Economic Feasibility Assessment Procedure for Climbing Lanes on Two-Lane Roads in Mexico

ALBERTO MENDOZA AND EMILIO MAYORAL

The development of procedures for analyzing the economic feasibility of constructing climbing lanes on two-lane roads in Mexico and for assessing the levels of service before and after implementing these facilities is presented. Initially, the weight-horsepower ratio that is representative of the Mexican freight vehicles is obtained. Then this ratio is compared with the value reported for this parameter in the United States. From this comparison and a data set collected in a series of grades specific to Mexico, the different operating conditions of the trucks and the vehicular flows between the two countries are shown. The foregoing also shows the need to adapt to the Mexican conditions the procedure and criteria for specific grades in the 1985 *Highway Capacity Manual* and to generate an economic feasibility assessment procedure for climbing lanes in Mexico. These tasks are carried out by using model calibration, simulation, and regression analysis techniques. From the procedures developed, the potential use of climbing lanes in Mexico is discussed briefly. Finally, a series of conclusions and recommendations is outlined.

In Mexico two-lane roads account for more than 95 percent of the 46 000 km that constitutes the federal trunk road system. The 1988 Mexican Government Program for the Modernization of the Transportation System established the convenience of carrying out comparatively inexpensive improvements on the two-lane trunk road segments with long and steep grades (longer than 800 m and steeper than 3 percent) and considerable traffic, particularly trucks (*1*). The provision of extra climbing lanes in such segments (hereafter referred as specific grades) traditionally has been considered among the most efficient of low-cost improvements.

The preceding represents the starting point of this Instituto Mexicano del Transporte (IMT) research project, whose main features and findings are described in this paper. The objective of this research was to develop procedures for analyzing the economic feasibility of constructing climbing lanes on two-lane roads in Mexico and for assessing the levels of service (LOS) before and after implementing these facilities.

REPRESENTATIVE WEIGHT-HORSEPOWER RATIO FOR MEXICAN TRUCKS

Initially, a study was conducted to determine the weight-horsepower ratio that is representative for Mexican freight vehicles. This parameter has an important effect on reducing the speeds of heavily loaded trucks moving uphill on specific grades. If this reduction is significant, trucks impede following vehicles, degrading traffic operations.

Truck Weight Limits Authorized in Mexico and Other Countries

Even though the weight and dimension regulation in force today (put into effect in 1980) authorizes 16 types of freight vehicle, only the following 5 compose the truck flows that travel on Mexican roads: Type 2 (35 percent), Type 3 (22 percent), Type 3-S2 (24 percent), Type 3-S3 (15 percent), and Type 3-S2-4 (2 percent). For these truck types, Table 1 presents a summary of the weight limits specified in Mexico (according to the 1980 regulation and to a new regulation project expected to be put into effect early in 1994) and in six other countries. As indicated in Table 1, American, Japanese, and Spanish regulations allow greater weight limits for single-unit trucks (Types 2 and 3) than does the 1980 Mexican regulation. However, the Mexican regulation allows much greater limits for the heavier trucks (tractor-semitrailer, doubles, and full trailer combinations). Such dissimilarities arise as a result of the different criteria used in each country for the determination of maximum vehicle weights; for instance, in the United States, truck weights are regulated through limits on axle load (to control pavement damage), a bridge formula (to control bridge damage), and a total maximum vehicle weight of 36 T; the 1980 Mexican regulation considers only axle load. The new 1994 regulation project has already incorporated a bridge formula criterion.

Representative Truck Weight-Horsepower Ratio

A truck weight and dimension survey was carried out in 1991 by the Secretaría de Comunicaciones y Transportes on 10 points of the trunk road system. This survey provided the information needed to estimate the required ratio. In each point, for each vehicle surveyed, the information gathered consisted of the weight, dimensions, horsepower rating (specified by the manufacturer), nature of the transported freight, and origin and destination. The vehicular weights were obtained using weigh-in-motion equipment. Nearly 100,000 trucks were surveyed. After the compiled information was analyzed, the following results were obtained:

- Of all trucks surveyed (about 100,000), 22 percent were overweight.
- Of only the loaded trucks surveyed (about 70,000), 34 percent were overweight.
- The overloaded vehicles were an average of 20 percent overweight.

These figures indicate the lack of appropriate mechanisms to guarantee the adequate enforcement of weight and dimension laws.

Infrastructure Division, Instituto Mexicano del Transporte, P.O. Box 1098, 76000 Querétaro, Mexico.

TABLE 1 Truck Weight Limits Authorized in Mexico and Other Countries[a]

COUNTRIES		Type 2	Type 3	Type 3-S2	Type 3-S3	Type 3-S2-4
MEXICO	1980	15.5	23.5	41.5	46.0	77.5
	1994	16.5	24.5	41.1	43.6	59.1
USA		18.2[b]	24.5[b]	36.4[b]	36.4[b]	36.4[b]
CANADA		19.0	27.8	44.5	57.5	61.8
JAPAN		Total weight not to exceed 20 ton[c]				
BRAZIL		15.0	22.0	39.0	45.0	73.0[d]
SPAIN		18.0[e]	25.0[ef]	44.0[ef]	44.0	40.0
AUSTRALIA		15.0[g]	22.5[g]	39.0[g]	42.5[g]	72.0[g]

[a] In metric tons.

[b] Regulations vary by Province or State. These values are based on Federal Bridge Formula.

[c] Special vehicles up to 34 ton in total weight can be operated in the National Motorway System.

[d] Can operate only with special authorization and on specific roads.

[e] Provided it does not exceed 5 tons per meter of length measured between the first and the last axle.

[f] Subject to axle spacing restrictions.

[g] Maximum gross weight assumes single tyre steer axle with all other axles having dual tyres. Axle spacing requirements also apply to all vehicles.

For this scenario (the practical nonexistence of effective enforcement), a representative weight-horsepower ratio of 210 kg/hp was obtained (as the 95th percentile on the corresponding cumulative distribution). Under a hypothetical scenario of effective enforcement mechanisms and considering the weight limits specified by the new 1994 regulation project, a representative weight-horsepower ratio of about 160 kg/hp was obtained. It is believed that the provisions in the new 1994 regulation will eliminate the problem of overloading.

The observed weight-horsepower ratio of 210 kg/hp contrasts with the value of 135 kg/hp reported for this parameter (heavy trucks) in the United States, in the 1985 *Highway Capacity Manual* (HCM) (*2*). The main reason for this difference is the much heavier freight vehicles that travel on the Mexican roads as a consequence of the higher weight limits permitted by the regulation, as well as the truck overloads. More than 25 years ago, the representative weight-horsepower ratio of heavy trucks was very similar in both countries, that is, about 180 kg/hp (*3,4*).

In Mexico, then, the weight-horsepower ratio of trucks has grown as a result of consistent payload increments that have exceeded tare weight decrements and horsepower increments provided by the development of automotive technology. Yet in the United States, the weight-horsepower ratio of trucks has decreased. In Mexico, growth in the efficiency of freight vehicles has resulted in more heavily loaded but not in faster vehicles. In the United States, though, such growth has resulted in faster and only slightly more loaded vehicles. In essence, the conditions prevailing in each country represent two strategies for moving freight in trucks: (a) few trips in heavily loaded and slow trucks, and (b) many trips in slightly loaded and fast trucks. In general, as will be shown later, the Mexican strategy results in slower trucks traveling on the roads, which contributes to slower traffic flows. This situation is magnified by the fact that the average proportion of trucks is much higher on Mexican roads [35 percent (*5*)] than it is on American roads [14 percent (*2*)].

Such operating peculiarities of vehicular flows as well as the characteristics of Mexican roads justify the IMT's efforts to develop an economic feasibility assessment procedure for climbing lanes on two-lane roads in Mexico. For this purpose, it was necessary to first adapt to the Mexican conditions the LOS criteria for specific grades in the 1985 HCM. This task was accomplished using a data set collected in a series of specific grades and the Australian simulation model for rural roads, TRARR (*6*).

FIELD DATA COLLECTED

A data set was collected in 10 specific grades with design speeds higher than 90 km/hr, climbing lanes, and good pavement surface condition. The data collection was planned so that it would show the benefits derived from installing these facilities under different conditions of traffic, visibility, and length and percentage of grade. In all grades surveyed, the relevant alignment characteristics were taken (lane and shoulder widths, length and percentage of grade, degree of curves, and percentage of no-passing zones) along with traffic counts with vehicle classification, average upgrade and downgrade speeds, and percentage of vehicles in both directions traveling in platoons behind a leader at headways of 5 sec or less (which provides a useful measure of the quality of the traffic flow). The last three aspects were measured with the climbing lane open and closed consecutively, in 15-min intervals, during 16 hr in each grade (from 6 a.m. to 10 p.m.). Analysis of the collected data obtained the following results:

- The traffic streams in all grades surveyed were composed, on average, of 49 percent passenger cars, 10 percent buses, and 41 percent trucks.
- In all grades surveyed with the extra climbing lane closed (two-lane section), 148 hourly average upgrade speeds were recorded. In addition, on the basis of the alignment and traffic characteristics registered in each grade, the corresponding average upgrade speeds were computed according to the procedure indicated in the HCM. As indicated in Figure 1, the computed speeds were, on average, 56.5 percent higher than the recorded values. This shows the different speed levels that prevail on two-lane roads in Mexico and the United States and the need to adapt to the Mexican conditions the LOS criteria for specific grades in the HCM.
- For the downhill direction, the average speeds resulted a little higher than uphill, thus indicating better LOS in that direction. How-

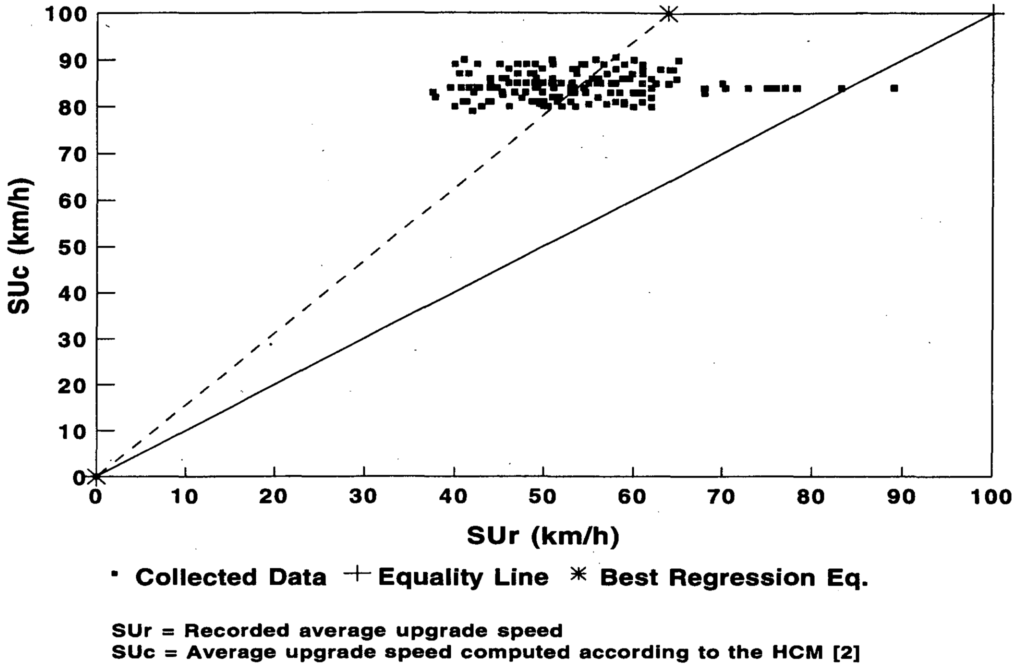


FIGURE 1 Speeds computed according to HCM versus speeds recorded in specific grades.

ever, like the uphill, the downgrade speeds showed a decreasing trend when the percentage of grade increases. This effect is attributed to the vehicles' risk of losing their brakes (which induces them to descend in low gear) and to the horizontal alignment curvatures. The following formula, valid for up to a 6 percent grade, describes the best regression relationship obtained ($R^2 = .82$) among the downgrade and upgrade speeds and the percentage of grade:

$$SD = SU/[1 - (M/21)] \quad (1)$$

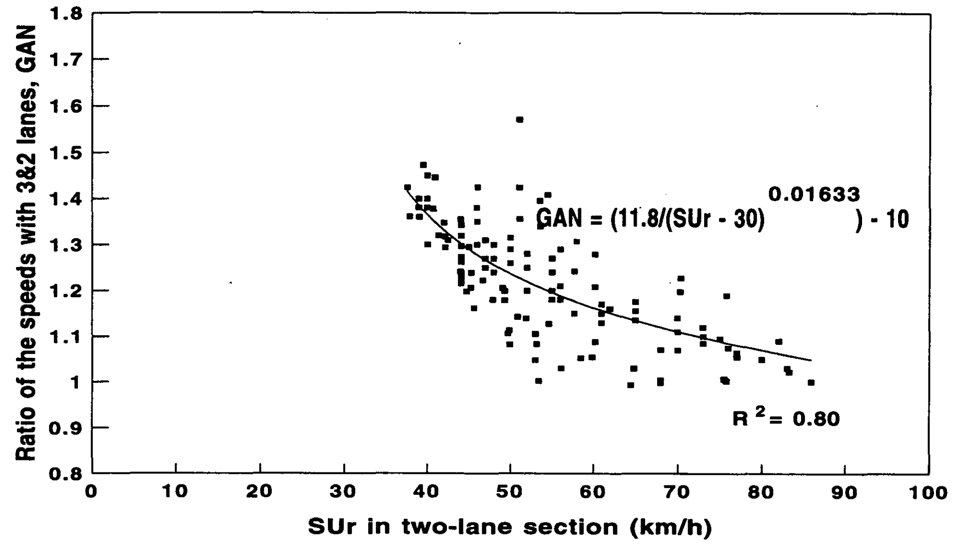
where

SD = average downgrade speed (km/hr),
SU = average upgrade speed (km/hr), and
M = grade (%).

- The LOS criteria for specific grades in the HCM were applied to the recorded upgrade speeds and to their corresponding computed values according to the HCM procedure. For the recorded speeds, which were low with regard to the speed scale from which the LOS were defined (Table 8.2 in the HCM), the most common LOS obtained were E and F (for 83.7 percent of the hourly data recorded). This situation suggests that the LOS criteria in the HCM are too rigorous for Mexico. For the computed speeds, on the other hand, which were rather high, LOS B was the most common (for 89 percent of the computed speeds). This situation indicates that to be applicable in Mexico, the HCM speed calculation procedure should be modified.
- For a subset of 134 data, the ratio of average speed with the climbing lane open (three-lane section) to average speed with the climbing lane closed (two-lane section) was computed (obviously, for traffic traveling in the same direction as the climbing lane). This ratio indicates the percentage of speed gained when a climbing lane is installed. In Figure 2, it is apparent that this gain is higher when the speed in the two-lane section is lower. Such a trend is suitably represented by the regression equation included in Figure 2 ($R^2 = .80$). For the 134 data points, the average gain was about 20 percent (an average ratio equal to 1.2).
- Figure 3 depicts an observed trend for the free-flow operating speed of passenger cars versus the percentage of grade. This trend was obtained for passenger cars operating on some of the shortest grades surveyed (between 400 and 600 m long) during conditions of very low traffic density. Likewise, Figure 3 shows the corresponding trends for cars in the United States and Colombia (*2,7*). The curve for the American cars was inferred from Table 8.7 in the HCM for a flow rate–to–capacity ratio of 0 and 0 percent no-passing zones. In Figure 3, the U.S. cars are less affected by the percentage of grade than the Mexican and Colombian cars. This apparent difference in behavior is due mainly to the fact that HCM Table 8.7 was obtained from a simulation based on an ideal tangent section of highway, whereas the Mexican and Colombian curves come from field data taken in real road conditions, particularly horizontal alignment.

TRARR MODEL

TRARR is a microscopic computer model that simulates the traffic operations on rural two-lane, two-way roads without intersections. The model takes into account the effect of overtaking prohibitions, auxiliary lanes (such as passing or climbing lanes), horizontal and vertical curves, variable sight distance, and driver/vehicle characteristics. TRARR generates the traffic entering the simulated road segment and reviews the progress of the position, speed, and acceleration of each vehicle along the road at frequent intervals (typically 1 sec). The program requires four input data files containing the following information:



SUr = Recorded average upgrade speed

FIGURE 2 Ratio of speeds with three and two lanes versus speed in two-lane section.

1. Traffic (volume, composition, directional split, and mean and standard deviation of desired speeds; also the settling down time and duration of the simulation run);
2. Road geometry (grades, curves, barrier lines, sight distances, and auxiliary lanes);
3. Driver/vehicle characteristics (length, acceleration, and following and overtaking behavior for up to 18 vehicle types); and
4. Type of output information required and location of observing points and intervals along the simulated segment.

For each direction of travel, the model gives output values at the specified observing points (spot mean speed and percentage of vehicles in platoons) and intervals (mean and standard deviation of travel time and speed, overtaking rate, percentage of travel time spent following, and fuel consumption).

TRARR was calibrated using the geometric characteristics of the specific grades surveyed as well as the operation information collected. The program input data were taken, specifically, from the field information gathered, typical characteristics of Mexican vehicles, and default values recommended for the model (*6*). Mean desired speeds of 96, 92, and 72 km/hr and standard deviations of 13, 12, and 9 km/hr were used for passenger cars, buses, and trucks, respectively, as obtained from the field data.

The model was calibrated to minimize the difference between simulated and field values for average upgrade speeds and percentage of travel time spent following (or percentage of vehicles in pla-

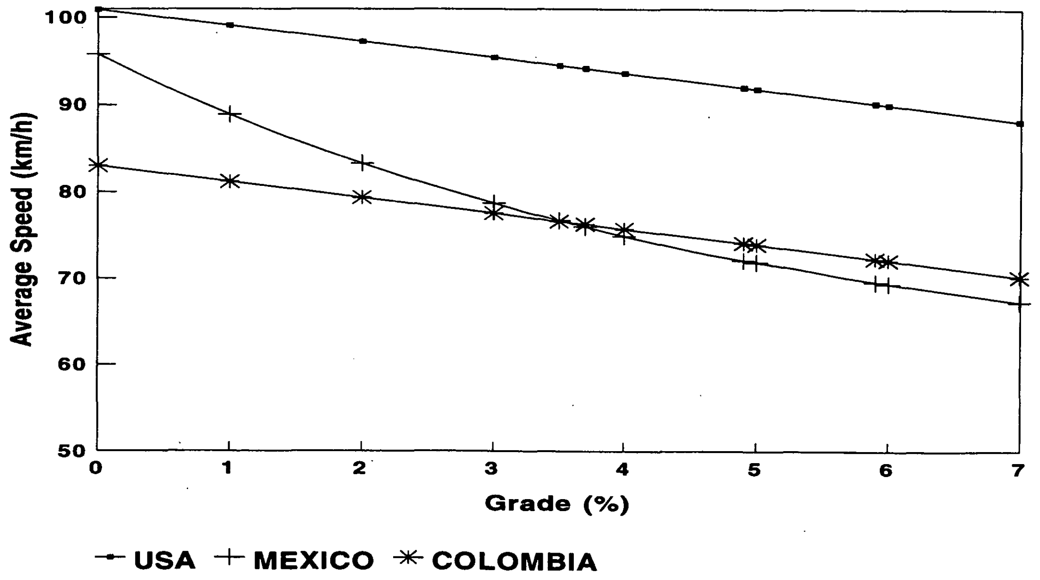


FIGURE 3 Free-flow operating speed of passenger cars versus percentage grade, in three countries.

toons). This was achieved not only by using characteristics of vehicles in Mexico, but also by redefining a series of multipliers for the desired speeds that the program uses to account for speed reductions due to certain road characteristics (mainly horizontal curves). After calibration, the model predicted average upgrade speeds for the different vehicle types and percentage of vehicles traveling in platoons with maximum errors of 15 and 17 percent, respectively, for a 90 percent confidence interval.

MODIFICATION OF LOS CRITERIA FOR SPECIFIC GRADES

From the calibrated model and the field data collected, the procedure and criteria in the HCM for LOS computation in specific grades were modified to better suit the Mexican conditions. The modifications lead to a procedure for evaluating the LOS of specific grades on two-lane roads in Mexico.

In different countries, the capacity under ideal conditions is typically assumed to be between 2,800 and 3,200 passenger cars per hour (pcph) (*2,7*). In each country, the particular value of this parameter depends on the characteristics of vehicles and drivers. For the United States, the HCM recommends a value of 2,800 pcph (*2*). Studies or field observations have not been carried out yet to determine the value of this parameter for Mexico. Some aspects suggest that it could be higher than 2,800 pcph (because Mexican drivers are more aggressive in their overtaking behavior), whereas others indicate that it could be lower (because American vehicles have more power). However, independent of the exact value of this parameter, the effect of its typical range of variation on the upgrade speeds is less important than the effect of other factors such as the presence of heavy vehicles in the traffic streams or the presence of curves in the horizontal alignment. For this reason, a value of 2,800 pcph was adopted for this study. However, it is recognized that studies are needed to refine this value.

Ratio of Flow Rate to Capacity Versus Average Upgrade Speed

For American passenger cars, ratios of flow rate to capacity versus average upgrade speed are contained in HCM Table 8.7, which was produced from simulation using a tangent section of highway.

For conditions in Mexico, these relationships were redefined using the TRARR model. However, in this case, for the different values of percentage of grade, instead of using a tangent section of highway, horizontal alignments of existing Mexican grades were used (about 400 m long). Table 2 gives the values obtained for Mexico. In the generation of Table 2, with exception of the horizontal curves, ideal conditions were used for the other factors (even directional distribution, passenger cars unaffected by grades, etc).

Table 2 is in complete agreement with the behavior of Mexican passenger cars depicted in Figure 3. Thus, in Table 2, the percentage of grade affects the operating speed of passenger cars more than

TABLE 2 Values of *F/c* Ratio[a] Versus Speed, Percentage Grade, and Percentage No-Passing Zones for Two-Lane Specific Grades in Mexico

PERCENT GRADE	AVERAGE UPGRADE SPEED	PERCENT NO PASSING ZONES (%)					
(%)	(km/h)	0	20	40	60	80	100
3	76	0.17	0.00	0.00	0.00	0.00	0.00
	68	0.58	0.43	0.31	0.14	0.00	0.00
	60	0.94	0.83	0.71	0.58	0.44	0.30
	52	1.00	1.00	1.00	0.94	0.83	0.71
	44	1.00	1.00	1.00	1.00	1.00	1.00
4	72	0.19	0.02	0.00	0.00	0.00	0.00
	64	0.59	0.46	0.31	0.17	0.00	0.00
	56	0.95	0.84	0.72	0.59	0.46	0.31
	48	1.00	1.00	1.00	0.95	0.84	0.72
	40	1.00	1.00	1.00	1.00	1.00	1.00
5	68	0.23	0.06	0.00	0.00	0.00	0.00
	60	0.64	0.51	0.37	0.22	0.07	0.00
	52	0.98	0.88	0.77	0.64	0.51	0.37
	44	1.00	1.00	1.00	0.98	0.88	0.77
	36	1.00	1.00	1.00	1.00	1.00	1.00
6	68	0.10	0.00	0.00	0.00	0.00	0.00
	60	0.52	0.38	0.23	0.08	0.00	0.00
	52	0.89	0.78	0.65	0.52	0.38	0.23
	44	1.00	1.00	0.98	0.89	0.78	0.65
	36	1.00	1.00	1.00	1.00	1.00	0.98
7	64	0.20	0.03	0.00	0.00	0.00	0.00
	56	0.62	0.48	0.34	0.20	0.04	0.00
	48	0.96	0.86	0.75	0.62	0.48	0.34
	40	1.00	1.00	1.00	0.96	0.86	0.75
	32	1.00	1.00	1.00	1.00	1.00	1.00

[a] Ratio of flow rate to ideal capacity of 2800 pcph, assuming passenger-car operation is unaffected by grades.

in HCM Table 8.7. Likewise, for the lower speed levels in Table 2 and for the horizontal curves typically associated in Mexico with the different values of grade percentage, a similar percentage of no-passing zones generates more interferences among the vehicles and therefore results in greater upgrade speed reductions than in HCM Table 8.7.

Passenger Car Equivalents

For U.S. conditions, passenger car equivalents are presented in HCM Table 8.9. These values were adapted to the Mexican conditions according to the following procedure:

- Average proportions of trucks and buses in Mexican two-lane roads equal to 35 and 10 percent, respectively, were assumed.
- On the basis of simulation of traffic operations on existing grades, the mixed flow rate corresponding to different combinations of average upgrade speed and length and percentage of grade was obtained. Then the passenger cars and heavy vehicles, components of that flow rate, were simulated separately and their separate speed distributions were assessed.
- From the speed distributions obtained, the corresponding passenger car equivalents were computed using the following expression:

$$E = r/R \qquad (2)$$

where

E = passenger car equivalent for a given length and percentage of grade and average upgrade speed;
R = number of passings between passenger cars per kilometer of road, assuming that each vehicle when passing or being passed continues at its corresponding speed in speed distribution; and
r = number of passings of heavy vehicles by passenger cars per kilometer of road.

The values of R and r were computed on the basis of the speeds and relative frequencies in the corresponding speed distributions of passenger cars and heavy vehicles (*3*).

- The equivalents thus obtained were refined slightly to improve the fit between the upgrade speeds recorded in the field and their corresponding computed values after considering the earlier modifications. This final fitting is justifiable because the procedure used to determine the equivalents provides only approximate values for these parameters.

Table 3 gives the set of equivalents finally obtained. After the modifications, the prediction of upgrade speeds using the calibrated procedure improved noticeably, as may be seen from comparing Figures 1 and 4. It may also be observed that the Mexican equivalents in Table 3 are much higher than the equivalents in HCM Table 8.9.

LOS Criteria

For the U.S. conditions, HCM Table 8.2 presents the boundary speeds for the different LOS. These speeds were redefined for the Mexican conditions as follows:

1. For each flow rate/capacity ratio in HCM Table 8.7 corresponding to a specific combination of upgrade speed, percentage of grade, and percentage of no-passing zones, the respective upgrade speed for the Mexican conditions was obtained from Table 2. Through this process, a data set of speeds from both tables, equivalents in terms of flow rate/capacity, was generated (186 data pairs).
2. A regression model was fitted through the speed data. In the model developed, $R^2 = .84$. From this model, the boundary speeds for Mexico that are equivalent in flow rate/capacity to the speeds in HCM Table 8.2 were defined. Finally, these values were refined by rounding them to multiple values of 5 and leaving a uniform speed interval between LOS (similarly to HCM Table 8.2).

Table 4 presents the boundary values finally obtained. In essence, the lower speeds in Table 4 as compared with the speeds in HCM Table 8.2 indicate that Mexican drivers are more tolerant than Americans regarding their travel speeds on specific grades (or their travel times).

In addition, Equation 3, which relates the exact speed at which capacity occurs with the flow rate at that speed, is more adequate for the Mexican conditions than Equation 8.8 of the HCM:

$$S_c = 35 + 3.75\,(F_c/1{,}000)^2 \qquad (3)$$

where S_c is the speed at which capacity occurs, in kilometers per hour, and F_c is the flow rate in capacity, in mixed vehicles per hour (mixed vph).

Equation 3 assumes a maximum flow rate of 2,000 vph, similar to HCM Equation 8.8. Likewise, Equation 3 considers that for specific grades between 3 and 7 percent and up to 6.4 km long, the average speed at which capacity occurs varies between the speed range specified in Table 4 for LOS E.

Other Considerations

Apart from the modifications suggested earlier, the remaining aspects of the LOS calculation procedure for specific grades in the HCM are considered applicable for Mexico. Other studies have shown that for the typical traffic conditions and cross sections of two-lane trunk roads in Mexico (lane widths between 3.30 and 3.50 m and shoulder widths between 0.6 and 1 m), the capacity adjustment factors in the HCM for directional distribution and for narrow lanes and restricted shoulder width can be used with accuracy (*5*).

In this study, Tables 2 and 3 include not only the operating limitations of Mexican vehicles in specific grades but also the effect of the horizontal alignment curves. Another way to consider this last effect besides including it in Tables 2 and 3 would consist of introducing in the procedure a capacity adjustment factor to account for the presence of curves of specific radii (a parameter that is closely related to the design speed of the road).

ECONOMIC FEASIBILITY

For specific grades shorter than 3000 m, the economic feasibility was analyzed for a series of cases corresponding to different combinations of the following factors at three levels: traffic flow rate, percentage of trucks in the traffic stream, percentage of traffic on an upgrade, percentage and length of grade, and percentage of no-passing zones. Table 5 gives the levels used for these factors.

TABLE 3 Passenger Car Equivalents for Specific Grades on Two-Lane Rural Highways in Mexico

GRADE (%)	LENGTH OF GRADE (m)	AVERAGE UPGRADE SPEEDS (km/h)								
		76	72	68	64	60	56	52	44	32
0	ALL	6.1	5.7	5.4	5.1	4.9	4.7	4.5	4.3	4.0
3	400	7.1	6.5	6.0	5.7	5.4	5.2	4.9	4.6	4.2
	800	7.4	6.7	6.2	5.8	5.5	5.2	5.0	4.6	4.2
	1600	8.9	7.9	7.2	6.6	6.2	5.8	5.5	5.0	4.4
	3200	16.9	14.4	12.5	11.1	10.1	9.2	8.5	7.4	6.2
	4800	38.3	31.0	25.9	22.2	19.4	17.3	15.5	12.9	10.3
	6400	91.2	70.4	56.7	47.0	39.8	34.4	30.1	23.9	18.0
4	400	7.7	7.1	6.6	6.2	5.8	5.6	5.3	4.9	4.5
	800	8.4	7.6	7.0	6.5	6.1	5.8	5.5	5.0	4.5
	1600	11.2	9.8	8.8	8.0	7.4	6.9	6.5	5.8	5.1
	3200	26.2	21.7	18.5	16.2	14.4	13.0	11.8	10.0	8.2
	4800	70.3	55.0	44.8	37.5	32.1	27.9	24.7	19.8	15.2
	6400	a	a	a	90.2	74.4	62.7	53.7	41.0	29.4
5	400	8.7	7.9	7.3	6.8	6.4	6.1	5.8	5.4	4.9
	800	9.9	8.8	8.1	7.5	7.0	6.6	6.2	5.7	5.1
	1600	14.6	12.6	11.2	10.1	9.3	8.6	8.0	7.1	6.1
	3200	41.4	33.6	28.1	24.2	21.1	18.8	16.9	14.0	11.2
	4800	a	98.9	78.4	64.1	53.7	45.9	39.8	31.0	22.9
	6400	a	a	a	a	a	a	96.5	70.9	48.4
6	400	9.9	9.0	8.3	7.7	7.2	6.9	6.5	6.0	5.4
	800	11.9	10.5	9.6	8.8	8.2	7.7	7.2	6.5	5.8
	1600	19.5	16.7	14.6	13.1	11.9	10.9	10.1	8.8	7.5
	3200	66.4	52.6	43.3	36.5	31.5	27.6	24.5	19.9	15.4
	4800	a	a	a	a	90.4	75.8	64.6	49.0	34.7
	6400	a	a	a	a	a	a	a	a	80.1
7	400	11.6	10.4	9.6	8.9	8.3	7.8	7.4	6.8	6.1
	800	14.6	12.9	11.6	10.6	9.8	9.1	8.6	7.7	6.7
	1600	26.6	22.5	19.5	17.3	15.5	14.1	13.0	11.2	9.3
	3200	a	83.1	67.0	55.7	47.3	40.9	35.9	28.5	21.5
	4800	a	a	a	a	a	a	a	77.6	53.0
	6400	a	a	a	a	a	a	a	a	a

[a] Speed not attainable on grade specified.

Specifically, the feasibility analysis was carried out for 243 combinations of the 729 total possible combinations (one-third of the complete factorial experiment). For these analyses, the widths of lanes and shoulders were fixed at 3.5 and 0.8 m. A uniform proportion of buses equal to 10 percent was also assumed. These values are typical of two-lane roads in Mexico.

For the different cases analyzed, the TRARR model was used to evaluate the upgrade speed gain obtained from adding a climbing lane for passenger cars, buses, and trucks. Subsequently, since these gains decrease the operating costs of the different vehicle types, the travel time value of automobile and bus passengers, and the opportunity cost of the freight transported, the corresponding economic benefits were quantified. The operating costs of passenger cars, buses, and trucks, as a function of speed, were computed on the basis of the World Bank model Vehicle Operating Costs (VOC), calibrated for Mexican conditions. The benefits were assessed using standard procedures (*8*).

In other countries, it is considered that the addition of these lanes reduces the number of serious accidents occurring on grades, particularly rear-end collisions involving trucks (*2*). However, in Mexico, since there is no reliable evidence of the preceding, benefits derived from improved safety were not included. In general, the benefits due to reductions in vehicle operating costs were much more significant than the other benefit types calculated. For this reason, while adopting a conservative approach in the evaluation of the economic feasibility, only those benefits were considered in subsequent stages of the study. The construction cost was also obtained for the cases analyzed.

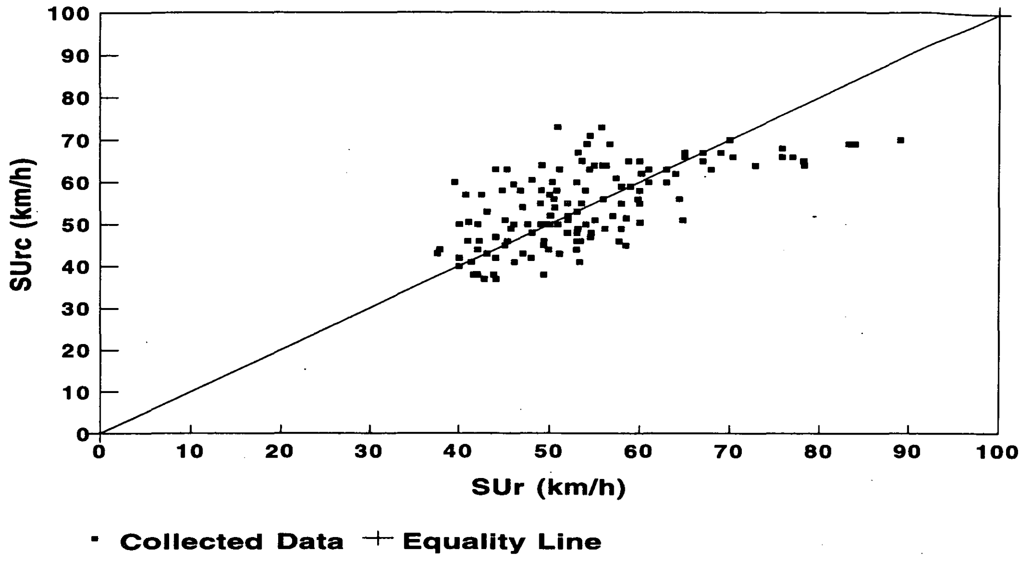
On the basis of the corresponding annual benefit and cost flows, the benefit/cost ratio and the internal rate of return were computed for each case analyzed for a 10-year period, which is considered in Mexico to be reasonable for the transition toward more costly multilane solutions (*4*). The analysis resulted in the following regression equations for predicting the upgrade speed gain obtained from the addition of the extra lane (Equation 4), the first-year benefit due to the reduction of vehicle operating costs (Equation 5), the benefit/cost ratio (Equation 6), and the internal rate of return (Equation 7):

$$\mathrm{GAN} = 0.845 + 1.61E - 4M^{2.9} + 3.71E - 8M^{2.9}\mathrm{PU}^{2.4} + 3.55E - 3L^{0.2}F^{0.5} + 2.77E - 4\mathrm{PNP}\ \mathrm{PT}^{0.5} \tag{4}$$

$$\mathrm{BEN}_o = \frac{1}{903.7\ e^{[22.47 - 0.032\ \mathrm{SU}(\mathrm{GAN} - 0.98)^{-0.653}]}} \tag{5}$$

$$\mathrm{B/C} = \frac{0.047\ \mathrm{BEN}_o^{0.88}\ (\mathrm{GR} + 20)^{2.17}}{(\mathrm{DR} + 5)^{0.444}\mathrm{C}_o^{0.935}} \tag{6}$$

$$\mathrm{IRR} = (2.257\mathrm{B/C} - 1.257)\ \mathrm{DR} \tag{7}$$



SUr = Recorded average upgrade speed
SUrc = Recalculated upgrade speed

FIGURE 4 Speeds recalculated according to modified HCM procedure versus speeds recorded in specific grades.

where

GAN = upgrade speed gain obtained from adding a climbing lane (ratio of average speeds after and before installation of extra lane);
M = grade (%);
PU = traffic on upgrade (%);
L = length of grade (m);
F = hourly flow rate corresponding to rate of peak 15 min (both directions) (mixed vph);
PNP = no-passing zones (%);
PT = trucks (%);
BEN_o = first-year benefit of climbing lane due to reduction of vehicle costs (1993 pesos/km);
e = 2.71828;
SU = average upgrade speed (km/hr) (can be measured directly in the field or computed by using the HCM procedure modified as suggested earlier);
B/C = benefit/cost ratio;
GR = annual traffic growth rate (%);
DR = annual discount rate (%);
C_o = first cost of climbing lane (1993 pesos/km) (should be deflated to the 1993 value if computed for another year later than 1993); and
IRR = internal rate of return (%).

In general, an adequate goodness of fit was obtained for the preceding equations ($R^2 > .80$). They can be used, consecutively, for assessing the economic feasibility of constructing climbing lanes on specific grades shorter than 3000 m. These equations can be programmed easily in hand calculators.

As mentioned earlier, Equation 4 was developed for grades up to 3000 m long. For grades longer than 3000 m, the speed gain obtained from adding the extra lane should be computed from the regression equation in Figure 2. This equation is valid for average upgrade speeds before installing the climbing lane between 35 and 100 km/hr. Obviously, to use this equation, the upgrade speed should be measured directly in the field. The rest of the feasibility analysis can be completed by using Equations 5, 6, and 7.

TABLE 4 LOS Criteria for Specific Grades in Mexico

LEVEL OF SERVICE	AVERAGE UPGRADE SPEED (km/h)
A	>= 65
B	>= 60
C	>= 55
D	>= 50
E	>= 35 - 50[a]
F	< 35 - 50

[a] The exact speed at which capacity occurs varies with the percentage and length of grade, traffic compositions, and volume; computational procedures are provided to find this value.

TABLE 5 Factors at Three Levels Used in Economic Feasibility Analyses

FACTOR	LEVELS		
	LOW	MEDIUM	HIGH
Flow rate (mixed vehicles/hour)	0	1000	2000
Percent of trucks	0	25	50
Percent of traffic on upgrade	25	50	75
Percent of grade	0	4	8
Length of grade (m)	400	1700	3000
Percent of no-passing Zones	0	50	100

Occasionally, in grades shorter than 3000 m, the length of grade cannot be defined in some cases since the beginning or end of the grade cannot be identified adequately. In these cases, as well as in all others in which one or more of the input variables of Equation 4 cannot be defined, the speed gain obtained from adding the climbing lane should also be evaluated by using the equation in Figure 2. Evidently, this equation is less precise than Equation 4, as it does not consider separately the effect of the different variables that affect the speed gain.

NOTE ON AMERICAN WARRANTS FOR CLIMBING LANES

The criteria used in the United States to justify economically the construction of a climbing lane (*2*) are based on a more limited number of variables than those presented in this paper. For this reason, it is considered that such criteria are simpler though less precise than the ones described herein; for example, the U.S. criteria do not consider that the construction cost of the extra lane may vary within a very wide range (depending on the existing pavement width and earthwork quantities) and that its exact value may significantly affect the economic feasibility.

POTENTIAL USE OF CLIMBING LANES IN MEXICO

The procedures described earlier allow the assessment of the potential use for climbing lanes in Mexico. When additional construction of the existing pavement width is not needed, these facilities are feasible in all specific grades with average annual daily traffic (AADT) greater than 3,000; in Mexico, 30 percent of the federal trunk roads fall under this condition. As more widening of the existing pavement is required, the accompanying construction costs restrict the feasibility of such facilities to road segments with more severe traffic and geometric conditions. In Mexico, it is considered that these facilities improve operation for AADTs of up to 6,000. For vehicular flows higher than this, the operation has been observed to become unsafe (*4*).

SUMMARY AND CONCLUSION

This work is one of the tools that the IMT has developed for analyzing the economic feasibility of constructing climbing lanes on Mexican two-lane roads and for assessing the LOS before and after implementing these facilities, partly or totally, in specific grades.

This paper represents an effort to generate highway engineering procedures for Mexico and to adapt to conditions in Mexico the most important criteria developed in other countries. In Mexico, the implementation of climbing lanes is considered as a first step in the process of providing four-lane roads on the most important national freight corridors.

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