Motor-Vehicle Performance on Ascending Grades

ROBERT E. DUNN, Assistant Traffic Engineer
Washington State Highway Commission

The purpose of this paper is to present a graphical type of analysis that was developed to provide sufficient information within reasonable time and cost limits for the determination of the proper location of climbing-lane termini.

The procedure employs various types of traffic studies to develop a profile of the average running speeds of commercial vehicles and unimpeded passenger cars and a measurement of the additional travel-time required by the overtaking and passing maneuvers of delayed traffic. The graphical analysis determines: (1) the length of the impeding zone within which the grade effects a reduction in the normal speed of trucks; (2) the proper positioning of a climbing lane based upon selected acceptable speed differentials between passenger cars and trucks; and (3) the rating of ascending grades through an economic comparison of time-delay and accident costs of motor vehicle operation.

The conclusion of this research is that it is an economical and dependable method of obtaining such supplemental information as may be required for the planning, programming and construction of safe and efficient highway facilities.

● THERE are over 5,800 miles of state highway on the rural system in the State of Washington. The heaviest-traveled routes of the network either cross the Cascade Mountain range that divides the State geographically, or, in many places, traverse rolling forested or agricultural terrain. Less than 200 miles of the system have been constructed to four lanes. Increasing volumes of traffic are causing accidents and congestion on certain critical two-lane facilities due to the capacity-reducing effects of slow-moving vehicles on ascending grades.

Sufficient dependable information is available to determine where climbing lanes for slow-moving vehicles are warrented on various gradients and lengths of grades. Other published information can be used to position the climbing lane on the grade so that it will meet the operational requirements of average reported traffic characteristics. There are certain physical and operational characteristics, however, found to be peculiar to some ascending grades, that involve a deviation from published criteria for the proper location and design of a climbing-lane facility.

Physical factors often limit the length that can be provided for a climbing lane. These include such considerations as: (1) the location of crossroads, particularly at or near the crest of the grade, (2) the economics of right-of-way acquisition in relation to the benefits to be derived, (3) adverse topographical features that affect excavation or fill quantities, and others.

Two principal operational features have been found in Washington that tend to lengthen the climbing lane normally required. First, Gypo loggers employing obsolete equipment in forest regions, and farmers utilizing underpowered trucks in agricultural areas, present performance problems different from the weight-power ratios of the big Rigs operating on interstate hauls to and from industrial centers. Second, state statutes limit the speed of commercial vehicles exceeding 10,000 lb. in gross weight to a maximum of 40 mph., while permitting day and night passenger car speeds of 50 mph. and, at some selected locations, 60 mph.

The extent to which the operational characteristics of the average running speeds of passenger cars and trucks was found to deviate from nationally-reported data in the instance of "Swauk Creek Hill" and vicinity, is shown in Table 1.

The observed speed of passenger cars and trucks operating on level terrain was 9 mph. and 10 mph. faster, respectively, than that of the average reported data. However, the differential between the speed of the two vehicle classifications was exsentially the same for both the observed and reported data. A greater deviation of observed speeds from reported speeds was found in passenger cars than trucks on 5 percent grades. This created a 46-percent higher differential in grade speed between the two vehicle classifications than is provided for by published design criteria.

PURPOSE OF STUDY

The preparation and review of contract plans for the provision of a climbing lane on an ascending grade involves three principal considerations: First, there is the application of available research data and design criteria to determine the warrants for and the requirements of the facility. Second, certain physical and economic factors have a tendency to effect a modification in the preliminary design. Third, deviations of observed motor-vehicle performance from average reported operational characteristics may require further adjustments in the design to compensate for local traffic peculiarities.

The resolving of these factors that influence the design of a climbing lane can sometimes be achieved through opinions based upon engineering judgment and experience. In other instances, the divergent nature of existing data may necessitate supplemental information before a decision can be reached as to the adequacy of the design. The survey procedure and graphical analysis process, hereinafter discussed, was specifically evolved to provide a hand-tailored method of determining the proper position and length of a climbing lane on an ascending grade at such locations where published design criteria are not applicable.

TABLE 1

REPORTED AND OBSERVED FREE VEHICLE SPEEDS
(Swauk Creek Hill and Vicinity)

Data Source	Grade Percent	Average Running Speed (mph) Passenger Cars	Trucks	Speed Differential
Reported [1]	Level	46 mph	37 mph	9 mph
Observed [2]	Level	55 mph	47 mph	8 mph
Reported [1]	+ 5%	40 mph	27 mph	13 mph
Observed [2]	+ 5%	49 mph	30 mph	19 mph

[1] Table III-17 AASHO Policy on Geometric Design of Rural Highways
[2] Swauk Creek Study of Motor Vehicle Performance on Ascending Grades

The study of motor vehicle performance on Swauk Creek Hill was an operational research project conducted for the purpose of improving methods of instrumentation, and to obtain data on the ascending grade prior to the construction of the climbing lane. Inasmuch as the climbing lane was in the programming stage at the time of the survey, the findings of the study had no effect upon its design.

SCOPE OF OPERATIONAL RESEARCH

The study of vehicle performance on the particular ascending grade of Swauk Creek Hill is one for which a climbing lane was proposed in 1953 and constructed in 1954. This is an ascending grade for westbound traffic, approximately 0.6 mile in length, on US 10 (Primary State Highway 3), 12 miles west of the City of Ellensburg. US 10 is an important and relatively heavy-traveled (4,300 vpd.) two-lane highway on the interstate system in this vicinity.

The Swauk Creek grade is on a general east-west alignment that parallels the Yakima River. The study section passes for 6.5 miles through a narrow and winding gorge. Railroads running along both river banks have prevented highway construction on a water-level grade, and this condition has necessitated several steep grade rises and sharp horizontal curves over the rolling terrain. The pavement is 20 feet in width, with substandard gravel shoulders and numerous passing-sight-distance restrictions. Valleys located at both ends of the river gorge allow for long tangents that are conducive to high vehicle speeds. The posted absolute speed limits on this highway at the time of the study were 50 mph. for passenger cars and 40 mph. for trucks.

Swauk Creek Hill is one of four ascending grades encountered by traffic traveling in either direction through the gorge. All four grades were included in the field survey, but Swauk Creek Hill was the only one involved in a program for climbing-lane construction. Due to the mechanics of presentation involved in the graphical analysis process, only the operational research findings on Swauk Creek Hill will be described. A comparison of the effect of the several factors of time delay and accident costs on this ascending grade, in relation to the other three, will, however, be presented in the scope of this paper.

PROCEDURE OF STUDY

The study of vehicle performance on ascending grades in the Swauk Creek Hill vicinity employed various traffic engineering procedures to measure the following basic operational characteristics: (1) volume and classification of traffic; (2) average running and spot speeds of passenger cars and trucks; and (3) distance an overtaking vehicle followed an impeding truck.

These measurements were procured by a three-man crew operating in a cruising survey car equipped with a calibrated survey odometer reading to 0.01 of a mile, and a sweep-second-hand stopwatch. The odometer and watch were both started from a zero reading as the cruising car followed

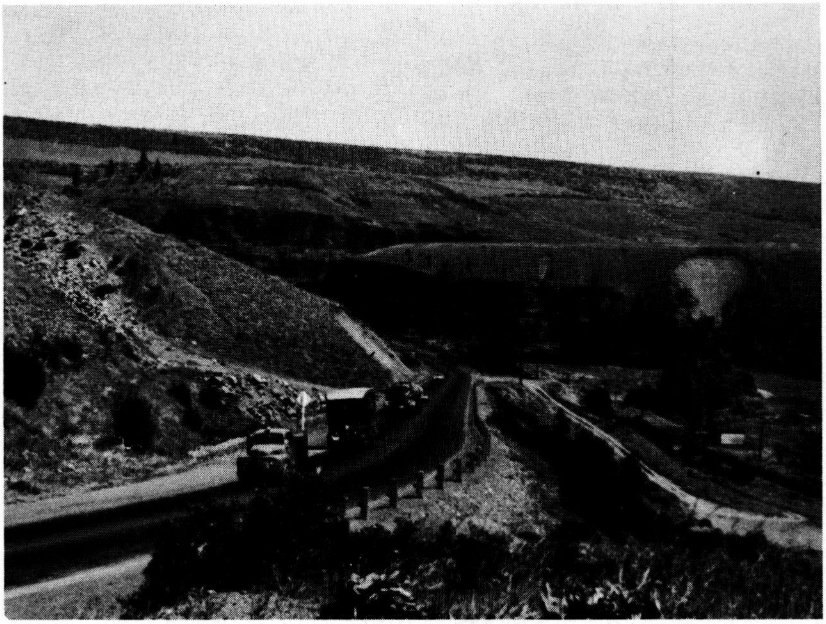

Figure 1. Swauk Creek Hill before construction of climbing lane.

TRAFFIC VOLUME AND VEHICLE CLASSIFICATION

Three consecutive weekdays in July 1953, having normal seasonal traffic conditions, were selected for the field instrumentations and observations; 24-hour directional traffic volumes were secured by a mechanical hourly recording traffic counter. The classification of vehicles by the license registration of passenger cars and the axle arrangement of 10 classes of trucks were conducted simultaneously with the operation of spot speed stations to utilize available manpower.

OPERATING SPEEDS OF PASSENGER CARS AND TRUCKS

Instrumentation of vehicle performance was made between 9 a.m. and 6 p.m., the hours of maximum traffic volumes. Operating speeds were calculated in the office analysis from time and distance measurements made in the field.

a sample vehicle past the initial point of the study section. A time recording to the nearest second was taken from the continuously-running stopwatch at each 0.05 or 0.10 distance readings of the odometer. The first interval was used for slow-speed operation, and the latter for high-speed recordings as a matter of safety and convenience. The time and distance readings

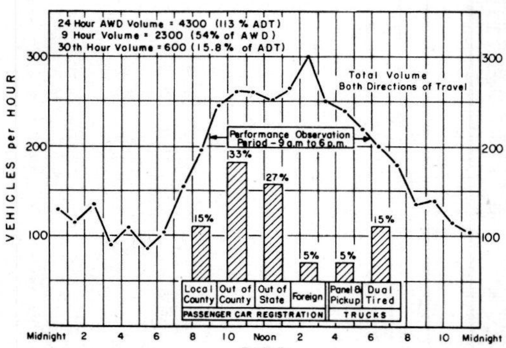

Figure 2. Traffic volume and classification.

for unimpeded passenger cars and for an adequate sample of trucks of various axle classifications selected at random from the traffic stream were secured in this manner.

Radar speed meter equipment was used to obtain a larger sample of operating speeds than was possible by the cruising-survey-car method. The spot speeds were taken just below the crest of the grade so as to secure a check on the minimum crawl speed of slow-moving vehicles.

DISTANCE OVERTAKING VEHICLES FOLLOWED IMPEDING TRUCKS

A measurement of the distance that an overtaking vehicle followed an impeding or slow-moving truck was recorded simultaneously with the time and distance data secured on the truck. The cruising car, in assuming the operational performance of the truck at a safe passing distance behind it, was considered as having an impeding influence similar to the truck. A passing maneuver around the cruising car (but not necessarily the truck) by an overtaking vehicle would, therefore, have been theoretically the equivalent of the passing of the truck, had the survey car not been in its position in the traffic stream. The distance that an overtaking vehicle followed the truck was secured by first recording the survey odometer reading at the location where the speed of the overtaking vehicle was influenced by the cruising car. A second form entry was made at the odometer station where a passing maneuver was completed around the survey vehicle.

SURVEY TIME AND MANPOWER REQUIREMENTS

The survey time required to conduct a study of vehicle performance on an ascending grade depends upon the length of roadway to be observed and the frequency of sample arrival for instrumentation. Swauk Creek Hill, with a grade 0.6 mile in length, a zone of influence of 1.2 miles, and a weekday volume of 4,000 vehicles, required two days of field observations for a crew of three. The office calculations and graphical analysis, exclusive of report preparation, entailed approximately three man-days for each man-day spent in field work.

GRAPHICAL ANALYSIS

The graphical analysis of vehicle performance on ascending grades is the primary objective of the method of procedure reported upon in the scope of this paper. The purpose of the analysis is to provide a graphical determination of: (1) passing-sight-distance restrictions on the ascending grade; (2) the length of the impeding zone within which the grade effects a reduction in the normal operating speed of trucks; (3) proper terminal locations of a climbing lane, based upon selected acceptable speed differentials between passenger cars and trucks; and (4) time-delay incurred by overtaking passenger cars that are impeded by slow-moving vehicles.

PLAN AND PROFILE OF THE GRADE

The plan and profile of the ascending grade under study (Figure 3) provides information of value in supplementing other data in the subsequent analyses. Swauk Creek Hill contains a grade rise of 130 feet in a run of 3,000 feet. There is a 400-foot vertical curve on either end of a 5-percent grade. The relationship between the length of grade, as measured in the field by the use of survey odometer stations 3.20 to 3.75, and the engineering stations of the construction plans, is conveniently indicated on the plan and profile. Scale measurements show that there is approximately 50 percent sight-distance restrictions for ascending traffic because of the combined effect of two 6-deg. horizontal curves and the vertical curve at the crest of the grade.

PASSENGER CAR AND TRUCK SPEED DIFFERENTIAL

The difference between the average running speeds of unimpeded passenger cars and various types of trucks (Figure 4) provides the data essential for the proper selection of the length of a climbing lane to fit the local traffic characteristics and physical grade conditions. A graphical presentation of the average running speeds for the length of the impeding zone within which the grade effects a reduction in the normal speed of trucks is of value in checking several design criteria.

The fundamental principal of climbing lanes is to reduce the differential in speed

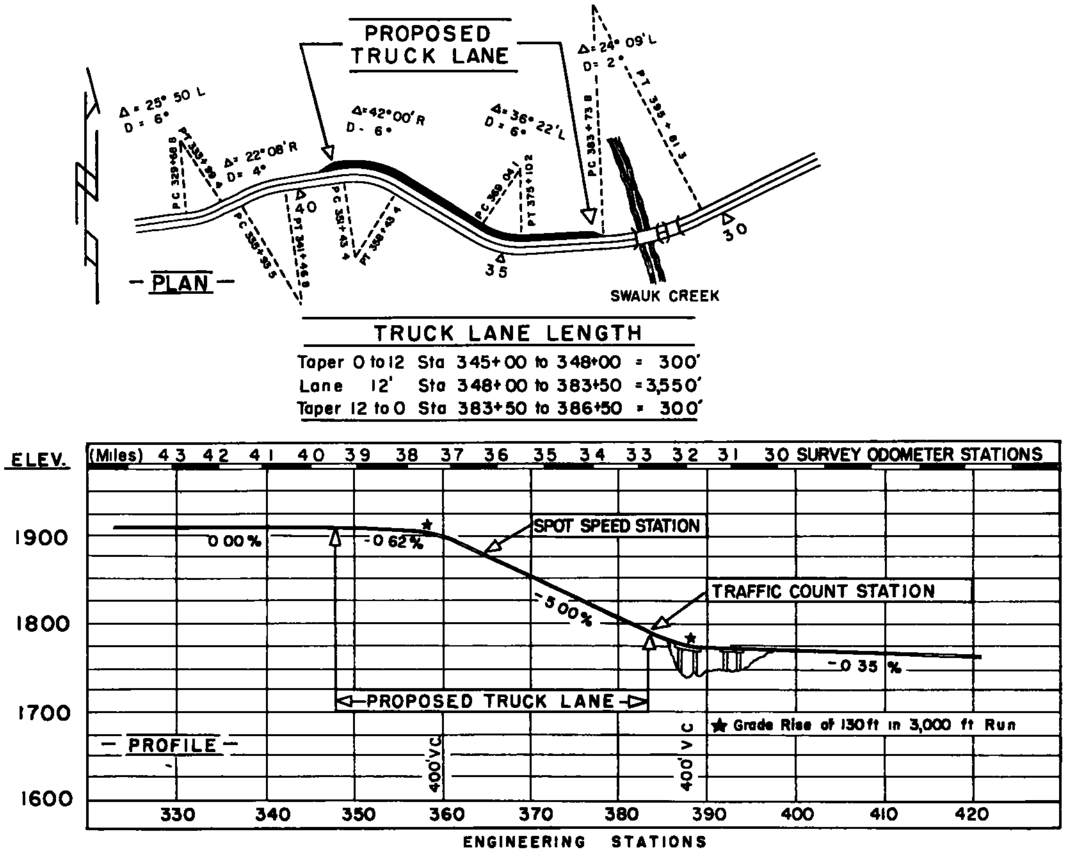

Figure 3. Plan and profile.

between passenger cars and trucks to a safe minimum. The length of a climbing lane is, therefore, predicated on an acceptable safe-speed differential for the conditions found at the specific location under consideration. It is not the purpose of this paper to enter into a discussion as to what constitutes such a speed differential but, rather, to illustrate the method by which the termini of a climbing lane can be located in special situations, once such criteria has been determined by the designing engineer.

Table 2 contains various graphical de-

TABLE 2

VARIOUS GRAPHICAL DETERMINATIONS OF CLIMBING-LANE LENGTH
(Swauk Creek Hill)

Selected Graphical Criteria	Climbing Lane Length	Equivalent In Grade Length	Speed Differential Start	Speed Differential End
Length of Grade including Vertical Curves	3,000 ft.	1.0	--	--
AASHO Design (Truck Speed less than 30 mph)	2,600 ft.	0.9	23 mph	19 mph
Proposed Truck Lane excluding Tapers	3,550 ft.	1.2	10 mph	19 mph
Permissible Speed Differential of 15 mph*	3,900 ft.	1.3	15 mph	15 mph
Normal Speed Differential of 10 mph	5,400 ft.	1.8	10 mph	10 mph
Truck Speed less than Legal 40 mph Limit	6,500 ft.	2.2	10 mph	8 mph

*If the average speed for trucks at the bottom of the grade were the same as for all vehicles, this differential would be comparable to the permissible speed reduction of 15 mph. in AASHO policy.

terminations of climbing lane length, based upon the findings of vehicle performance on Swauk Creek Hill. The climbing lane, as originally proposed and constructed, starts at a point on the grade where there is an approximately normal 10-mph. differential between the average speeds of passenger cars and trucks and, also, where the latter is reduced by the effects of the grade to less than 40 mph. The end of the climbing lane is at a location beyond the crest of the grade where the speed differential is 19 mph. and at which point the trucks have accelerated from an average minimum crawl speed of 20 mph. to 30 mph. The climbing lane, as constructed, is 1.2 times the length of the grade.

cars and trucks and would inject them back into the travel lane at a differential of 19 mph.

The selection of a speed differential of 15 mph. would create a climbing-lane length that is 0.1 mile longer than the proposed design, but the beginning point would be moved approximately 550 feet up the grade. The investigation of other climbing-lane design criteria, based upon a local legal speed differential of 10 mph. between passenger cars and trucks, or a speed of trucks that falls below the legal limit of 40 mph., produces abnormal equivalents of 1.8 to 2.2 times the length of grade. The application of these last two standards would probably be unfeasible or

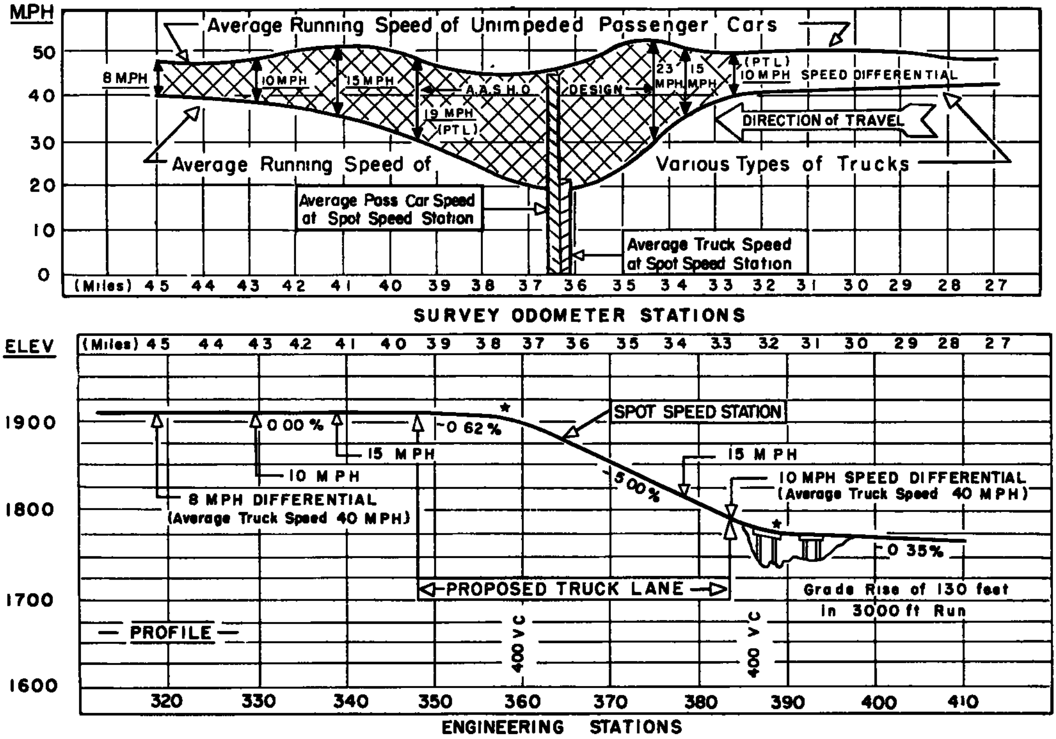

Figure 4. Passenger-car and trucks speed differential.

The investigation of one AASHO design criterion that locates the termini at the points where the truck speed falls below, and rises above, 30 mph. provides a climbing lane that is 0.9 times the length of the grade. The application of this standard to Swauk Creek Hill, however, would not remove the slow-moving vehicles from the traffic stream until there was a speed differential of 23 mph. between passenger

uneconomical in most cases. Nevertheless, they show the true length of the zone at Swauk Creek Hill within which the grade effects a reduction in the speed of trucks and creates an ensuing delay and hazard to passenger-car operation.

OVERTAKING AND PASSING PERFORMANCE

Passing maneuvers on a two-lane as-

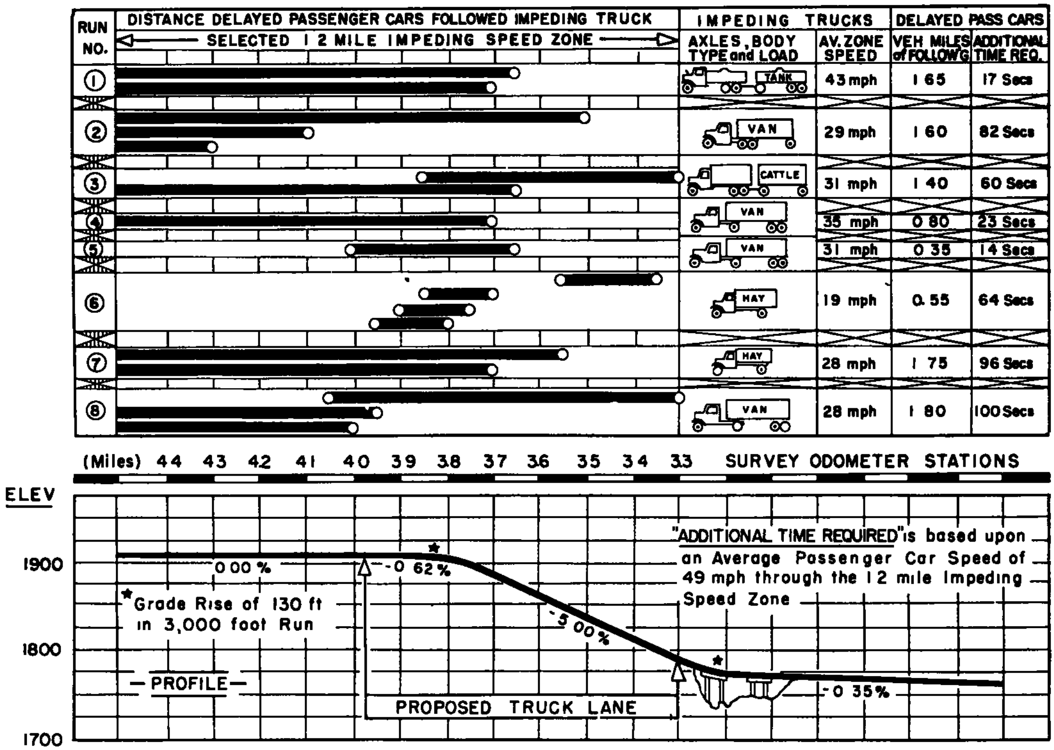

Figure 5. Overtaking and passing.

cending grade are primarily controlled by the two factors of sight distance and the volume of traffic in the opposing lane. The graphical presentation (Figure 5) of the data procured on the overtaking and passing performance of vehicles on Swauk

TABLE 3

ANNUAL COST OF MOTOR VEHICLE IMPEDIMENT

on

ASCENDING GRADES IN THE SWAUK CREEK HILL VICINITY

(Based upon the Hours of Maximum Traffic -- 9 a.m. to 6 p.m.)

Item	Ascending Grade Swauk Cr. Westbound	2 Westbound	3 Eastbound	4 Eastbound
July 1953 AWD (9 am - 6 pm)	1,107	1,107	1,185	1,185
ADT 1953 (9 am - 6 pm)	819	819	878	878
Number of Trucks (Dual-Tired) [1]	117	117	125	125
Average Pass. Car Delay/Truck [2]	50 secs.	65 secs.	51 secs.	32 secs.
Vehicle-Hours Delay/Year	592 Veh-Hr	780 Veh-Hr	645 Veh-Hr	405 Veh-Hr
A. Time-Delay Cost to Pass. Cars [3]	$592	$780	$645	$405
Number 1953 Accidents Involving Trucks	1	6	2	1
B. Annual Accident Cost [4]	$710	$4,260	$1,420	$710
C. TOTAL ANNUAL IMPEDIMENT COST	$1,302	$5,040	$2,065	$1,115

[1] 14.3% of ADT (9 am - 6 pm)
[2] Based upon Figure 5 for Swauk Creek Hill and similar tabulations for other grades
[3] Time Costs are based upon $1.00 per vehicle-hour
[4] Based upon all reported property damage costs

Creek Hill is based upon the observed operation of passenger cars and trucks between 9 a.m. and 6 p.m. During this period, the directional traffic volume exceeded 100 vehicles per lane per hour. The analysis presents: (1) the type of truck observed in each cruising survey car run, (2) the location where the overtaking vehicles were impeded, (3) the distance the delayed cars followed the truck, and (4) the additional passenger car travel time required due to the reduction in the normal operating speed. The overtaking and passing performance was recorded for vehicle operation through the 1.2-mile length of the impeding zone.

Cruising-survey-car Run 1 was the observation of a six-axle high-horsepower combination gas truck and trailer running empty up the Swauk Creek Hill. The average speed of this vehicle through the impeding zone was 43 mph. It was overtaken, but not passed, by two passenger cars that followed it through most of the zone for a total of 1.65 vehicle-miles. The overtaking vehicles required 17 additional seconds of operating time in following the impeding truck through the zone above that which would have been necessary could they have traveled at the average unimpeded passenger car speed of 49 mph.

Cruising-survey-car Run 6 was the observation of a two-axle underpowered farm truck loaded with hay that represented the other extreme of observed operational performance. The average speed of this vehicle through the 1.2-mile impeding zone was 19 mph. It was overtaken and passed by four vehicles after each had followed but a short distance. The total vehicle miles of following was 0.55, and the total additional travel time required amounted to 64 seconds. The average speed of all trucks through the impeding zone, as observed by the cruising survey car, was 30 mph. The minimum crawl speed recorded at the spot speed station, located near the crest of the grade, was 10 mph.

APPLICATION OF THE ANALYSIS

The principal application of the data secured in this type of survey is perhaps that previously described concerning the selection of proper climbing-lane termini, based upon a selected safe differential in the average running speeds of passenger cars and trucks. There are, however, other useful applications that can influence the considerations involved in the proper use and design of climbing lanes: (1) effect of commercial vehicles in lowering highway capacity, (2) effect of slow truck speeds upon delayed vehicles, and (3) effect of impeding trucks on traffic accidents.

EFFECT OF "SWAUK CREEK HILL" ON HIGHWAY CAPACITY

The relating of the findings of the survey analysis with research data contained in the "Highway Capacity Manual," prepared by the Committee on Highway Capacity of the Highway Research Board, serves to illustrate the effect that commercial vehicles had on the two-lane highway ascending Swauk Creek Hill prior to the construction of the climbing lane.

The manual states that one commercial vehicle has approximately the same effect as 2.5 passenger vehicles on two-lane roadways in level terrain. Applying this to the classification of traffic on the level tangent approaches in the Swauk Creek Hill vicinity, the thirtieth-hour volume of 300 vehicles per hour per lane with 15 percent dual-tired trucks, has the equivalent volume of 368 passenger cars per hour per lane.

Table 14 of the "Highway Capacity Manual" indicates that one commercial vehicle has the same effect as 10.1 passenger cars on Swauk Creek Hill, where there is sight distance restriction of 50 percent and a length of grade of 0.6 mile. The 15 percent of trucks during the thirtieth-highest hour, under these conditions, has the effect of 455 passenger cars. This, added to the actual number of passenger cars, raises the equivalent volume on the grade to that of 710 passenger cars per hour per lane. In terms of pure passenger-car equivalents, therefore, the operational characteristic of traffic on the two lanes of Swauk Creek Hill had nearly twice the volume effect as that on the two-lane level tangent section approaching the grade.

TIME-DELAY AND ACCIDENT COSTS

The application of the survey data to the economics of operation provides a method of comparison that is useful in relating the effects of vehicle performance on several ascending grades in the same vicinity hav-

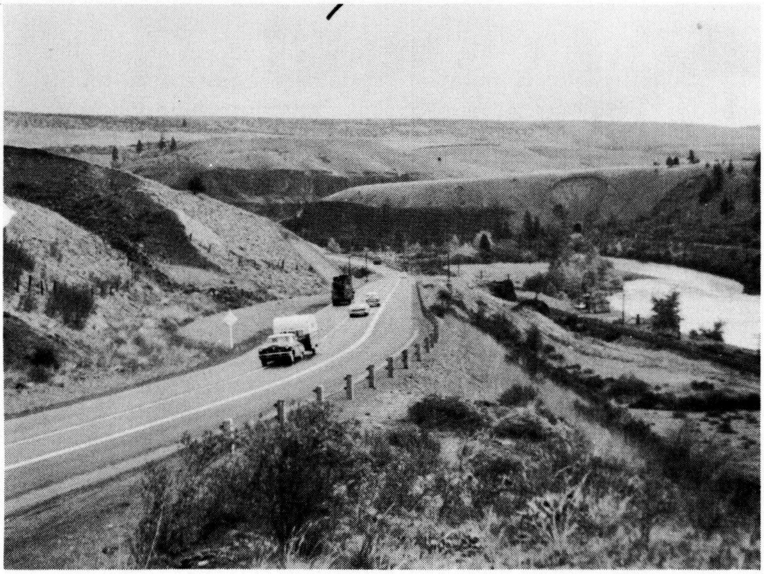

Figure 6. Swauk Creek Hill after construction of climbing lane.

ing identical traffic characteristics but different physical features. The annual costs of vehicle impediment on the ascending grades in the vicinity is contained in Table 3. The comparison of the annual time-delay costs to passenger cars (Item A) reveals that Swauk Creek Hill ranked third in the four ascending grades studied in the scope of the survey. This same ranking is also maintained in the summary of annual accident costs and total impediment costs (Items B and C) for the four ascending grades. The application of the economics of operation can serve a useful purpose to establish the priority of need when construction funds are limited or a stage development of an ultimate plan is contemplated.

CONCLUSIONS

The first objective of operational research on motor-vehicle performance is to obtain such information as may be necessary for the planning, programming and construction of safe and efficient highway facilities. The second objective is to develop a technique in the application of various types of traffic-study methods that will provide sufficient dependable information within reasonable time and cost limits. The procedure evolved and discussed in this paper for the study of vehicle performance on ascending grades has satisfactorily achieved these objectives with respect to the location and design of climbing lanes.

Two general conclusions were derived from the complete study of the 6.5-mile length of highway in the vicinity of Swauk Creek Hill. First, the total section is nearing its practical capacity due to the effect of the rolling terrain on sight distance and the operational performance of commercial vehicles. Second, climbing lanes for slow-moving vehicles on all of the four ascending grades are warranted and should be considered as part of a stage development plan for ultimate four-lane construction to increase highway capacity and reduce accidents and congestion.