Uniform Delay Approach to Warrants for Climbing Lanes

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Current warrants for climbing lanes are discussed, and the consequences of their usage are explored. Data were obtained and analyzed to derive relationships among flow, gradient, and speed on South African roads. These relationships were used to calibrate TRARR, a simulation program developed by the Australian Road Research Board, and this, in turn, was used to establish relationships between delay and flow for various gradients. Actual delay is offered as an alternative warrant, it being pointed out that the Highway Capacity Manual offers delay as a criterion of Level of Service. The paper postulates that delay suffered would not be a function of the gradient on which it occurs if the climbing lane were the subject of economic analysis. Various isochronistic warrants are offered for consideration with the consequences of adoption of this approach being pointed out.

Most vehicles can maintain relatively high speeds on level terrain; consequently, the flow on these grades is characterized by low speed differentials and minimal turbulence, and high flow levels may occur. As soon as a gradient of any consequence is encountered, (in excess of about 3 percent) the situation changes dramatically. Speed differentials increase, leading to an increase in platooning of vehicles and reduction in the level of service. This phenomenon has long been recognized, and auxiliary lanes (variously known as climbing lanes, crawler lanes, truck lanes and, confusingly, passing lanes) have been provided to overcome this problem. In this paper, reference will be made throughout to climbing lanes. Passing lanes are generally found on flat gradients and are intended to increase the overall capacity of a road above that of a normal two-lane road, whereas climbing lanes, found on gradients, serve to match the capacity of the grade to that of the flatter sections of the road and eliminate excessive delay due to the low speeds of trucks.

The first problem confronting the designer in the provision of climbing lanes along a route is to determine at which points along the route climbing lanes can be installed to best advantage. This problem is invariably resolved by the use of warrants. Warrants may be described as surrogates for economic analysis and are often based on fairly arbitrary but easily measured parameters. A general economic analysis procedure is proposed by the British Department of Transport (*1*). Other than this, economic analysis has seldom, as far as can be established, been seriously attempted by practitioners.

The form and value of these warrants are legion. Warrants can be subdivided into five broad groups: truck speed reduction, speed differential between trucks and passenger cars, either of the above in association with a traffic volume, and, lastly, reduction in level of service. Reference to the literature reveals that, in each group, a range of values is encountered.

AASHTO (*2*) recommends the inclusion of climbing lanes where the critical length of grade, that distance which causes a reduction of 10 mph in the speed of a loaded truck, is exceeded. AASHO (*3*) used a truck speed reduction of 15 mph, whereas Glennon and Joyner (*4*) recommend the criterion of 10 mph, quoting increased accident risk in support of their contention. Polus et al. (*5*) proposed a truck speed reduction of 12 mph (20 km/h) as the speed warrant for climbing lanes, using the truck speed/gradient relationship quoted in the 1965 edition of "A Policy on Geometric Design of Rural Highways," and this suggests that the entry speed to a gradient be accepted as 40 mph (64 km/h). South Africa (*6*) also uses a truck speed reduction of 20 km/h, but assumes a truck speed of 80 km/h on level grades. Canada (*7*) considers that a truck speed reduction of 15 km/h warrants a climbing lane but measures the speed reduction from the 85th percentile or running speed. It is not clear whether this is the 85th percentile speed of trucks or of the whole traffic stream. Botswana (*8*) uses a truck speed reduction of 25 km/h.

The use of truck speed reduction as a warrant implies that passenger car speed is totally unaffected by gradient. Some authorities take cognizance of the fact that passenger car speed is, in fact, influenced by gradient and refer to the speed differential between cars and trucks as a warrant. For example, the *Transportation and Traffic Engineering Handbook* (*9*) refers to a speed differential of 10 mph between trucks and the mainline flow.

Very often, the speed reduction warrant is associated with a volume warrant. *The Highway Capacity Manual* (*10*) considers climbing lanes as an alleviating treatment when the following warrants are met:

- upgrade volumes exceed 200 vph,
- upgrade truck volumes exceed 20 vph, and
- a speed reduction of 10 mph or more is expected for the average truck.

Wolhuter also provides a volume warrant, based on the catch-up rate on various grades and with various percentages of trucks in the traffic stream, as illustrated in table 1.

The above warrants are intended for application to individual grades. The philosophy adopted by Australia (*11*), on the other hand, considers the need for climbing lanes based on examination of a considerable length of the road in question. The justification for climbing lanes is based on traffic

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TABLE 1 VOLUME WARRANTS FOR CLIMBING LANES

Gradient (%)	Traffic volume in design hour	
	5 % trucks	10 % trucks
4	632	486
6	468	316
8	383	243
10	324	198

volume, the percentage of trucks in the traffic stream, and the availability of overtaking opportunities on the route. The speed reduction criterion is reduction to 40 km/h. Climbing lanes should span the full length of the grade, but partial climbing lanes may be considered when truck speeds fall below 40 km/h and a full lane is not justified because of low traffic volumes or high construction cost. On extreme grades, where truck speeds are reduced to 20 km/h or less, passing bays, typically less than 100 m long, can be considered when all the following conditions are met:

- long grades over 8 percent,
- high percentage of heavy vehicles,
- low overall traffic volumes, and
- high construction costs.

A separate class of warrants refers to level of service. Level of service is a descriptor of operational characteristics in a traffic stream, measured in terms of delay, speed, and ratio of volume to capacity. An important feature of this descriptor is that it is a representation of driver perception of the traffic environment and bears little or no relation to the cost of creating that environment or the cost of operating in it. The warrants suggested by the *Highway Capacity Manual* are—

- a reduction of two or more levels of service in moving from the approach segment to the grade and
- Level of Service E (LoS E) exists on the grade.

Polus et al. suggest that a climbing lane is warranted if the design hourly volume exceeds the specific grade service volume for a level of service one lower than that adopted for the design of a level section of the road.

Typically, the motivation given for selection of a particular warrant is based on qualitative arguments. An alternative approach to warrants for climbing lanes is presented in this paper.

BACKGROUND TO STUDY

Whereas estimation of the construction and maintenance costs of a climbing lane usually does not present any problem, derivation of the benefit accruing from this investment is more intractable. Economic analyses have often indicated that the benefit derived from time savings alone overshadows other benefits. However, to achieve a correct perspective, the overall benefit is briefly discussed below.

The benefit subdivides into benefit to the road user and benefit to the community as a whole as represented by the road authority. Benefit to the road user involves changes in—

- extent of delay, a time benefit;
- operating cost, an economic benefit;
- accident exposure, a safety benefit; and
- level of stress, a comfort benefit.

Benefit to the community derives from—

- higher levels of service, hence postponement of the obsolescence of a facility and
- reduced need to provide additional passing sight distance elsewhere, hence a potential reduction in construction cost.

Although sometimes described differently, it is clear that all these benefits have strong economic overtones, but, as stated above, the value accrued from time savings alone tends to overshadow the economic benefits derived by other means. For this reason, the attention of this paper is focused on the calculation of delay. The contention is that a specific climbing lane, warranted by time savings alone, could show a "profit" if the other factors were also taken into account; that is, such a warrant tends to be conservative.

Delay does not lend itself readily to direct measurement in the field, hence the use of alternative criteria, such as the percentage of time spent following. Seeing, however, that delay is simply the time added to a trip by travelling at a speed lower than desired, simulation offers a convenient technique for its determination.

MODUS OPERANDI EMPLOYED

Time mean speeds were measured at various sites, covering a range of gradients and under widely varying traffic flows, and classified according to vehicle type. These were used to calibrate a simulation model, TRARR, developed by the Australian Road Research Board, to local prevailing conditions.

Delay is a function of space mean speed. The simulation model was used to derive space mean speeds achieved by passenger cars on a range of gradients across a range of traffic flow. Gradients varied between 3.6% and 8.4%, and flow from 30 vehicles per hour (vph) to 1,500 vph. Space mean speeds achieved by vehicles traveling at headways of 10 s or longer are considered to be desired speeds, in other words, dictated by the hill)climbing capability of the individual vehicle or by the preference of the driver when the gradient is not sufficiently steep to govern vehicle performance. Increasing flow levels inevitably lead to a drop in space mean speed below that desired, and this reduction in speed is the basis for calculation of delay.

Data collection, calibration and calculation of delay are described in more detail in the following sections.

DATA COLLECTION

Data Acquisition System

The data were acquired for this analysis using the Traffic Engineering Logger (TEL) developed by the National Insti-

TABLE 2 DESCRIPTION OF VEHICLE CLASSES

Class		Length (m)	Description
Light	Short	<5.9	Passenger car
	Long	5.91 - 10.0	Passenger car with trailer
Heavy	Short	<10.0	Single-unit truck
	Medium	10.1 - 16.8	Tractor + semi-trailer
	Long	>16.8	Tractor + semi + trailer

tute for Transport and Road Research, South Africa. The TEL is a microprocessor-based system capable of collecting traffic data in one of three modes of operation. These are—

- roadside installation,
- vehicle mounted installation, and
- hand-held operation.

For this study, the roadside installation was employed, in which traffic data are collected from successive induction loops buried in the road surface.

The TEL differentiates among classes of vehicles on two bases. Cars, in spite of their lesser mass, show a greater disturbance of the magnetic field than do trucks because of their lower center of gravity. The length of vehicles is measured on the basis of their speed and corresponding time of occupation of the loops. Data acquired by this system include time of arrival (to nearest 0.1s), speed (to nearest 1 km/h), vehicle length (to nearest 0.1m), and class of vehicle, for each vehicle.

Table 2 lists the classes of vehicles among which the TEL can differentiate. For the purpose of this study, vehicles in the light category were grouped together as it was found that the percentage of cars in the traffic stream that were towing caravans (trailers) was very low. It was also found, as discussed later, that further aggregations could also be employed with advantage.

Data Acquired

Two sets of data were collected and subdivided as shown in table 3. The observation points were located sufficiently far along the grade for vehicle speeds to have stabilized to the gradient.

PRELIMINARY ANALYSIS OF DATA

Speed distributions for uninterrupted flow conditions were derived by considering only those speeds associated with headways of 10 s and longer and by aggregating them into 5 km/h intervals. Typical distributions for the various classes of vehicles are illustrated in figure 1 for the Ben Schoeman site.

The means and the standard deviations of the speed distributions were calculated for each of the sites as shown in table 4. The means are plotted as shown in figure 2, which illustrates what appears to be an inconsistency with expectations, as speeds at the four-lane sites are lower than those at the two-lane sites. These lower speeds are attributed principally to the fact that the speeds recorded on the freeway sections refer only to the slow lane. There is also a difference between the occurrence of headways longer than 10 s on two-lane roads and freeways, as illustrated in figure 3, and it is presumed that this would also account, even if only in part, for the difference. Further analysis established that the difference in speeds between two) and four-lane roads is statistically insignificant at the 5 percent confidence level. It is thus possible to ignore differences in cross-section in the study that follows.

It was also found that the difference in speeds between medium-heavy and long-heavy vehicles is statistically insignificant. Operators match the mass hauled to the capacity of the tractor, and the additional trailer serves to accommodate high-volume, low-mass loads. It is thus not surprising that there should be relatively little difference in performance

TABLE 3 DESCRIPTION OF DATA SETS

Site	Lanes	Gradient (%)	Distance along grade (m)	Sample size (veh)
Cornelia	2	3.62	1 600	9 232
Colenso	2	5.21	3 000	17 196
Long Tom	2	8.38	2 000	15 980
Rigel North	4	3.54	3 100	16 132
Rigel South	4	4.45	4 000	4 651
Ben Schoeman	4	4.97	1 400	20 945
Krugersdorp	4	6.44	1 800	21 254

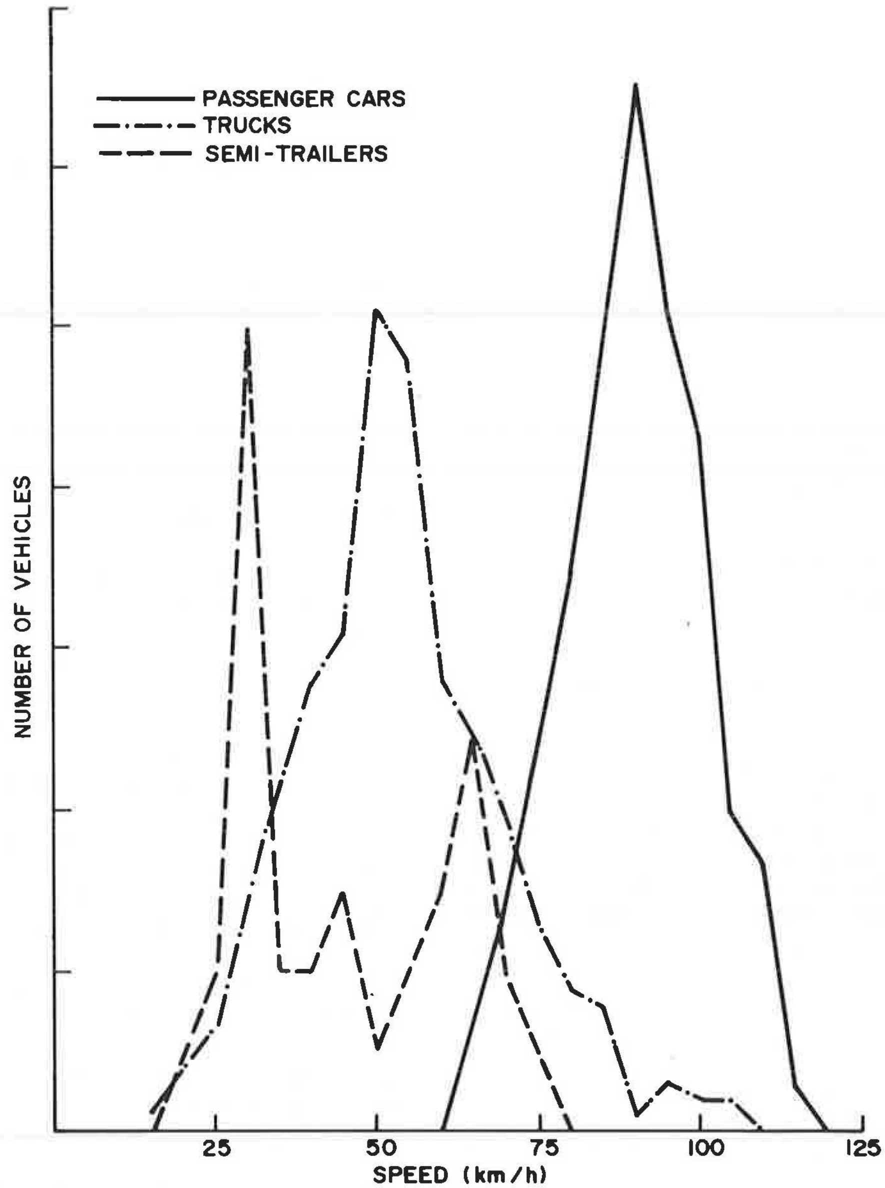

FIGURE 1 Distribution of speed on a gradient of 4.97% by class of vehicle.

between the two vehicle configurations. Consequently, only three classes of vehicles, passenger cars, single unit trucks, and semitrailers, are considered in this study. Average speeds derived for the semi-trailers are shown in table 5.

RELATIONSHIP BETWEEN GRADIENT AND SPEED

The speeds shown for the various vehicles on the observed gradients (as reflected in table 4) and the aggregated speeds for the semitrailers (as listed in table 5) represent what can be considered desired speeds for the purposes of this study. In short, they represent the limiting performance of the vehicle class in question or, alternatively, the speed preferences of the drivers where the performance of the vehicle does not dictate the selection of speed.

The following relationships between gradient and desired speed (or limit of vehicle performance) were derived by means of regression:

$$V_c = 123.32 - 6.99\,G\ (R^2 = 0.986)$$

$$V_t = 76.89 - 4.79\,G\ (R^2 = 0.994)$$

$$V_s = 69.13 - 5.33\,G\ (R^2 = 0.946)$$

where

V_c = passenger car speed (km/h)
V_t = truck speed (km/h)
V_s = semi-trailer speed (km/h)
G = gradient (%)

These relationships are plotted in figures 4 and 5 as dotted lines and represent actual performances by the various classes of vehicles as measured on South African roads. These are

TABLE 4 SPEED VERSUS GRADIENT FOR VARIOUS VEHICLE CLASSES

Num. of Lanes	Grade (%)	Vehicle class							
		Light		Heavy					
				Short		Medium		Long	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
2	3.62	100.6	15.6	60.6	15.6	51.8	14.3	49.8	15.4
2	5.21	89.2	16.0	52.3	18.4	37.6	13.8	34.6	12.9
2	8.38	64.5	12.9	37.7	11.8	32.4	15.9	19.0	10.2
4	3.54	95.7	14.3	60.2	16.1	52.1	16.8	50.9	16.8
4	4.45	92.5	14.4	55.1	14.4	47.4	16.2	48.2	15.9
4	4.97	86.7	15.8	52.2	16.7	40.4	15.3	42.3	16.8
4	6.44	78.2	15.1	44.9	17.3	32.7	12.3	26.4	9.3

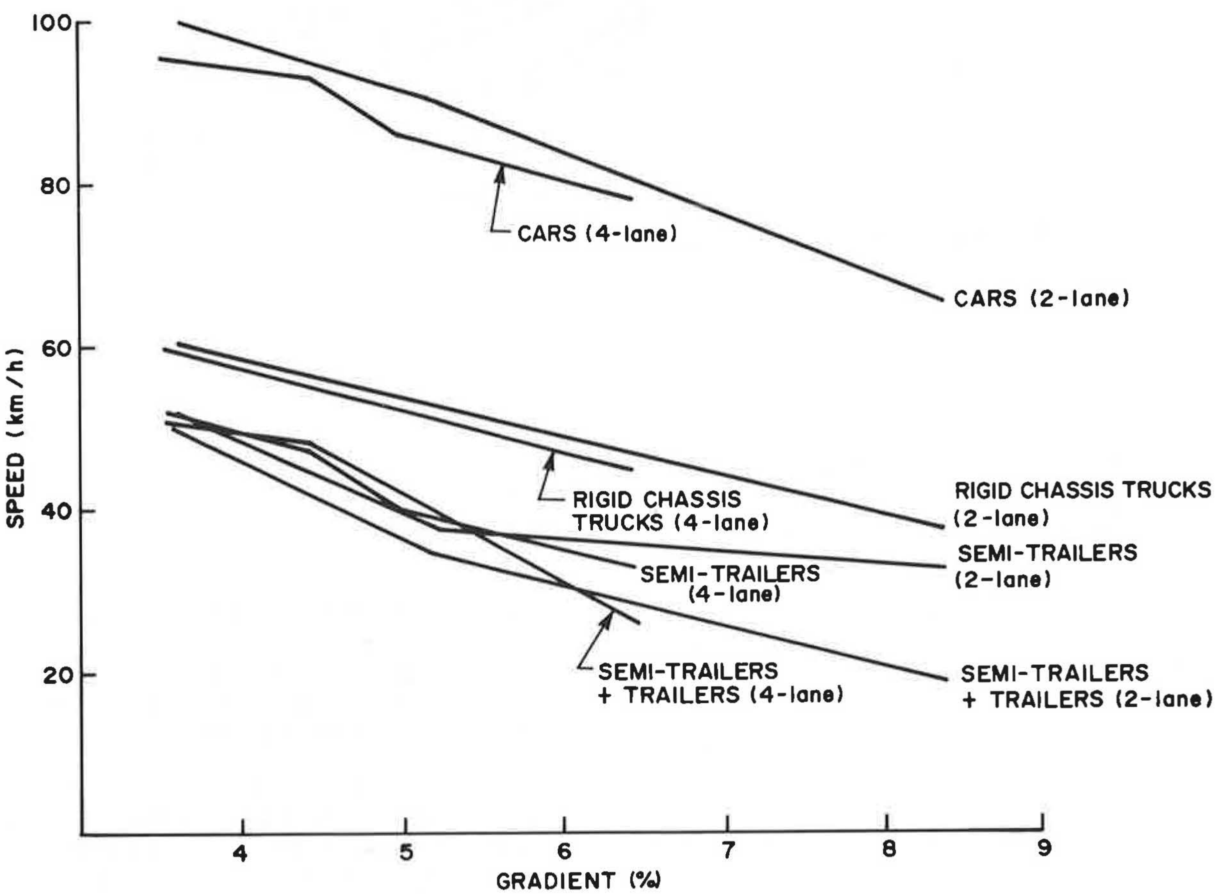

FIGURE 2 Observed mean speeds on gradients by class of vehicle.

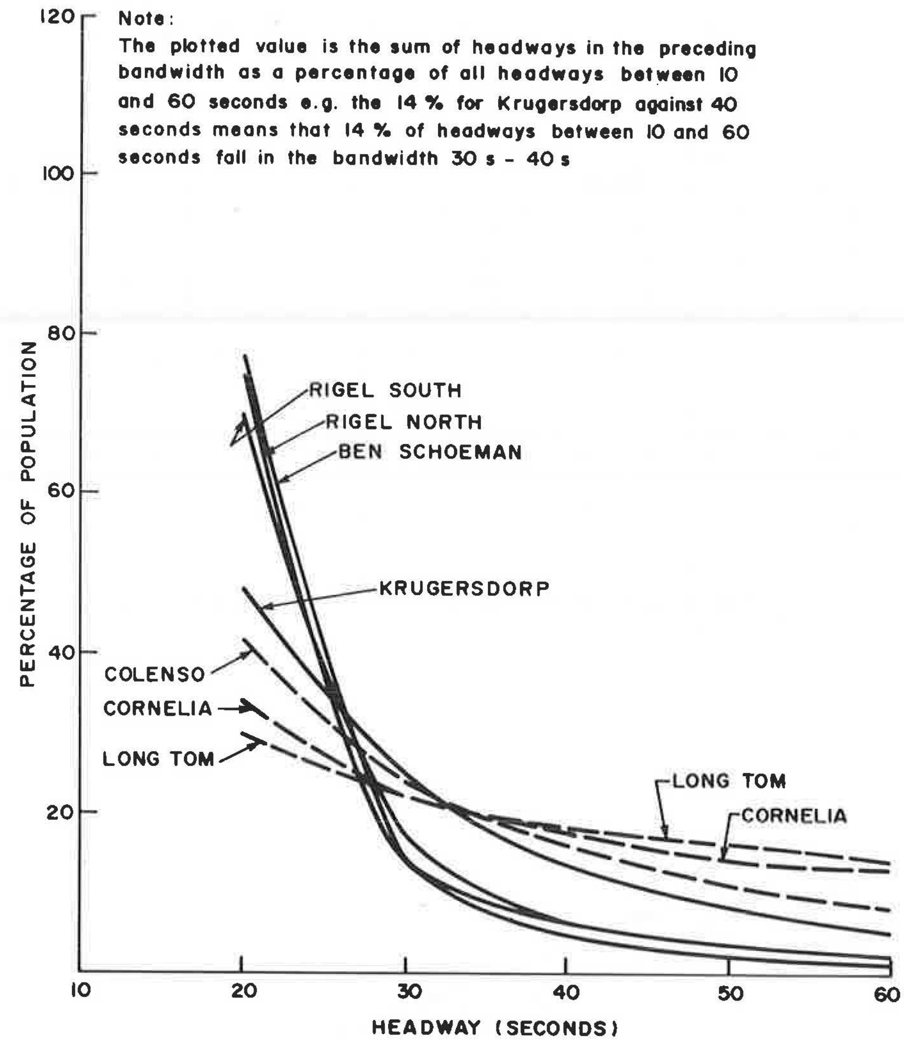

FIGURE 3 Distribution of observed headways greater than 20 s.

TABLE 5 AGGREGATED SPEED ON GRADIENTS FOR SEMITRAILERS

Gradient (%)	Speed (km/h)
3.54	52.60
3.62	51.44
4.45	47.49
4.97	40.83
5.21	36.66
6.44	31.93
8.38	28.00

speeds measured at a point, or spot speeds, whereas, for the purposes of study of delay, reference to speed will imply space mean speed.

RELATIONSHIP BETWEEN FLOW AND SPEED

The relationship between flow and speed on each grade was derived by a laborious process consisting of a number of computational steps, as described below:

1. The entire period of observation at each site, typically with a duration of 72 hours, was divided into successive 2-minute intervals, and the volume of vehicles in each class for each 2-minute interval was derived. A volume of between 1 and 50 vehicles is thus equivalent to a flow of between 30 and 1,500 vph.
2. The range of speeds, between 0 km/h intervals, and the

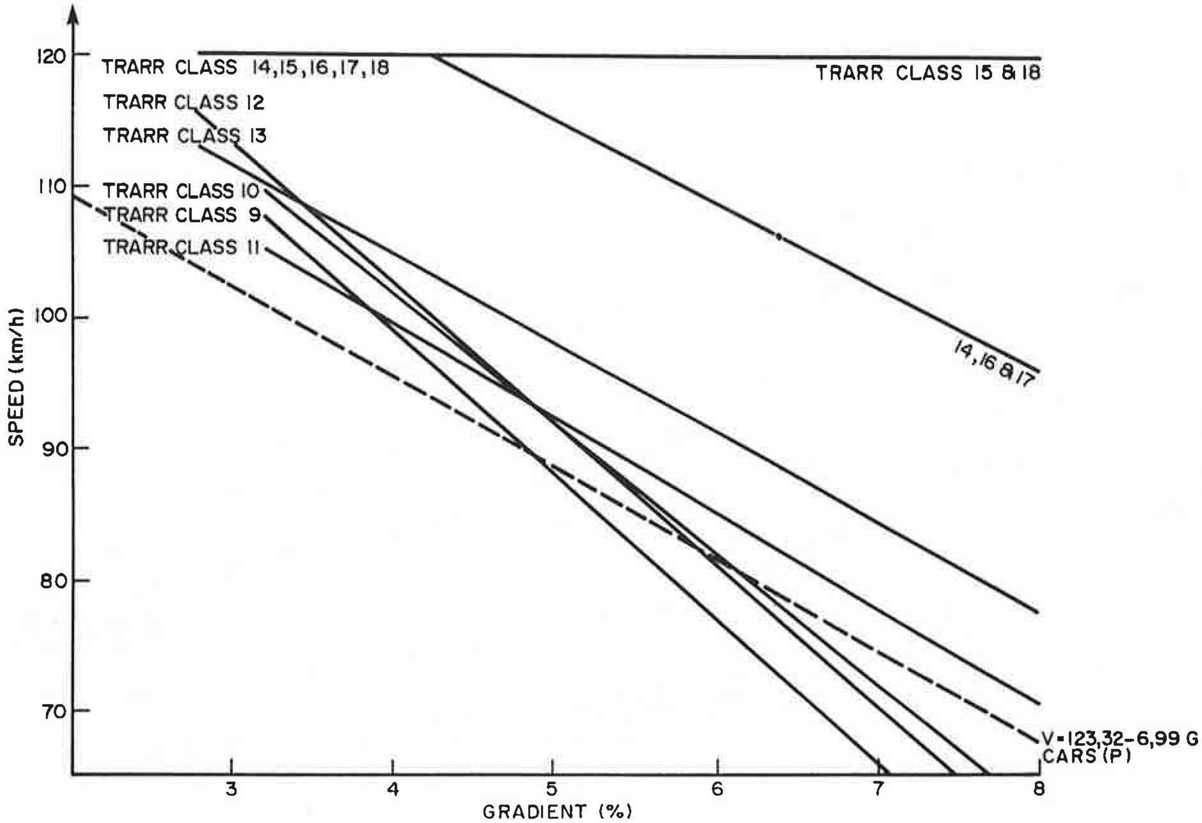

FIGURE 4 Comparison of observed mean speeds of passenger cars and TRARR Vehicle Classes 9 to 18.

number of vehicles of each class falling into each individual speed range calculated.

3. The histogram of speed so derived was then aggregated with the histograms of other two-minute intervals with the same flow.

4. Step 3 thus leads to the creation of a three-dimensional surface, with speed and flow as its base and number of vehicles as the vertical coordinate.

5. For convenience, and to apply a degree of smoothing, five successive flow levels were aggregated, representing steps of 150 vph between the various flow levels, or a total of ten points between zero and 1,500 vph.

6. Finally, the mean speed for each class of vehicle and for each aggregated flow level was calculated.

7. The process described above was repeated for each of the seven sites.

It was found that the relationship can be expressed as

$$V_{ca} = 128.38 - 6.89\ G - 0.008\ Q\ (R^2 = 0.87)$$

where

V_{ca} = actual speed for passenger cars (km/h)
G = gradient (%)
Q = flow along upgrade (vph)

Calibration of Model

The simulation model, TRARR (Traffic on Rural Roads), was obtained from the Australian Road Research Board and calibrated in two stages.

This model employs eighteen different classes of vehicles, and, as a first step, runs were carried out with each of the eighteen classes of vehicles on each of the seven gradients. The conditions of the runs were that the position of the observation points in the simulation corresponded with the points at which data were actually gathered on the various gradients, and that flows were selected to represent headways of 10 s or longer.

The desired speeds for each of the classes of vehicle on the various gradients as derived from the simulation were also regressed to secure relationships between speed and gradient, and these are shown as solid lines in figures 4 and 5. Visual inspection suggested that the best correspondence could be obtained by using—

- for cars TRARR Class 11
- for trucks TRARR Class 7
- semi-trailers TRARR Class 6

The next stage involved running traffic streams containing these classes of vehicles, in the percentages observed in the field, on the various gradients. The delays of particular interest in this study are those suffered by passenger vehicles. Further analysis was carried out to derive a relationship between average passenger car speed versus gradient and flow for the chosen classes of vehicles in the simulation model. The relationship found is—

$$V_{cs} = 131.660 - 6.538\ G - 0.017\ Q\ (R^2 = 0.95)$$

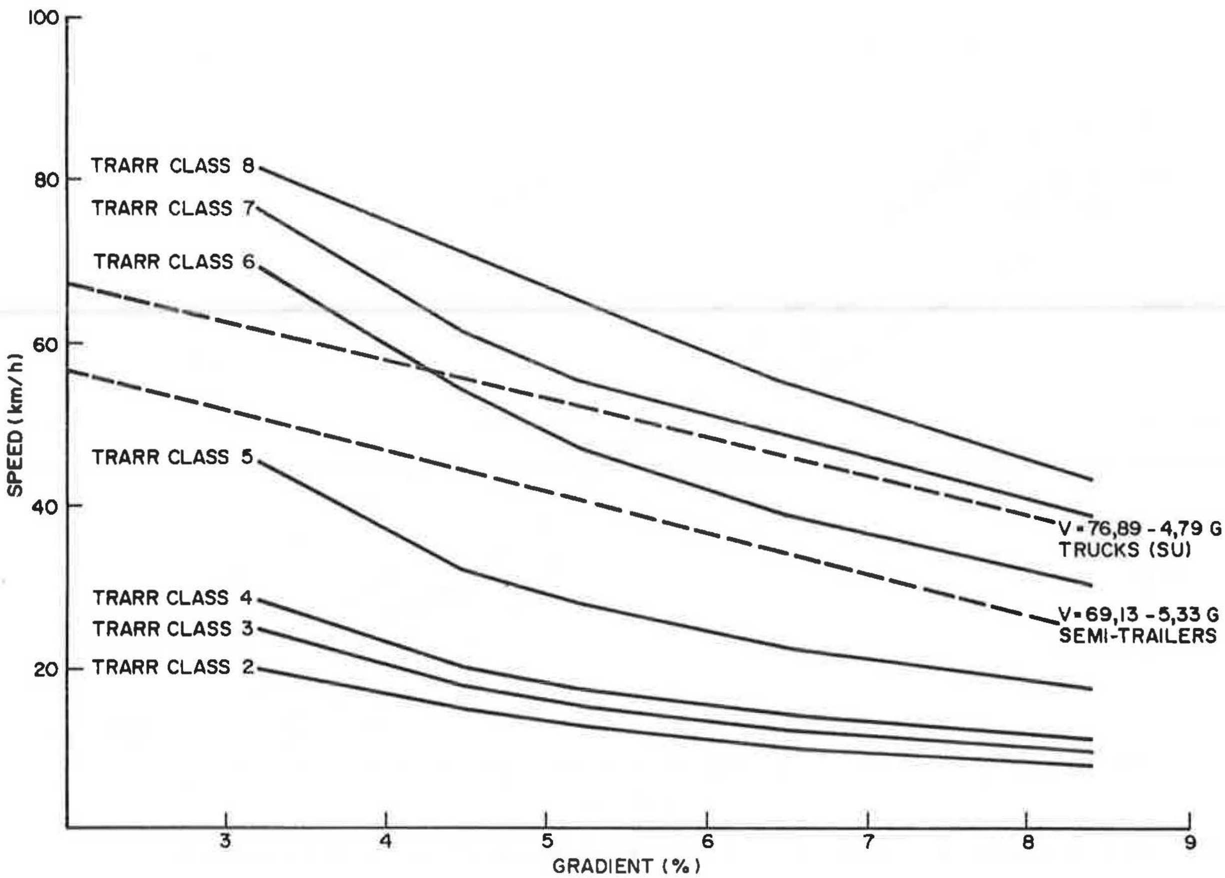

FIGURE 5 Comparison of observed mean speeds of trucks and semitrailers and TRARR Vehicle Classes 2 to 8.

where

V_{cs} = simulated speed for passenger cars (km/h)
G = gradient (%)
Q = flow along upgrade (vph)

This relationship compares reasonably well with that found for the field data.

DELAY

As suggested earlier, delay is that period of time added to a trip by a reduction of space mean speed to a value less than the desired. Space mean speed is calculated as the quotient of distance and mean journey time, and the speeds compared are those attained on the various grades at various flow levels against speeds attained on the same grades at very low flow levels.

Delay is thus calculated as:

$$T_d = 3600\ (1/V_a - 1/V_d)$$

where

T_d = delay/km/passenger car(s)
V_a = speed achieved by passenger cars at varying flow levels (km/h) = 131.660 − 6.538 G − 0.017 Q
V_d = speed achieved by passenger cars at headways of 10 s or longer (km/h) = 131.660 − 6.538 G

G and Q have the same meaning as before.

Ultimately, the product of delay per passenger car and the passenger car flow provides the total delay per kilometer experienced per hour, assuming that the flow rate remains constant for the entire hour.

There could be fluctuations in flow within the hour, which would introduce an underestimation in the calculated delay. For example, a flow of 750 vph could either be absolutely uniform or a volume of 749 vehicles in 30 minutes followed by a vehicle with a headway of 30 minutes. Using the above relationships, the total delay to passenger cars (on a 5 percent gradient with an assumed 15 percent trucks in the traffic stream) would amount to 57.15 min/km in the case of the uniform flow; whereas, in the second case, the total delay would be 134.14 min/km. It is suggested that the likelihood of such an extreme fluctuation is remote. However, if a flow of 750 vph represents a flow of 600 vph for 30 minutes followed by a flow of 900 vph for a further 30 minutes, there is still an underestimation of delay, although the error reduces from 76.99 min/km (134.14 − 57.15) to 3.01 min/km, an error of 5.27 percent. Clearly, further research is required to establish typical ranges of variation and to introduce appropriate corrections into the calculation of delay.

Using the relationships derived above, delay, suffered per kilometer by an individual passenger car, was calculated for a range of gradients, 3 to 9 percent, and flows along the upgrade varying from zero to 1,500 vph. These are plotted as shown in figure 6.

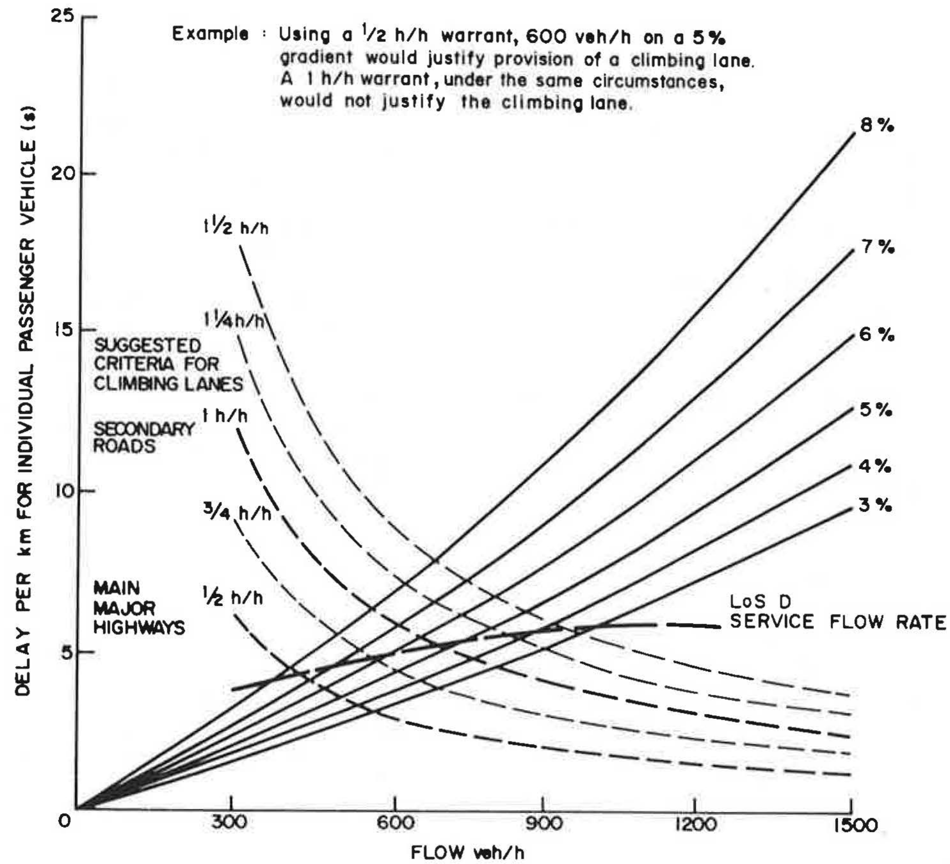

FIGURE 6 Relationship between flow, gradient, and delay.

DELAY CONSEQUENCES OF EXISTING WARRANTS

On level sections, rural roads typically operate in the range of LoS A or LoS B, except when close to urban areas. Seasonal fluctuations on recreational routes could produce the same result. *The Highway Capacity Manual* suggests, as one of the warrants for climbing lanes, a reduction by two levels of service, such as from LoS B to LoS D. The contention is that most drivers would be prepared to accept that operating conditions on a steep upgrade need not be comparable to those on level sections, suggesting that a reduction would be acceptable. However, a reduction through two levels, such as from LoS B to LoS E, would not be acceptable, and could thus lead to a reduction in safety being generated by impatience and ill-considered overtaking maneuvers. Such a reduction could also lead to a considerable increase in delay.

By way of illustration, a curve representing service flow rates for LoS D for various gradients is also shown on figure 6. The plotted values are based on the assumption of 15 percent trucks in the traffic stream and a grade 2.5-km (1.5-mi) long. This distance allows for a substantial length of gradient over which vehicle speeds are no longer influenced by preceding gradients.

It can be observed that the level of service warrant indicates a reasonably constant delay per vehicle regardless of the gradient. Because of the higher flows that can be accommodated on the flatter slopes before LoS D occurs, the overall delay to the traffic stream required to warrant a climbing lane is considerable.

AN ALTERNATIVE WARRANT FOR CLIMBING LANES

Also presented in figure 6 are five lines that represent isochronistic warrants for climbing lanes. These lines are based on the assumption that the total hourly delay for a given section, 1 km in this example, should remain constant regardless of the gradient. Thus, lines for ½, ¾, 1, 1¼, and 1½ hours of total delay per hour are presented. These are simply hyperbolae of the form:

$$W = Q * D * Pp/ 3600$$

where

W = constant, equal to selected warranting total delay = ½, ¾, 1, 1¼ or 1½ (h/h/km)
Q = flow (vph)
D = delay per individual passenger car(s)
Pp = percentage passenger cars in stream

A climbing lane will be justified to the right of each line and not justified to its left.

The selection of a particular criterion (½, ¾, etc.) is left to the individual agency and ought to be determined beforehand, based on general and economic design policies. It is suggested, for example, that on major highways an agency may prefer a higher standard by opting for the ½ h/h criterion and on secondary roads accept the 1 h/h criterion.

A decision to adopt delay as a warrant in preference to those currently in use has consequences that may not be overlooked. The most obvious of these is that the flow at which a climbing lane is warranted shows a dramatic decrease on the flatter grades and a similar increase on steeper grades. The ¾ h/h warrant demonstrates a break-even point with the current LoS warrant at 600 pcph and a 5 percent gradient. Experience indicates that the majority of gradients on any route are likely to be less steep than 5 percent, and flows in excess of 600 pcph are not uncommon. It is therefore reasonable to expect that, if the values in the above example are adopted, delay would illustrate a need for more climbing lanes than current warrants would suggest. At low volumes there would be some reduction in the number of climbing lanes called for on steeper grades. Construction costs, in the more rugged terrain that these gradients imply, could be substantially reduced.

A further consequence of delay as a warrant is that levels of service on steeper gradients may decrease, theoretically to beyond capacity. There is thus a logical cut-off point, in terms of flow and gradient, beyond which delay becomes meaningless and, therefore, a level of service criterion may have to be employed. This cut-off point, as well as the exact criterion of total delay, is still to be established. The basic concept, however, of a diminishing level of service with increasing gradient is seen as matching driver expectations which anticipate worsening of conditions with increasing steepness of grades. This expectation can be used to advantage to provide climbing lanes where drivers do not expect unnecessary delay.

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