

Effects of Pavement Roughness on Vehicle Speeds

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Vehicle speeds on highways as affected by a variety of factors, such as geometric characteristics of the roadway and traffic conditions, have been extensively studied. One factor that has received little attention is that of pavement condition. This report describes a study conducted in the summer of 1974 to develop relationships between average vehicle speed and pavement condition for two-lane highways. The condition factor chosen was roughness, and 72 sites covering a wide range of roughness were selected. Measurements included speed, roughness, geometric characteristics, and traffic counts. Capacities and volume-capacity ratios of the sections were calculated. A regression model relating average speed to roughness in terms of riding comfort index, volume-capacity ratio, and speed limit was developed. The model is simple and plausible and has a reasonable multiple correlation coefficient (0.77).

The operating speed of a highway is one of the major indicators of the level of service provided to the user and one of the major factors to be used in the analysis and justification of highway projects. A number of studies have been conducted to establish vehicle speed characteristics for different highways and conditions. These have shown that operating speeds are affected mainly by the following five groups of variables:

1. Driver characteristics,
2. Vehicle characteristics,
3. Roadway characteristics,
4. Traffic conditions, and
5. Environmental conditions.

Driver characteristics include age, occupation, sex, and experience as well as trip length, trip purpose, and presence or absence of passengers. Vehicle characteristics include engine size and power, type, age, weight, and maximum speed.

Roadway characteristics such as geographic location, sight distance, lateral clearance, frequency of intersections, gradient length and magnitude, and type of surface

have been shown to be important in speed analysis.

Traffic volume and density, composition, access control, and passing maneuvers are the most important variables related to traffic.

Time of day and climatic conditions are the major environmental factors. Although the effects of time and weather on speed have not yet been well established, experience has shown that they cannot be neglected.

One of the major unknowns in speed studies is the effect of pavement condition or roughness on operating speed. Recent improvements in the economic evaluation component of pavement design and management suggest that all agency and user costs need to be included (1). As a consequence, an existing pavement condition that significantly affects operating speeds can have significant economic implications in terms of extra user time and vehicle operating costs and potential extra accident and discomfort costs.

SCOPE AND OBJECTIVES OF STUDY

The basic purpose of this study was to establish initial relationships of speed and roughness for rural highways through a field study of a range of representative highway sections. Riding comfort index (RCI) was chosen as the indicator of roughness. [RCI is the Canadian equivalent of present serviceability index (PSI) except that a scale of 0 to 10 is used instead of a scale of 0 to 5 as for PSI values.]

Highways with both 80-km/h (50-mph) and 96-km/h (60-mph) speed limits were chosen for the study. These represent speed limits for many highway sections in Canada, and they encompass the current, common 88-km/h (55-mph) speed limit in the United States.

The following sections describe the scope and results of the field study, the analysis of the data, and the potential use of the relationships developed in pavement design and management systems.

FIELD STUDY

Selection of Study Sites

In selecting the location of the sites, we made an attempt

to obtain as many sections as possible for each range of RCI values. RCI was taken in 10 groups (0.0 to 0.9, 1.0 to 1.9, . . . , 9.0 to 10). Actual measurements of the sections were taken by Ontario Ministry of Transportation and Communications (MTC) personnel with a roughness meter, which had been correlated with RCI. It was thought that the results of the study would be mainly used for pavements with an RCI value between 4.0 and 7.0. Therefore, special consideration was given to finding sections in this range. Sections with very low and very high RCIs were also needed, however, to establish a complete range of conditions and for regression analysis. Figures 1 and 2 give the general geographic location of the study sites in southern Ontario and the number of sections used in this study for each group of RCIs respectively.

Many potential sites were initially selected from scaled maps. However, because the sections were required to have certain characteristics (level, tangent, good sight distance, an RCI within the desired range), the final selection was made by extensive field observations.

All sections selected were on two-lane paved highways with both 80- and 96-km/h (50- and 60-mph) speed limits so that the effect of speed limit on actual highway speed could be determined. Information concerning type of surface and other physical roadway characteristics oc-

curing at the various sites is given in Table 1.

Traffic counts were also taken because traffic characteristics can have a significant influence on speeds. These counts were made during the speed measurements. Capacities and volume-capacity (V/C) ratios were calculated [by using the Highway Capacity Manual (14)]. Table 2 gives detailed information on the traffic characteristics of the sites.

Speed Measuring Equipment

The two most important features of speed measuring equipment for field studies are that

1. It should be easy to use and be reliable and accurate so that measurements can be obtained easily and with reasonable accuracy and
2. It should be of such a nature that it can be camouflaged and thus not influence the motorist.

After taking these factors into consideration, we decided that an electromatic radar speed meter would be most suitable for the study. A graphic recorder was also used to obtain permanent records and more accurate readings.

To ensure the reliability of the equipment, several preliminary tests were run. The effect of the position of the receiver was checked. The receiver was set on the dash, rear window ledge, and outside the side windows facing to the front and rear of the vehicle. The right window position was found to be the best. The receiver was therefore installed at the outside of the right rear window, facing the traffic approaching from the rear of the test vehicle. It was not noticeable to motorists; moreover, the test vehicle was an older type of car

Figure 1. Area of speed station locations.

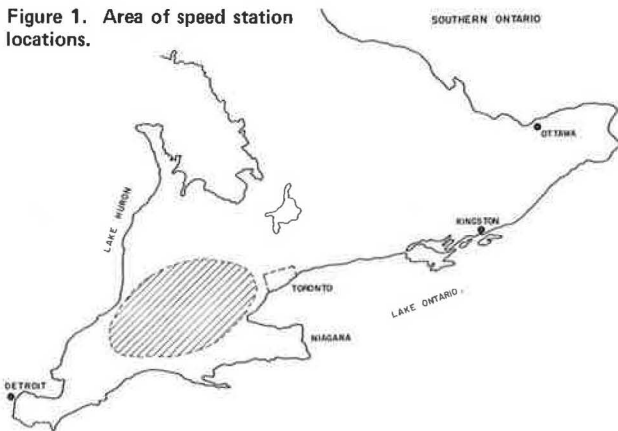


Figure 2. Distribution of roughness for sections used in speed studies.

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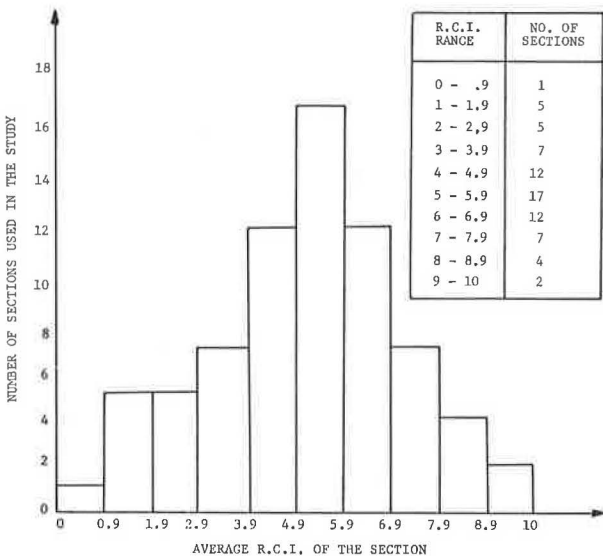


Table 1. Roadway characteristics at speed stations.

Section Number	Lane Width (m)	Shoulder Width (m)	Section Number	Lane Width (m)	Shoulder Width (m)
1	3.20	0.61	37	3.35	1.83
2	3.20	0.61	38	3.35	1.83
3	3.05	3.35	39	3.35	3.35
4	3.05	3.35	40	3.35	3.35
5	3.35	2.59	41	3.35	2.59
6	3.35	2.59	42	3.35	2.59
7	2.74	0.91	43	3.35	2.44
8	2.74	0.91	44	3.35	2.44
9	2.74	0.61	45	3.35	2.44
10	2.74	0.61	46	3.35	2.44
11	3.05	0.91	47	3.66	2.44
12	3.05	0.91	48	3.66	2.44
13	3.35	1.52	49	3.35	2.44
14	3.35	1.52	50	3.35	2.44
15	3.66	0.61	51	3.35	3.05
16	3.66	0.61	52	3.35	3.05
17	2.90	2.13	53	3.35	3.05
18	2.90	2.13	54	3.35	3.05
19	3.35	3.35	55	3.35	3.35
20	3.35	3.35	56	3.35	3.35
21	3.35	3.05	57	3.05	2.74
22	3.35	3.05	58	3.05	2.74
23	3.35	3.96	59	3.05	2.59
24	3.35	3.96	60	3.05	2.59
25	3.35	2.74	61	3.05	0.76
26	3.35	2.74	62	3.05	0.76
27	3.66	3.05	63	3.05	0.91
28	3.66	3.05	64	3.05	0.91
29	3.05	0.91	65	3.05	0.30
30	3.05	0.91	66	3.05	0.30
31	3.35	2.44	67	3.35	0.91
32	3.35	2.44	68	3.35	0.91
33	3.05	3.05	69	3.35	1.52
34	3.05	3.05	70	3.35	1.52
35	3.35	2.13	71	3.81	0.91
36	3.35	2.13	72	3.81	0.91

Notes: 1 m = 3.28 ft.
Each section has two lanes; all pavements are asphalt; and all shoulders are gravel.

with no resemblance to police vehicles.

After several test runs, it was found that traffic in both directions could be observed from the single position. As a consequence, speeds in both directions were measured at the same time, at each study site. Traffic volumes did not create any difficulty because they were relatively low (free-flow conditions). In the case of two vehicles passing the station at the same time, the data were canceled by the observer sitting on the front seat of the test vehicle simply by putting a mark on the records.

As a check on the reliability of the radar during the field study, tuning forks were used to simulate speeds of 48, 80, and 112 km/h (30, 50, and 70 mph). Adjustments were made before the actual speed measurements.

Field Measurements

After the selection of speed stations for the study, roughness was measured at each station on a 0.4-km (0.25-mile) section. The measurements were taken with a BPR roughometer, and the readings were converted to RCI from a previously established correlation with mean panel ratings. Table 3 gives roughness readings and RCI values for each study station.

The next step consisted of speed measurements. For these, the test vehicle was parked on the far edge of the shoulder at each station. In the case of inadequate shoulder widths, private driveways were used. The radar and recorder were set, and the receiver was placed in position. Standard field sheets were used to record traffic and roadway data. The following information was obtained from each station:

1. Speeds of vehicles by type and direction;
2. Hourly traffic volumes by type and direction; and
3. Roadway characteristics (land and shoulder widths, type of pavement, and the like).

It should be noted that all observations were made during daytime but not in a specific time period. Rush hours, when traffic volumes are very heavy, were avoided. The speed measurements were generally made under free-flow conditions so that the effect of slow-moving vehicles or congestion could be minimized.

Motorcycles were excluded from the study. Similarly, "unusual" drivers (such as very slow-moving, elderly drivers) were not taken into account. When a vehicle was felt to be influenced by such a slow-moving vehicle or opposing traffic, the measurement was omitted.

The sample size was calculated by the formula given in the Manual of Traffic Engineering Studies (2). An attempt was made to observe 60 vehicles at each station; however, at some stations (especially those on secondary county roads), this number could not be obtained in a reasonable length of time because of the very low traffic volumes.

ANALYSIS OF FIELD DATA

A total of 4105 vehicle speeds were measured during the field studies. Although measurements were made by type of vehicle, the data were combined for the final analysis and an overall average speed for each station was calculated. Because the objective of the study was to determine the relationship between average highway speed and roughness of the pavement, this approach was considered reasonable. The calculated mean speeds and standard deviation of the speed distributions at each station are given in Table 4.

Figure 3, which was obtained from the information given in Table 4, shows the speed measurements deter-

mined by the field studies. It shows that, on county roads with a speed limit of 80 km/h (50 mph), a high proportion of the motorists usually drive somewhat too fast, even on very rough pavements. This situation may be partially explained by the lack of speed limit enforcement on these facilities. On main highways, most drivers tend to obey the speed limit.

The data given in Table 5 and plotted in Figure 3 were first analyzed separately for each group of speed limits and capacity levels. Various regression models were tested. Because of the data limitations, however, a generally acceptable model could not be developed.

The data for 80- and 90-km/h (50- and 60-mph) speed limits were then combined, and one general regression model was tested. Several different forms of models were checked. The final four equations considered are as follows:

$$y = 34.4718 + 0.0199x_1x_4 + 0.0044x_4^2 \quad (1)$$

$$y = 32.9584 + 0.0183x_1x_4 + 0.0055x_4^2 - 0.0075x_2x_3 \quad (2)$$

$$y = 2.596x_1^{0.0928} \times x_3^{-0.0275} \times x_4^{0.704} \quad (3)$$

$$y = 30.7368 + 1.0375x_1 - 11.2421x_3 + 0.0062x_4^2 \quad (4)$$

where

- y = average highway speed in kilometers per hour,
- x_1 = RCI,
- x_2 = total capacity of roadway in vehicles per hour,
- x_3 = V/C ratio, and
- x_4 = speed limit in kilometers per hour.

Statistical characteristics of these models, as indicated by the data given in Table 5, are similar. All coefficients are statistically significant; constant terms are alike; and all of them have similar multiple correlation coefficients. Mean, absolute mean, and standard deviation of residuals were calculated for further analysis. However, the results were not particularly helpful for selecting the best model.

Subjective, logical tests were then applied. Model 3 was eliminated because of the production nature of the equation. It would give zero speeds for zero RCI value, which means no vehicle movement on very rough sections. This is unrealistic.

The remaining models were then studied thoroughly. Model 4 was finally selected mainly because of its simplicity. Caution should, however, be exercised in use of the x_3 term in the model. The reason for this is that field measurements were conducted mostly under free-flow conditions. The effect of V/C ratio in speed, therefore, is perhaps not accurately represented by the model over the whole range of possible V/C ratios (from 0.0 to 1.0). Thus the recommended model should not be used for highway sections with very high traffic volumes. Similarly, the model is not too accurate for RCI values of less than 2.0.

COMPARISON OF RESULTS

Figure 4 compares the data of this investigation with those of previously presented relationships.

The relationships used by the Ontario MTC in their pavement management system OPAC (1) are represented by heavy solid lines for various speed limits between 80 and 112 km/h (50 and 70 mph). Also shown are the linear regressions (model 4) for data from the 80-km/h (50-mph) speed limit roads and the 96-km/h (60-mph) speed limit roads.

The MTC relationship for the 80-km/h (50-mph) speed limit roads compares reasonably well with the observed

Table 2. Traffic characteristics at speed stations.

Section Number	Total Capacity (vehicles/h)	Directional Volume (vehicles/h)	Volume-Capacity Ratio	Speed Limit (km/h)	Section Number	Total Capacity (vehicles/h)	Directional Volume (vehicles/h)	Volume-Capacity Ratio	Speed Limit (km/h)
1	1253	7	0.01	80	37	1531	51	0.07	80
2	1253	12	0.02	80	38	1531	63	0.08	80
3	1409	17	0.02	80	39	1531	120	0.16	96
4	1409	16	0.02	80	40	1531	108	0.14	96
5	1531	35	0.05	96	41	1531	108	0.14	96
6	1531	49	0.06	96	42	1531	72	0.09	96
7	1183	33	0.06	80	43	1531	96	0.13	96
8	1183	34	0.06	80	44	1531	96	0.13	96
9	1131	25	0.04	80	45	1531	72	0.09	96
10	1131	24	0.04	80	46	1531	84	0.11	96
11	1262	28	0.04	80	47	1740	84	0.10	96
12	1262	111	0.18	80	48	1740	96	0.11	96
13	1496	69	0.09	80	49	1531	96	0.13	96
14	1496	78	0.10	80	50	1531	120	0.16	96
15	1479	203	0.27	80	51	1531	156	0.20	96
16	1479	225	0.30	80	52	1531	144	0.18	96
17	1357	94	0.13	96	53	1531	96	0.12	96
18	1357	69	0.10	96	54	1531	192	0.25	96
19	1531	336	0.43	96	55	1531	156	0.20	96
20	1531	252	0.33	96	56	1531	228	0.29	96
21	1531	108	0.14	96	57	1409	216	0.31	96
22	1531	144	0.19	96	58	1409	156	0.22	96
23	1531	131	0.17	96	59	1409	156	0.22	96
24	1531	125	0.16	96	60	1409	144	0.20	96
25	1531	69	0.09	80	61	1253	48	0.06	80
26	1531	63	0.08	80	62	1253	48	0.06	80
27	1740	70	0.08	96	63	1262	36	0.06	80
28	1740	88	0.10	96	64	1262	48	0.08	80
29	1262	42	0.07	80	65	1140	33	0.06	80
30	1262	37	0.06	80	66	1140	39	0.07	80
31	1531	156	0.20	96	67	1375	47	0.07	96
32	1531	120	0.16	96	68	1375	61	0.09	96
33	1409	96	0.14	96	69	1496	58	0.08	80
34	1409	132	0.19	96	70	1496	40	0.05	80
35	1531	132	0.17	96	71	1557	156	0.20	80
36	1531	132	0.17	96	72	1557	144	0.18	80

Note: 1 km/h = 0.621 mph.

Table 3. Roughness data for speed stations.

Section Number	Roughness Index (mm/km)	RCI ^a	Section Number	Roughness Index (mm/km)	RCI ^a
1	4762	0.5	37	1080	6.9
2	3493	1.8	38	1016	7.2
3	—	3.4	39	762	8.4
4	—	3.6	40	826	8.1
5	572	9.7	41	953	7.5
6	699	8.8	42	1016	7.2
7	2858	2.7	43	1080	6.9
8	3175	2.2	44	1651	5.1
9	3556	1.7	45	1397	5.8
10	3874	1.4	46	1524	5.4
11	3747	1.5	47	1461	5.6
12	3175	2.2	48	1143	6.7
13	2032	4.2	49	1016	7.2
14	1588	5.2	50	889	7.8
15	4064	1.2	51	1080	6.9
16	3366	2.0	52	1080	6.9
17	2032	4.2	53	1080	6.9
18	2223	3.8	54	1461	5.6
19	1016	7.2	55	2159	4.0
20	1016	7.2	56	2096	4.0
21	2032	4.2	57	1524	5.4
22	2096	4.0	58	1461	5.6
23	2413	3.4	59	1588	5.2
24	2159	3.9	60	1651	5.1
25	1080	6.9	61	1715	4.9
26	1143	6.7	62	1524	5.4
27	635	9.2	63	1651	5.1
28	699	8.8	64	1461	5.6
29	1715	4.9	65	1651	5.1
30	1905	4.4	66	2032	4.2
31	1588	5.2	67	1778	4.7
32	1334	6.0	68	1270	6.2
33	1651	5.0	69	1842	4.6
34	1461	5.6	70	2223	3.8
35	1270	6.2	71	2667	3.0
36	1270	6.2	72	3302	2.1

Notes: 1 mm/km = 15.78 mm/mile.
The length of each section is 0.40 km (0.25 mile).

^aRCI = 25.25 - 10.0093 log R where R = roughness index.

Table 4. Speed data for speed stations.

Section Number	Mean Speed (km/h)	Standard Deviation (km/h)	Section Number	Mean Speed (km/h)	Standard Deviation (km/h)
1	67	8.79	37	82	10.06
2	67	9.10	38	83	8.72
3	86	14.76	39	98	10.90
4	85	10.32	40	101	12.08
5	96	9.24	41	94	12.49
6	96	9.34	42	99	12.17
7	77	8.52	43	91	15.39
8	78	8.97	44	94	12.99
9	78	10.34	45	94	11.95
10	78	14.04	46	96	11.56
11	62	4.59	47	94	10.59
12	61	7.65	48	98	12.70
13	78	17.23	49	98	10.77
14	78	11.59	50	94	10.21
15	69	11.51	51	93	14.52
16	72	8.77	52	94	11.09
17	91	17.36	53	91	11.85
18	90	11.90	54	86	9.26
19	93	10.21	55	85	9.74
20	91	8.65	56	83	9.35
21	99	9.27	57	90	9.19
22	93	10.21	58	88	12.77
23	88	10.42	59	91	9.68
24	93	10.18	60	88	9.97
25	91	11.11	61	83	12.48
26	88	10.79	62	77	10.79
27	96	14.81	63	86	11.79
28	93	12.30	64	82	11.74
29	78	10.90	65	85	13.09
30	86	14.57	66	85	13.15
31	91	12.06	67	93	12.99
32	91	11.33	68	91	14.31
33	86	11.22	69	72	12.59
34	86	12.08	70	72	10.13
35	85	10.14	71	75	11.16
36	90	11.22	72	74	10.92

Note: 1 km/h = 0.621 mph.

data although its slope could be adjusted. For the 96-km/h (60-mph) speed limit roads, it also compares reasonably well with the data, but again the slope could be adjusted. The MTC relationship also appears to reduce speed too severely for the lower RCI values (vehicles travel somewhat faster on very rough roads under free-flow conditions than originally postulated).

Finally, McFarland's original postulated relationship for 96-km/h (60-mph) speed limit roads (11) is also shown in Figure 4. It agrees reasonably well with the observed data for high RCI values (greater than about 7), but it reduces speed too severely for the lower RCI values.

Figure 3. Distribution of mean vehicle speeds.

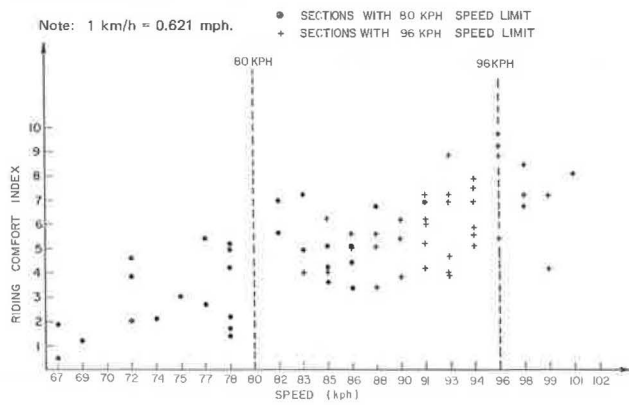
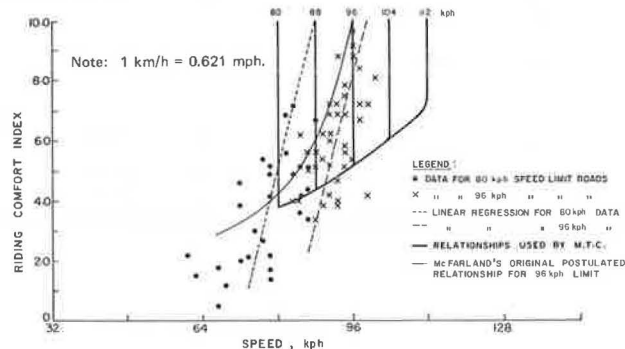


Table 5. Statistical characteristics of regression equations.

Model Number	Multiple Correlation Coefficient	Student's t-Values ^a	Standard Error of Estimate	Goodness of Fit
1	0.73	t ₁ = 5.87	2.67	96.78
2	0.77	t ₁ = 5.56 t ₂ = 6.41 t ₃ = 2.67	2.56	72.77
3	0.79	t ₁ = 7.40 t ₂ = 2.90 t ₃ = 8.54	0.05	85.16
4	0.77	t ₁ = 5.74 t ₂ = 2.67 t ₃ = 8.25	2.52	60.41

^aTheoretical t = 2.32.

Figure 4. Speed-riding comfort index data and relationships.



USE OF SPEED-ROUGHNESS RELATIONSHIPS IN PAVEMENT MANAGEMENT

General Implications

The pavement design and management concept that has been used recently for developing real working systems within various highway agencies (3, 4, 5, 6, 7, 8, 9, 10) includes the generation and analysis of alternative design strategies. In the analysis procedure, the performance output of each strategy is predicted. Then the cost and benefit implications of these performance outputs are determined and compared for selecting the optimal strategy.

Today many pavement authorities have agreed that both agency costs (initial capital, resurfacing, and maintenance costs) and user costs (traffic delay, vehicle operation, travel time, accident, and discomfort) need to be considered in the economic evaluation of alternative pavement design strategies. Recent studies (1, 11) have quantitatively illustrated the importance of the user costs component.

User costs vary significantly with pavement performance. This variation is a function of roughness, which affects vehicle speeds and operating costs. As the pavement deteriorates, the lower speeds result in higher user costs. Therefore, a pavement strategy that provides a low level of serviceability over a longer period of time causes higher user costs than a strategy that serves the traffic on a smoother surface for most of the time.

Figure 5. Speed profiles for two example strategies.

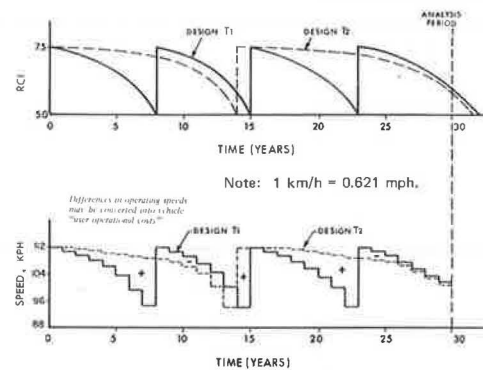
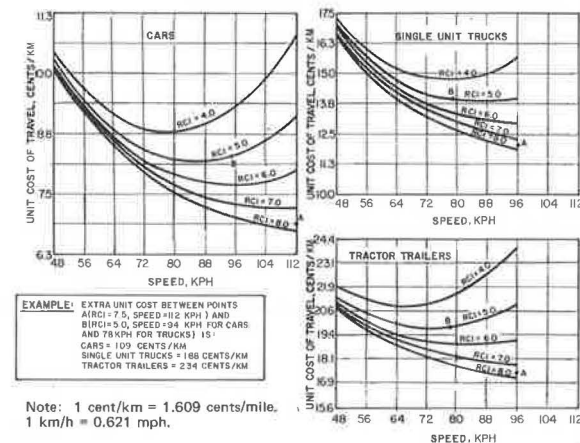


Figure 6. Unit costs (excluding taxes) of speed reductions at different RCI levels on a rolling tangent in Ontario.



EXAMPLE: EXTRA UNIT COST BETWEEN POINTS A(RCI=7.5, SPEED=112 KPH) AND B(RCI=5.0, SPEED=94 KPH) FOR CARS AND TRUCKS IS:
CARS = 107 CENTS/KM
SINGLE UNIT TRUCKS = 188 CENTS/KM
TRACTOR TRAILERS = 234 CENTS/KM

Note: 1 cent/km = 1.609 cents/mile.
1 km/h = 0.621 mph.

As a consequence, determination of speed profiles during the life of a pavement becomes extremely important because it provides a means for relating user costs to pavement performance.

When the performance history of a pavement design strategy is determined, as shown in the upper portion of Figure 5, the speed profile of the strategy can then be easily found by the types of relationships shown in Figure 4. An example is shown in the lower portion of Figure 5, which is patterned after Kher, Phang, and Haas (1). The corresponding user costs can be calculated from data available in the literature (12, 13) or from relationships such as those shown in Figure 6, also patterned after Kher, Phang, and Haas (1). (In Figure 6, unit costs = vehicle operation and travel time.)

The effect of the traffic volume on vehicle speeds should also be considered in the analysis for more accurate results because speed reductions may occur as a result of increased traffic volumes as well as low pavement serviceability levels. Therefore, speed versus roughness and traffic (combined) relationships should be the object of future research for more comprehensive user cost analysis.

Example

A simple example can serve to illustrate the economic implications of speed-roughness variations.

Suppose that a two-lane highway with an annual average daily traffic (AADT) of 5000 and a 96-km/h (60-mph) speed limit has reached a terminal serviceability (i.e., RCI) level of 4.5. The extra user costs involved in delaying the resurfacing (which is expected to raise the RCI level to 8.0) by 1 year should be calculated.

If we assume that the 5000 AADT represents all passenger cars, then Figure 4 indicates an 88-km/h (55-mph) average speed for an RCI of 4.5 and a 96-km/h (60-mph) average speed for an RCI of 8.0. Figure 6 then indicates user costs of 8.8 and 6.9 cents/km (14.1 and 11.2 cents/mile) respectively for the before and after resurfacing conditions.

For a 1.6-km (1-mile) section and 350 days, the extra user costs of delaying resurfacing are $5000 \times 350 \times (0.141 - 0.112)$, which is \$50 750. This would be reduced slightly by the delay in the extra user costs due to resurfacing (using present worth of costs analysis), but it still represents quite a significant extra cost. Of course budget restrictions of the agency involved might require many such resurfacing delays despite the extra user costs. Nevertheless, these extra user costs should be determined and used as a factor in determining investment priorities.

The foregoing example has been chosen to cover a fairly narrow range and conditions in which the observed data of Figure 4 agree quite closely with the relationship that the Ontario MTC uses in its pavement management system. Allowing the serviceability to drop to lower levels than those of the example would result in higher extra user costs as well as possible extra capital costs for resurfacing (i.e., extra thickness).

CONCLUSIONS

Three major points of this paper can be summarized.

1. Speeds of motor vehicles on highways are significantly affected by pavement condition. Neglecting this effect may result in major errors in the economic evaluation of alternative pavement design strategies.

2. Field observations were made at 72 selected stations in southern Ontario. Vehicle speeds were measured for various roughness levels (which were trans-

formed into RCI values). Geometric characteristics of the roadway section at each station were also determined. Traffic counts were conducted and V/C ratios were calculated.

3. A regression equation was developed for two-lane rural highways to express vehicle speeds in terms of RCI, V/C ratio, and speed limit. The relationship has potential application to individual pavement projects or to a series of projects within a network. It compares reasonably well with previously postulated relationships over a certain range of conditions.

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