle classes is present. Consideration of the performance for the overall traffic mix may allow a longer critical length of grade at the 12.5 percentile performance level.

The characterization of performance within truck and road classes, as has been determined in this work, results in a more complex decision-making process for the rational design of climbing lanes. There is need for improved methodology to guide the decision-making process which properly considers the distribution of vehicle performance on a grade. Insights from this work have been suggested. The notion that the goal in the decision process is to minimize the frequency of encounters with low-speed trucks in a highway network points to the need for treatment from a probabilistic approach. The 12.5 and 50 percentile performance levels, plus the observation that deceleration distributions are approximately linear, provides a basis for describing the distributions of performance among vehicles. Further research in this area is recommended.