CHAPTER 4
RESULTS OF FREE-FLOW SPEED SURVEYS

4.1 FREE-FLOW SPEEDS ON POSITIVE GRADES (TB-1) AND NEGATIVE GRADES (TB-2)

On highway segments of homogeneous characteristics it can be generally assumed that vehicles tend to run at a speed appropriate to their class and load, and limited by the type and state of maintenance of the surfacing. It can also be assumed that this speed always tends to keep constant and that the phases of acceleration and deceleration constitute transitory stages during which the vehicles seek to reach it.

To define this behaviour, road test sections were selected. They were straight with uniform grades, without any restrictions or obstacles that could interfere with the vehicles' speeds, allowing drivers to freely choose the most convenient speed for them with regard to road characteristics and to vehicle type and load.

Vehicle spot speeds were also measured by radar at predetermined points along these sections. The data were thus obtained to establish the equations which would translate vehicle behaviour as a function of the independent variables related to road type and maintenance state.

The analysis of the data set thus obtained determined the degree of influence of each of the variables (type of surface, roughness and grade) selected for study.

Equations were then developed: (1) to predict steady-state speed proper to each vehicle class on a given grade (Table 4.1), and (2) to simulate the variation in speed among the different vehicle classes as a function of the distance run from the beginning of the slope till the point where the vehicle stabilizes at the steady-state speed (Table 4.2) (Moser, 14/02/79, 19/02/79).

On unpaved roads the degree of a negative grade hardly influences the steady-state speed of vehicles, with the exception of buses and loaded trucks, which tend to have a higher steady-state speed as the declivity increases, even exceeding the speeds of light vehicles on negative grades around 6% (Figure 4.1a). On positive

TABLE 4.1 - STEADY-STATE SPEED ON UNIFORM GRADES (km/h)

Cars	$V = S1 \times (91.9 - 2.7 \times G_P - 0.154 \times QI) + S2 \times (99.6 - 3.7 \times G_P + 0.6 \times G_{N1} - 0.214 \times QI)$
Buses	$V = S1 \times (84.3 - 0.5 \times G_N - 10.8 \times G_{P1} - 5.1 \times G_{P2} - 0.154 \times QI) + S2 \times (67 - 6.8 \times G_{N1} - 6.2 \times G_P - 0.093 \times G_{P3} \times QI)$
Empty utilities	$V = S1 \times (84.3 - 2.4 \times G_P - 0.154 \times QI) + S2 \times (89.4 - 3.7 \times G_P + 0.6 \times G_{N1} - 0.177 \times QI)$
Loaded utilities	$V = S1 \times (84.3 - 3.7 \times G_P - 0.154 \times QI) + S2 \times (83.9 - 3.7 \times G_P + 0.6 G_N - 0.177 \times QI)$
Empty trucks	$V = S1 \times (74.6 - 3.0 \times G_N - 3.7 \times G_P - 0.154 \times QI) + S2 \times (80.9 - 3.7 \times G_P + 0.6 \times G_{N1} - 0.177 \times QI)$
Loaded trucks	$V = SL \times (74.6 - 3.0 \times G_N - 12.6 \times G_{P1} - 3.5 \times G_{P2} - 0.154 \times QI) + S2 \times (67 - 3.7 \times G_P - 6.8 \times G_{N1} - 0.177 QI)$

$S1$ = 1 if paved; 0 if unpaved

$S2$ = 1 if unpaved; 0 if paved

G_N = G if G < 0%; 0 otherwise

G_{N1} = G if -3,6% < G < 0%; -3,6% otherwise

G_P = G if G > 0%; 0 otherwise

G_{P1} = G if 0% < G ≤ 3%; 3 if G > 3%; 0 otherwise

G_{P2} = (G-3) if G > 3%; 0 otherwise

G_{P3} = (6-G)/6 if 0% < G 6%; 0 otherwise

QI = Roughness Index

G = percent grade

TABLE 4.2 - SPEED VARIATION ON POSITIVE GRADES (km/h)

Cars	ΔV	=	$D(-0.0001 \times G1 - 0.008 \times G2 - 0.0158 \times G3) \times S1 + DS_2 Ga$
Buses	ΔV	=	$D(-0.0003 \times G1 - 0.0167 \times G2 - 0.0312 \times G3) \times S1 - 0.006 DS_2 G$
Empty utilities	ΔV	=	$D(-0.0003 \times G1 - 0.008 \times G2 - 0.01 \times G3) \times S1 + DS_2 Ga$
Loaded utilities	ΔV	=	$D(-0.0003 \times G1 - 0.008 \times G2 - 0.0152 \times G3) \times S1 + DS_2 Ga$
Empty trucks	ΔV	=	$D(-0.0016 \times G1 - 0.008 \times G2 - 0.0125 \times G3) \times S1 + DS_2 Ga$
Loaded trucks	ΔV	=	$D(-0.0037 \times G1 - 0.008 \times G2 - 0.0620 \times G3) \times S1 - 0.006 DS_2 G$

D = distance from beginning of acclivity up to the point where speed stabilizes

$$S1 = \begin{cases} 1 & \text{if paved} \\ 0 & \text{if unpaved} \end{cases}$$

$$S2 = \begin{cases} 1 & \text{if unpaved} \\ 0 & \text{if paved} \end{cases}$$

$$G1 = \begin{cases} G & \text{if } 0 < G < 3\% \\ 3 & \text{if } G \geq 3\% \end{cases}$$

$$G2 = \begin{cases} 0 & \text{if } G \leq 3\% \\ (G-3) & \text{if } 3\% < G < 5\% \\ 2\% & \text{if } G \geq 5\% \end{cases}$$

$$G3 = \begin{cases} 0 & \text{if } G \leq 5\% \\ (G-5) & \text{if } G > 5\% \end{cases}$$

$$a = \begin{cases} -0.000794 & \text{if } G \leq 3\% \\ -0.000794 - 0.001976 \left(\frac{G-3}{3}\right) & \text{if } 3\% < G < 6\% \\ -0.00277 & \text{if } G \geq 6\% \end{cases}$$

G = percent grade

slopes, Class 1, 3, 4 and 5 vehicles (see p. 56) are subject to a speed variation proportional to the inclination of the positive grade. Buses and loaded trucks (Class 2 and 6, respectively), whose steady-state speeds on positive grades are significantly reduced as the grade increases to 3%, show a substantial change in behaviour from this point on, with a smaller speed reduction on steeper inclines.

On unpaved roads, while Class 1, 3, 4 and 5 vehicles run at a steady-state speed almost independent of the steepness of the negative grade, buses and loaded trucks tend to run at higher steady-state speeds as the declivity grows steeper till approximately -3.5%. On unpaved positive grades, the decrease in steady-state speed due to the steepness is also substantial and very similar for all classes (Figure 4.1b). As for the deceleration mode, it was found that on positive grades, all classes of vehicles tended to lose speed in proportion to the acclivity's steepness, both on paved and unpaved roads, even though the decreases in speed caused by the steepness of the incline were substantially different on both types of surfacing. The equations in Table 4.2 define the behaviour of the five classes of vehicles studied, and quantify the speed loss of each class on positive grades as a function of the distance run from the beginning of the slope till the vehicles stabilize their speeds, the type of surfacing and the acclivity's steepness. Figure 4.2a graphically represents these equations for a grade of 5% on a paved road. On negative grades, it was found that only on paved roads would the vehicles accelerate proportionately to the declivity's steepness, according to the expression below (Moser, 14/02/79 and 19/02/79):

$$\Delta V = DG_N(0.00198 + 0.00120C_1 - 0.00166C_2 - 0.00134C_3 - 0.00157C_4) \qquad (4.1)$$

Where : D =distance for the vehicle to stabilize its speed

G_N =absolute value of grade

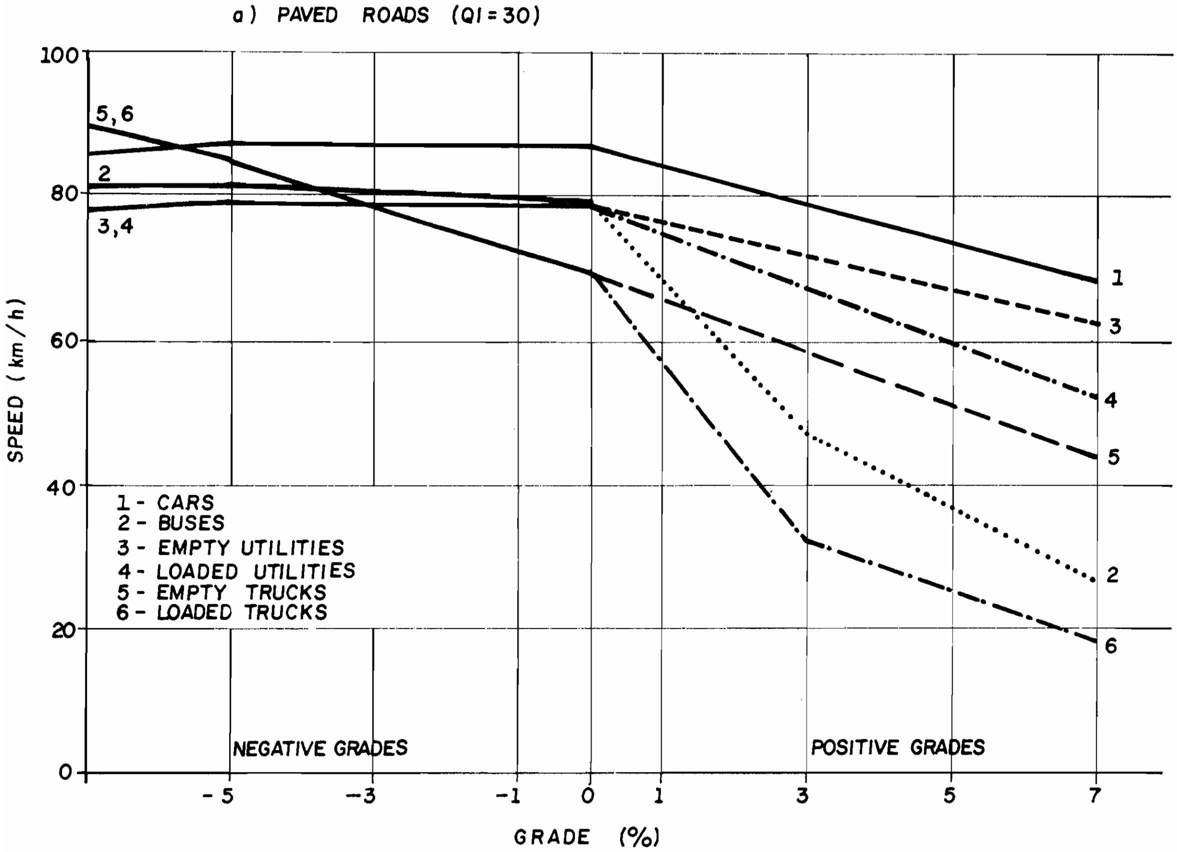
C_1 =1 if an automobile; 0 if another class

C_2 =1 if a bus; 0 if another class

C_3 =1 if an empty utility; 0 if another class

C_4 =1 if a loaded utility; 0 if another class

Figure 4.2b depicts this equation graphically, and exemplifies the behaviour of the different vehicle classes on a paved



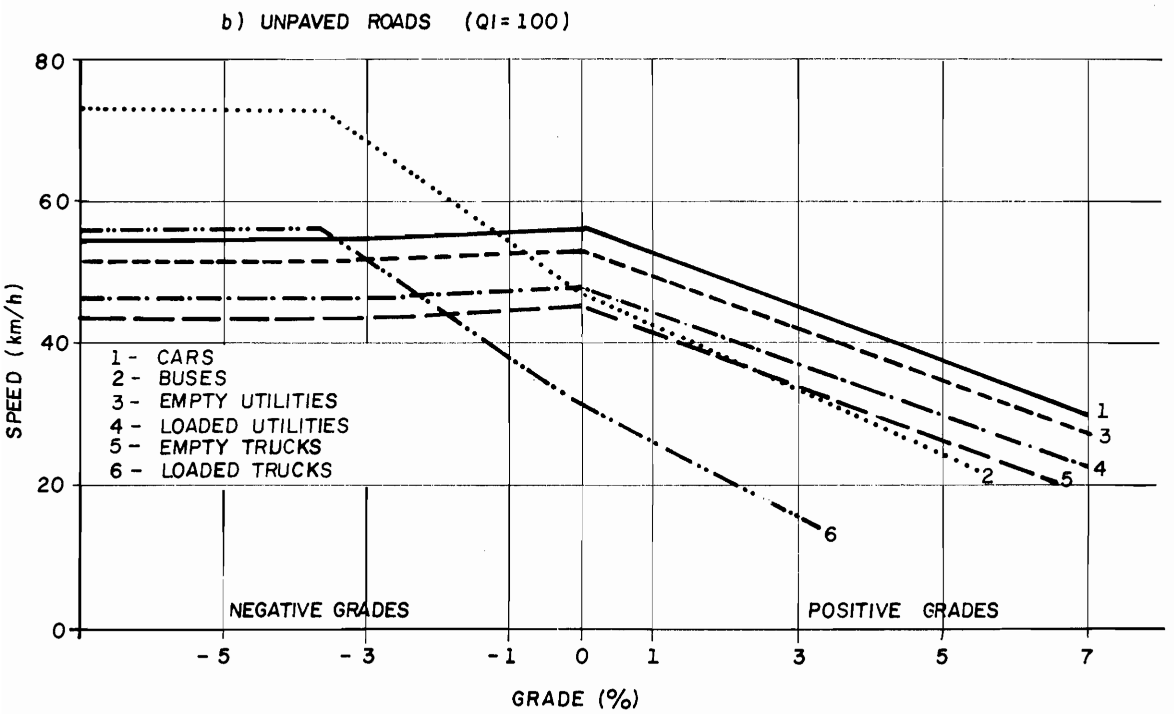
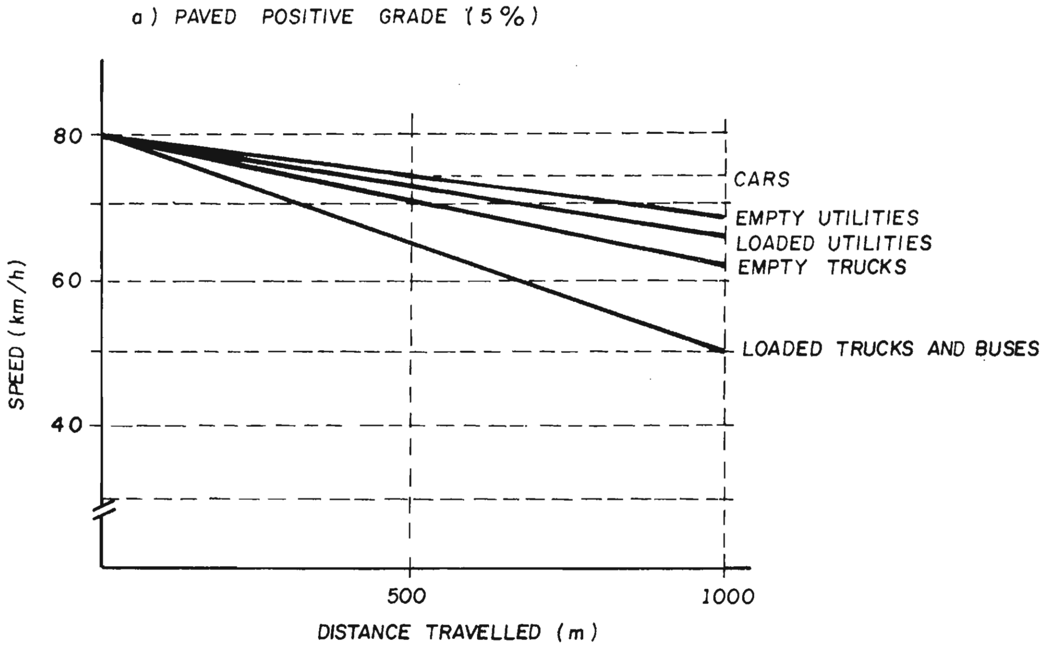


FIGURE 4.1 – VEHICLE PERFORMANCE ON UNIFORM GRADES (STEADY-STATE SPEED)



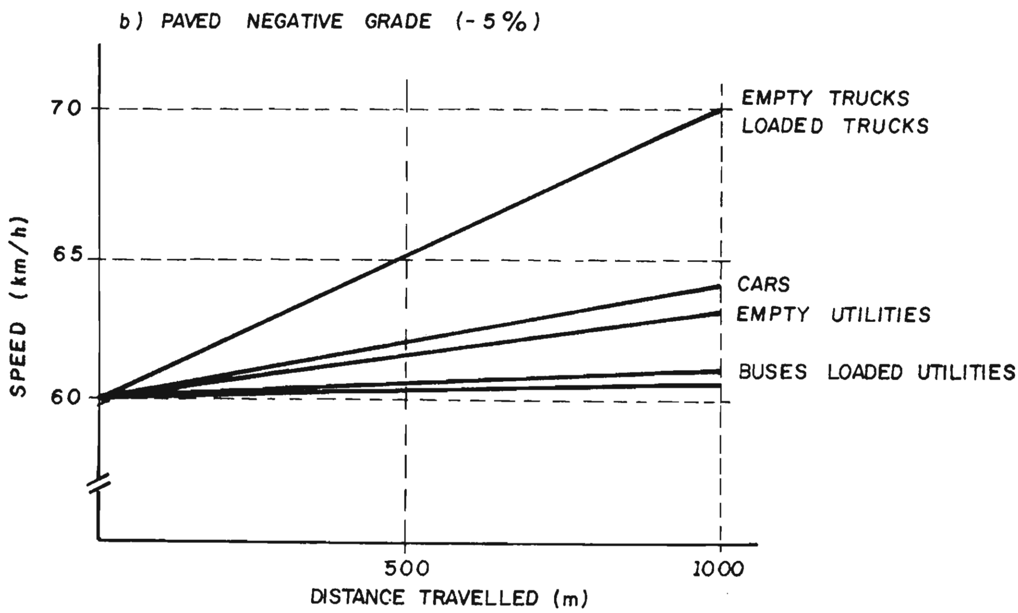


FIGURE 4.2 - VARIATION OF FREE-FLOW SPEED ON CONSTANT GRADES

declivity of 5%. It can be noted that buses and loaded utilities hardly change their speeds along the declivity. However, trucks, both empty and loaded, take advantage of the declivity and increase their speed by as much as 10 km/h for every 1000 meters, until they reach their steady-state speed for that declivity.

4.2 *FREE-FLOW SPEEDS ON CURVES (TB-4)*

The variables included in the study of vehicle behaviour on curves were: curve radius, type of surfacing, vertical geometry, state of surfacing, maintenance and superelevation.

Curves with radii from 20 m to more than 1000 m were included in the study, and as many as three curves for each profile and radius length were selected, depending on the position of the curve relative to the road profile (curve at the beginning of the slope, curve on the middle of the slope, and curve at the end of the slope). Thus over 150 curves were surveyed, about one hundred of which were found to have satisfactory conditions for statistical analysis.

In the analysis of variance of the data obtained, the type of surfacing, roughness, curve radius, superelevation, and vehicle class proved to significantly affect the variation in free-flow speeds on curves. Superelevation turned out to be significant for both types of surfacing, but on paved sections curve radius and superelevation are highly correlated; therefore, only radius was considered in the subsequent regression analysis.

The effects of curvature and roughness turned out to be non-linear. In the case of frequent variation in the radius of curvature, the speeds oscillated more on curves with short radii than on those of large radii. Similarly, the increase in roughness influenced speed more on well maintained roads (with a low level of initial roughness) than on poorly maintained roads (GEIPOT, 6/80).

Finally, it was found that curves with radii of less than 600 m significantly affect speed on paved curves, whereas on unpaved curves no significant effect was found on curves with a radius of more than 400 m. This can be attributed to the fact that vehicles tend to maintain lower speeds on unpaved roads.

Table 4.3 presents, for each vehicle class and for each surfacing type, the equations obtained from the statistical analysis of the data of Experiment TB-4. Table 4.4 presents a definition of those independent variables whose influence is significant. Figure 4.3 is the graphic representation of these equations for curves situated on level sections, both paved and unpaved, with roughness equal to 40 and 100 QI, respectively.

TABLE 4.3 - EXPRESSIONS FOR FREE FLOW SPEEDS ON CURVES

PAVED ROADS

Car

$V = 17.756+0.428R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-0.71G-0.01QI_1-0.28QI_2$

Bus

$V = 17.756+0.29R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-0.71G-0.045QI_1-0.28QI_2$

Empty utility

$V = 17.756+0.39R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-0.71G-0.045QI_1-0.28QI_2$

Loaded utility

$V = 20.906+0.39R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-0.71G-0.14QI_1-0.28QI_2$

Empty truck

$V = 24.976+0.39R_{100}+0.12R_{200}+0.035R_{400}+0.014R_{600}-071G-0.14QI_1-0.28QI_2$

Loaded truck

$V = 17.756+0.39R_{100}+0.12R_{200}+0.35R_{400}+0.014R_{600}-0.71G-0.14QI_1-0.28QI_2$

UNPAVED ROADS

Car

$V = 20.87+0.35R_{100}+0.11R_{200}-0.21G-0.042QI_3-0.083QI_4+44.41SE$

Bus

$V = 20.87+0.19R_{100}+0.11R_{200}-0.85G-0.007QI_3-0.083QI_4+44.41SE$

Empty utility

$V = 30.71+0.19R_{100}+0.11R_{200}-0.21G-0.042QI_3-0.083QI_4+44.41SE$

Loaded utility

$V = 20.87+0.19R_{100}+0.11R_{200}-0.52G-0.083QI_4+44.41SE$

Empty truck

$V = 25.75+0.19R_{100}+0.11R_{200}-0.52G-0.042QI_3-0.083QI_4+44.41SE$

Loaded truck

$V = 20.87+0.19R_{100}+0.11R_{200}-0.52G-0.042QI_3-0.083QI_4+44.41SE$

TABLE 4.4 - DEFINITIONS OF VARIABLES IN EXPRESSIONS OF FREE-FLOW SPEEDS ON CURVES

$$R_{100} = \begin{cases} R & \text{if } R < 100 \text{ m} \\ 100 & \text{if } R \geq 100 \text{ m} \end{cases}$$

$$R_{200} = \begin{cases} 0 & \text{if } R < 100 \text{ m} \\ (R - 100) & \text{if } 100 \leq R < 200 \text{ m} \\ 100 & \text{if } R \geq 200 \text{ m} \end{cases}$$

$$R_{400} = \begin{cases} 0 & \text{if } R < 200 \text{ m} \\ (R - 200) & \text{if } 200 \leq R < 400 \text{ m} \\ 200 & \text{if } R \geq 400 \text{ m} \end{cases}$$

$$R_{600} = \begin{cases} 0 & \text{if } R < 400 \text{ m} \\ (R - 400) & \text{if } 400 \leq R < 600 \text{ m} \\ 200 & \text{if } R \geq 600 \text{ m} \end{cases}$$

$$QI_1 = \begin{cases} QI & \text{if paved road with } QI \leq 75 \\ 75 & \text{if paved road with } QI > 75 \end{cases}$$

$$QI_2 = \begin{cases} 0 & \text{if paved road with } QI \leq 75 \\ (QI - 75) & \text{if paved road with } QI > 75 \end{cases}$$

$$QI_3 = \begin{cases} QI & \text{if unpaved road with } QI \leq 140 \\ 140 & \text{if unpaved road with } QI > 140 \end{cases}$$

$$QI_4 = \begin{cases} 0 & \text{if unpaved road with } QI < 140 \\ (QI - 140) & \text{if unpaved road with } QI \geq 140 \end{cases}$$

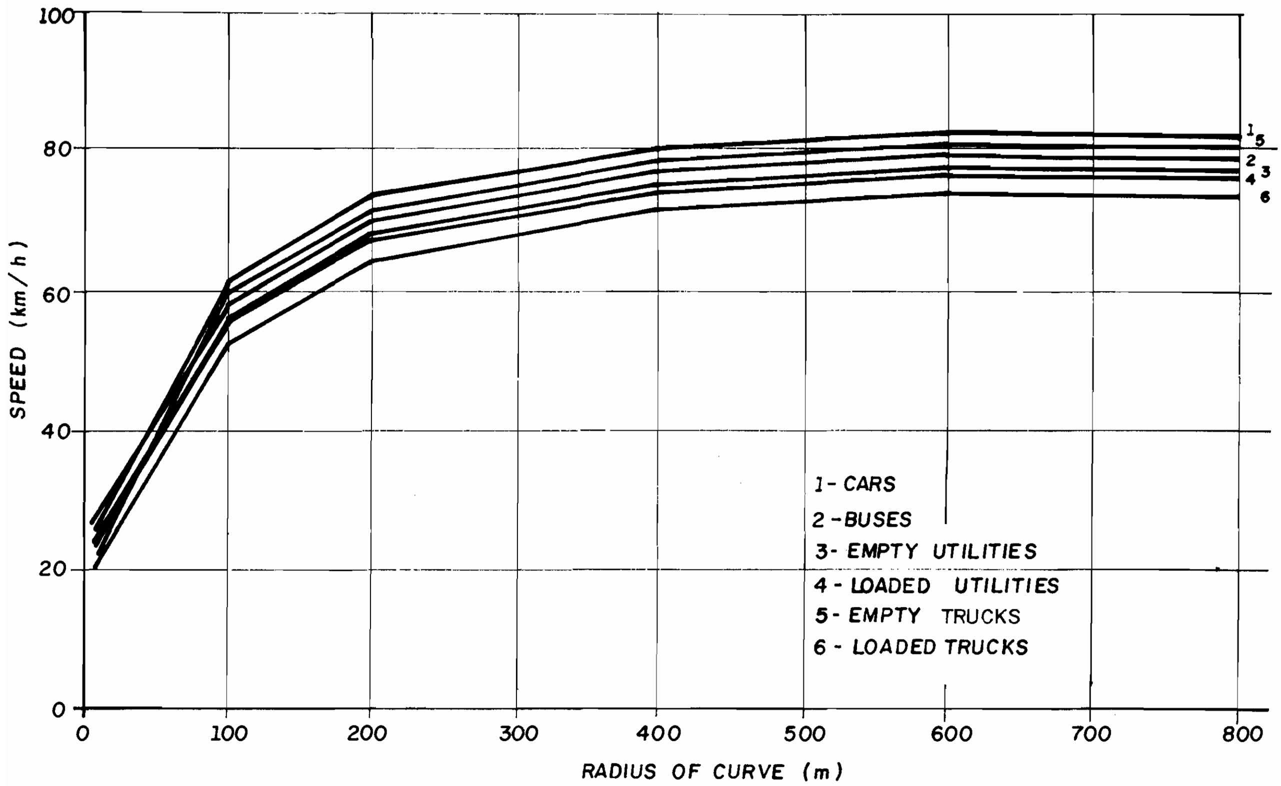
G : percent grade

SE : superelevation, in decimals

R : curve radius, in meters

QI : roughness of riding surface

LEVEL PAVED ROADS WITH ROUGHNESS = 40 QI



LEVEL UNPAVED ROADS WITH ROUGHNESS = 100 QI

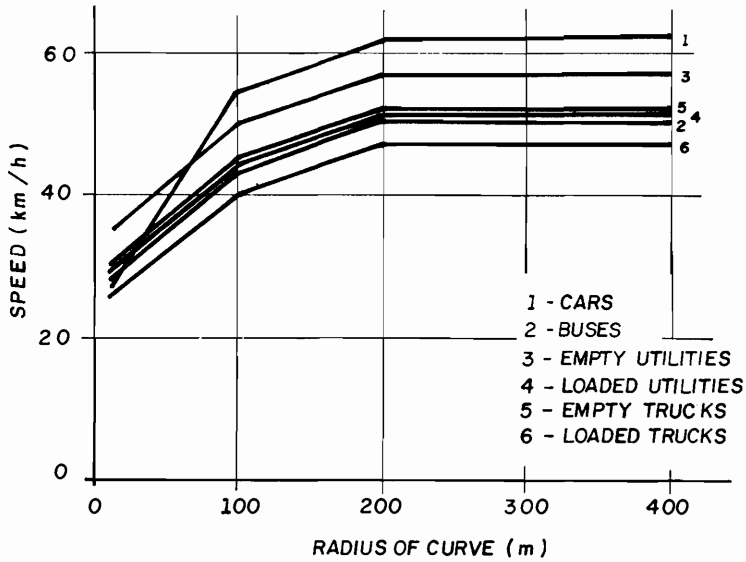


FIGURE 4.3 - SPEED ON CURVES