An Analysis of Speed Changes for Large Transport Trucks

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By means of a force and momentum balance a method was devised for calculating the speed vs distance history of large trucks traversing various types of vertical highway curves at wide-open throttle. The equations that resulted were solved with the aid of electronic computing machines over the following ranges of values of vehicle and highway properties:

Vehicle wt = 30,000 to 72,000 lb;
$\frac{\text{Wt}}{\text{Horsepower}}$ = 200 to 400;
Vehicle speed = 10 to 50 mph;
Highway grade = -8 to + 8 percent;
Vertical curve radius = 2,500 to 20,000 ft; and
Uniform grades.

The results of the calculations are presented as charts relating vehicle speed to distance along the vertical highway curve. A comparison of calculated and experimental values showed satisfactory agreement. Various possible methods of utilizing the charts for highway design or vehicle selection purposes are discussed.

• OF ALL VEHICLES operating on our highways the large transport trucks have the lowest engine power relative to their weight. Hence these vehicles are generally the slowest on upgrades and require the longest distances to accelerate. Realistic design of highway grades and acceleration lanes should be based on the performance of these particular vehicles inasmuch as all others can perform better. This study was undertaken to develop a means of calculating the speed and acceleration properties of large transport trucks on various grades and acceleration lanes.

NOMENCLATURE

The following nomenclature is used:

S = slope of highway, radians;
G = grade of highway, percent;
G_o = grade at the start of a section of highway, percent;
L = horizontal distance along a highway section, ft;
r = radius of curvature of a highway in a vertical plane, ft;
t = time, sec;
t_s = average time required to shift between gears, sec;

g	= gravitational constant, ft per sec per sec;
F_O	= net initial force acting on a truck at the start of a highway section, lb;
F_R	= total rolling resistance force of a truck, lb (includes both tire resistance and air resistance);
F_T	= thrust force on a truck due to engine torque, lb;
v	= truck speed, ft per sec;
v_O	= truck speed at entry to a section of highway, ft per sec;
v_{max}	= maximum truck speed attainable in a particular gear setting as limited by maximum useable engine rpm, ft per sec;
mph	= truck speed, mph; per hour;
(GVW)	= gross vehicle weight, lb;
(BHPW)	= horsepower delivered by the engine to the clutch at wide open throttle
NE	= engine rpm;
NEW	= engine rpm at which BHPW was measured;
R_1	= main transmission gear ratio $= \frac{\text{Engine RPM}}{\text{Transmission output shaft RPM}}$;
R_2	= auxiliary transmission gear ratio $= \frac{\text{Transmission output shaft RPM}}{\text{Auxiliary transmission output shaft RPM}}$;
R_3	= rear axle gear ratio $= \frac{\text{Auxiliary transmission output shaft RPM}}{\text{Drive wheel RPM}}$; and
TF	= tire factor* $= \frac{\text{Drive wheel RPM}}{\text{Truck speed, mph}}$.

FORCE AND MOMENTUM BALANCE

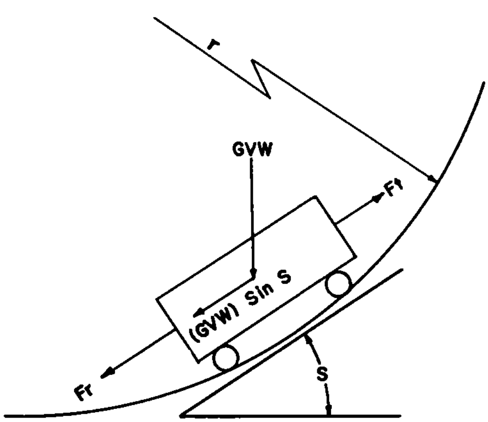

Figure 1. Force diagram of a vehicle on a general section of highway.

Figure 1 shows a vehicle on a general section of highway of slope S and radius of vertical curvature r together with the several forces acting on the vehicle. In general the engine thrust force, F_T, will not always equal the sum of the rolling resistance force, F_R, and the vehicle weight force, (GVW) sin S, and the vehicle will either accelerate if F_T exceeds this sum or decelerate if F_T is less than this sum. From Newton's law the acceleration may be calculated:

$$\frac{(GVW)(dv)}{g\,(dt)} = F_T - F_R - (GVW)\sin S \qquad (1)$$

A solution to this equation provides the desired relation between truck performance, highway geometry, and truck properties.

*For values of TF for various tire sizes, see (1).

The engine thrust force, F_T, must be determined for (a) clutch engaged and engine at wide open throttle, and (b) clutch disengaged while shifting gears. Engine operation at part throttle is not considered here because this means that driver choice, rather than highway geometry, is determining the vehicle performance which is thus indeterminate. Hence the results presented herein are the maximum attainable speed characteristics of a vehicle. A skillful driver will generally achieve these maximum attainable speeds except as limited by traffic congestion, legal speed restrictions, or safe-operating speed limitations.

With the clutch disengaged; F_T is clearly zero. At wide open throttle, F_T may be calculated when the following are known:

1. The horsepower delivered by the engine to the clutch at wide open throttle, BHPW, and the engine RPM at this power output, NEW.
2. The operating gear ratios of the main transmission, R_1, the auxiliary transmission, R_2, and the rear axle, R_3.
3. The drive wheel tire size and tire factor, TF.

Road test methods for measuring the BHPW and NEW of a vehicle are described by Sawhill and Firey (2). The gear ratios and tire size are known for a vehicle or can usually be obtained from the manufacturer.

The value of F_T can then be calculated from the following equation:

$$F_T = \frac{(BHPW)}{(NEW)}(R_1)(R_2)(R_3)(TF)(375) \qquad (2a)$$

Implicit in the use of this equation to calculate F_T is the assumption that engine torque at wide-open throttle is constant over the operating speed range of the engine. Though not strictly correct, this assumption is a reasonable approximation for most unsupercharged commercial truck engines.

The vehicle rolling resistance force, F_R, may be calculated by means of the following equation from (2):

$$F_R = \frac{GVW}{148.5} + 195 \qquad (2b)$$

This total rolling resistance force equation was based on coasting tests of several large transport trucks and, as discussed in (2), is subject to the limitations of these experimental data. For significant upgrades generally the precision of Eq. 2 for F_R is not too important because the major resistance to vehicle motion is then the vehicle weight force, (GVW) sin S.

On the general section of highway shown in Figure 1 the slope, S, of the highway may vary with the distance, L, along the grade; and thus, S may be a function of time, t. For circular vertical highway curves the simple approximate relation, shown on Figure 2, exists between curve radius, r, distance, L, and slope, S.

$$S = S_O + \frac{L}{r} = \sin S \qquad (3)$$

The approximation that sin S equals S is accurate to within 0.2 percent for highway grades of 10 percent or less. The sign convention for Eq. 3 is as follows:

1. Distance, L, is positive in the direction of vehicle motion.
2. For concave upward curves (i.e., sag curves), r is positive and S increases with L.

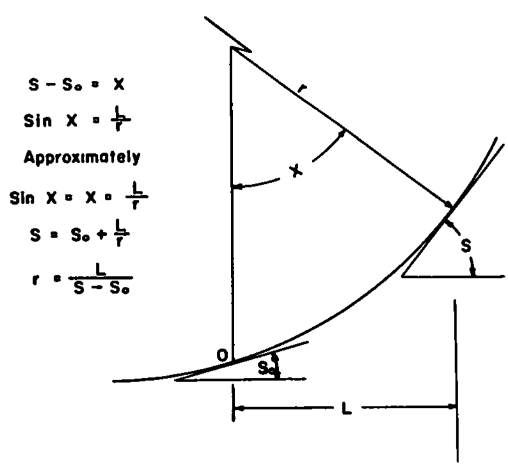

Figure 2. Relation between slope and distance for circular vertical highway curves.

3. For convex upward curves (i.e., summit curves), r is negative and S decreases with L.

4. Slope, S, is positive for upgrades and negative for downgrades.

Real vertical highway curves are not simple circles but can be adequately approximated as such without introducing appreciable error for highways of less than about 10 percent maximum grade. To determine the equivalent radius of a real vertical curve only the entering and leaving slopes and the horizontal distance between them need be known, as shown in Figure 2. The following equations are approximately correct for small angles.

$$r = \frac{L_o}{S_1 - S_2} \tag{4}$$

In highway design, slope is most commonly expressed as percent grade, G, rather than in radians. The following equations are expressed in terms of G:

$$G = 100S \tag{5a}$$

$$G = G_o + \frac{100L}{r} \tag{5b}$$

$$r = \frac{100L_o}{G_1 - G_2} \tag{5c}$$

$$(GVW) \sin S = (GVW)\, S = \frac{(GVW)G_o}{100} + \frac{(GVW)\, L}{r} \tag{5d}$$

Distance, L, along the highway is related to vehicle velocity, v, and time, t, as follows:

$$v = \frac{dL}{dt} \quad \frac{dv}{dt} = \frac{d^2L}{dt^2} \tag{6}$$

The force and momentum balance equation for a vehicle operating on a general section of highway with the clutch engaged and the throttle wide open now becomes:

$$\frac{GVW(d^2L)}{g\ (dt^2)} = \frac{(BHPW)}{(NEW)}(R_1)(R_2)(R_3)(TF)(375) - \frac{GVW}{148.5} - 195 - \frac{(GVW)G_o}{100} - \frac{(GVW)L}{r} \tag{7}$$

With the clutch disengaged during gear shifting the equation becomes

$$\frac{GVW(d^2L)}{g\ (dt^2)} = -\frac{GVW}{148.5} - 195 - \frac{(GVW)G_o}{100} - \frac{(GVW)L}{r} \tag{8}$$

These differential equations provide a mathematical relation between distance and time inasmuch as all other factors are constant for a particular vehicle in a particular gear and on a particular vertical curve. The vehicle may be presumed to enter the section of highway at initial velocity v_o when L = O and t = 0. Under these conditions the solution of Eq. 5, 6, 7, and 8 takes the forms of

$$L = \frac{(F_o r)}{(GVW)} - \frac{(F_o r)}{(GVW)}\cos\sqrt{\frac{g}{r}}\,t + \frac{v_o}{\sqrt{g/r}}\sin\sqrt{\frac{g}{r}}\,t \tag{9}$$

$$V = V_o \mathrm{Cos} - \sqrt{\frac{g}{r}}\,t + \frac{(F_o r)}{(GVW)}\sqrt{\frac{g}{r}}\sin\sqrt{\frac{g}{r}}\,t \tag{10}$$

The net initial force, F_o, acting on the vehicle at the start of the highway section is defined by the following relations. At wide open throttle:

$$F_O = \frac{(BHPW)}{(NEW)}(R_1)(R_2)(R_3)(TF)(375) - \frac{GVW}{148.5} - 195 - \frac{(GVW)G_O}{100} \qquad (11)$$

With the clutch disengaged:

$$F_O = - \frac{GVW}{148.5} - 195 - \frac{(GVW)G_O}{100} \qquad (12)$$

METHOD OF CALCULATION

The preceding vehicle motion relations are not handy to use for highway design inasmuch as many different motion equations apply even to a single section of highway. These many equations result from the wide variation in truck design and operation. To put the force and momentum balance equations into a potentially useful form, certain assumptions were found necessary.

On many vertical highway curves, the driver of a large transport truck will change gears several times. With each gear change the value of F_O at wide-open throttle changes and the equation of vehicle motion is altered. On a general section of highway the value of G_O may also change for each gear setting. Thus, on a vertical curve requiring five gear changes, ten different vehicle motion equations may apply to a particular vehicle.

Available to the purchaser of a large transport truck are a wide selection of main transmissions, auxiliary transmissions, and rear axles, and an even wider selection of gear ratios and number of gear settings. The result has been that there is no such thing as "typical" or "standard" gearing in these trucks, each being geared for the needs of the purchaser at the time of ordering. Hence for a selected vertical highway curve, each truck will have its own set of vehicle motion equations.

The weight of a particular truck may vary between the empty weight and the maximum legal weight depending on the type of cargo being carried and the availability of cargo for particular sections of highway.

The total number of equations to be considered by the highway designer has a minimum value equal to the sum, for all vertical curves on the highway, of the product of the number of large transport trucks using the highway and about twice the number of gear changes required. With so many equations, useful calculations become tedious.

To reduce the complexity introduced by these variations the following assumptions were made:

1. Only those trucks were considered whose properties lay within the following ranges:

$$\frac{GVW}{BHPW} = 200 \text{ to } 400;$$

$$GVW = 30{,}000 \text{ to } 70{,}000 \text{ lb; and}$$

$$mph = 10 \text{ to } 50.$$

2. The ratio of minimum to maximum useable engine rpm was assumed to be 0.80.
3. Only those sections of highway were considered whose geometry lay within the following ranges:

$$G = -8 \text{ to } +8 \text{ percent; and}$$
$$r = 2{,}500 \text{ to } 20{,}000 \text{ ft or } r = \text{infinity.}$$

The vehicle properties limitations do not appear serious because the majority of large transport trucks are included except when empty or very lightly loaded. In this latter condition these trucks are not usually a highway design limitation. Although it would be desirable to include speeds up to 60 or 70 mph, the rolling resistance data available did not extend beyond 50 mph. In general, large transport trucks reach speeds in excess of 50 mph only on nearly level or downhill sections of highway where the principal force opposing vehicle motion is the rolling resistance force, F_R. Hence, to obtain useful results in this higher speed range, reliable data on F_R above 50 mph are required.

The useable engine speed ratio of 0.80 was selected as the average value for the several vehicles described in (1) for which this ratio varied from 0.67 to 0.86.

The highway geometry limitations do not appear serious because modern highways generally lie well within the indicated ranges.

The equation for the engine thrust force, F_T, was modified to eliminate the specific vehicle gear ratios and tire factor:

$$v = \frac{1,465(NE)}{R_1 R_2 R_3 (TF)} \tag{13a}$$

$$v_{max} = \frac{1,465\ (NEW)}{R_1 R_2 R_3 (TF)} = \text{maximum vehicle speed attainable in the gear setting, } R_1,\ R_2,\ R_3. \tag{13b}$$

$$F_T = \frac{(BHPW)}{(v_{max})} 550 \tag{13c}$$

The detailed steps to calculate the velocity vs distance history of a selected vehicle on a selected vertical curve were as follows:

1. Specific values of the following were assumed; GVW, $\frac{GVW}{BHPW}$, initial G_o, initial v_o, r.

2. On vertical curves causing the vehicle to slow down (deceleration curves) v_{max} equals v_o. On vertical curves causing the vehicle to speed up (acceleration curves) v_{max} was assumed equal to $(v_o/0.8)$.

3. The vehicle motion equations for wide-open throttle were solved for values of distance, L, and velocity, v, as a function of time, t, from which v could be determined as a function of L.

4. On deceleration curves the first gear shift was assumed to occur when v reached the value 0.8 v_o. On acceleration curves the first gear shift was assumed to occur when v reached the value $v_o/0.8$.

5. The truck was assumed to follow the vehicle motion equations for clutch disengaged during the gear shift time interval, t_s. An average measured value for t_s of 2 sec was obtained from (1). The values of v_o and G_o for the gear shift interval were the terminal values for the preceding wide-open throttle period (step 4).

6. Steps 2 and 3 were repeated using the vehicle motion equations for clutch disengaged for the time interval t_s.

7. For the second wide-open throttle period steps 2, 3, and 4 were repeated with values of v_o and G_o obtained from the terminal condition of the preceding clutch disengaged period (step 6).

8. The foregoing calculations were repeated through each gear until v reached the value of 10 mph on deceleration curves or the value of 50 mph on acceleration curves, or the end of the curve (G = ± 8 percent) was reached.

9. For the special case of uniform grades (r = infinity) the vehicle motion equations become

$$L = v_o t + \frac{F_o g}{GVW} \frac{t^2}{2} \tag{14a}$$

$$v = v_o + \frac{F_o g}{GVW} t \tag{14b}$$

10. For uniform grades steps 1 through 8 were carried out with the additional limit of reaching maximum sustained speed, v_{max}. Maximum sustained speeds occur only on upgrades when the net initial force acting on the vehicle, F_o becomes zero. Thereafter the vehicle velocity cannot change on a uniform grade.

As the calculations progressed it was found possible to make a further simplification by using only an average value of vehicle weight, GVW = 50,000 lb. For a particular value of vehicle weight to horsepower ratio, $\frac{GVW}{BHPW}$, the value of $\frac{F_o}{GVW}$ was found to vary only slightly with GVW within the range of GVW of 30,000 to 70,000 lb. As an indication of the magnitude of error introduced by this assumption maximum sustained speeds on grades in excess of 2 percent were within less than 6 percent of the approximate value within the preceding vehicle weight range.

An actual graph of vehicle velocity vs distance along an upgrade will have steps due to the shifting of gears, as shown in Figure 3. In these calculations the assumed usable engine speed ratio of 0.80 determined the locations of the shift points which may not correspond to any real vehicle. Accordingly only the smoothed curves, rather than the stepped curves, were used.

The detailed calculations were carried out with the aid of an IBM 610 computing machine which greatly reduced the tedium of the work.

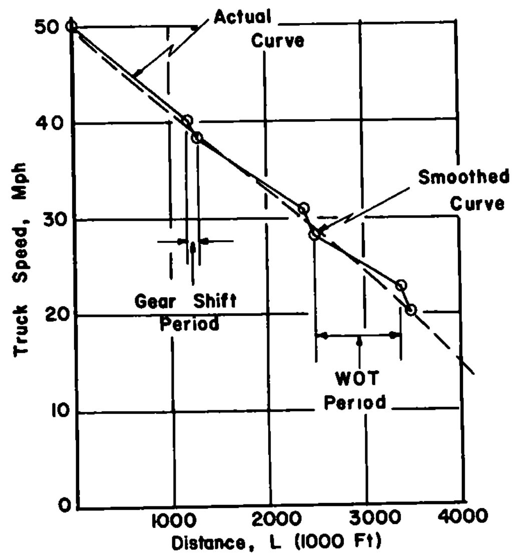

Figure 3. Example of truck speed vs distance history on an upgrade.

RESULTS AND COMPARISON WITH EXPERIMENT

The results of the foregoing calculations are shown in chart form in Figures 4 through 28 as follows:

1. Figures 4 through 6 inclusive show vehicle velocity vs distance on uniform upgrades for values of $\frac{GVW}{BHPW}$ of 400, 300, and 200 for an entering velocity of 50 mph.
2. Figures 7 through 9 inclusive show vehicle velocity vs distance on uniform downgrades for values of $\frac{GVW}{BHPW}$ of 400, 300, and 200 for an entering velocity of 10 mph.

For uniform grades when the entering velocity is other than 10 or 50 mph, the curves of items 1 or 2 are used by shifting the zero distance point to the actual entering velocity.

3. Figures 10 through 12 inclusive show vehicle velocity vs distance on circular vertical sag curves for values of $\frac{GVW}{BHPW}$ of 400, 300, and 200 for entering velocities of 30, 40, and 50 mph, and for curve radii of 2,500, 5,000, 10,000, 15,000, and 20,000 ft.
4. Figures 13 through 15 inclusive show vehicle velocity vs distance on circular vertical summit curves of radii, 2,500, 5,000, 10,000, 15,000 and 20,000 ft for a value of $\frac{GVW}{BHPW}$ of 400, and for entering velocities of 10, 20, 30, 40, and 50 mph.
5. Figures 16 through 18 inclusive are identical to item 4 except the value of $\frac{GVW}{BHPW}$ is 300.
6. Figures 19 through 21 inclusive are identical to item 4 except the value of $\frac{GVW}{BHPW}$ is 200.
7. Figures 22 through 24 inclusive show vehicle travel time vs distance on uniform upgrades for values of $\frac{GVW}{BHPW}$ of 400, 300, and 200 for an entering velocity of 50 mph.

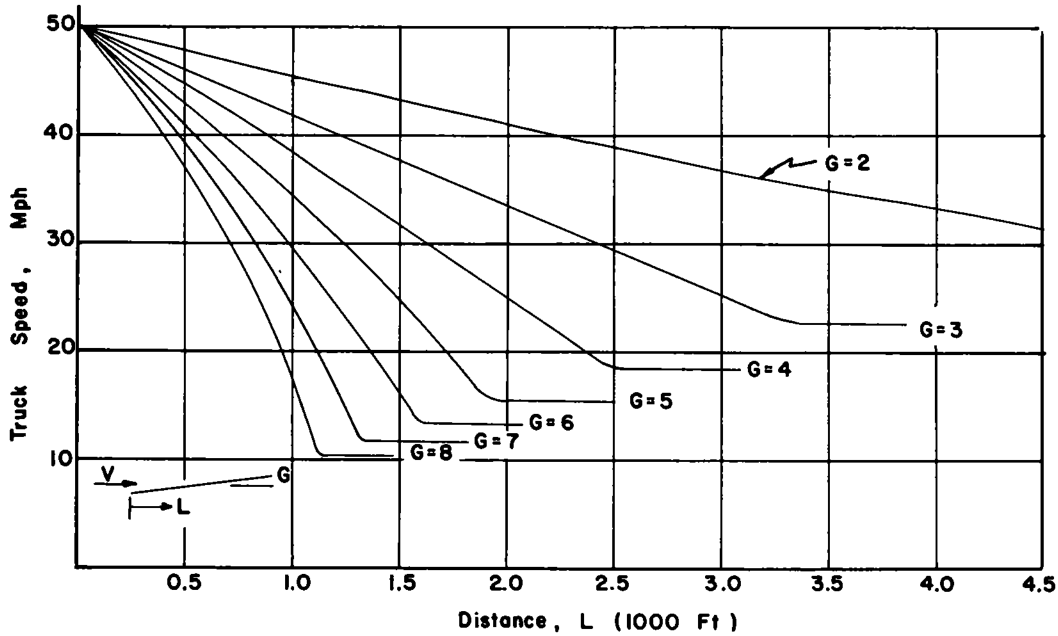

Figure 4. Velocity vs distance chart on uniform upgrades for trucks with GVW/BHPW = 400 and an entering speed of 50 mph.

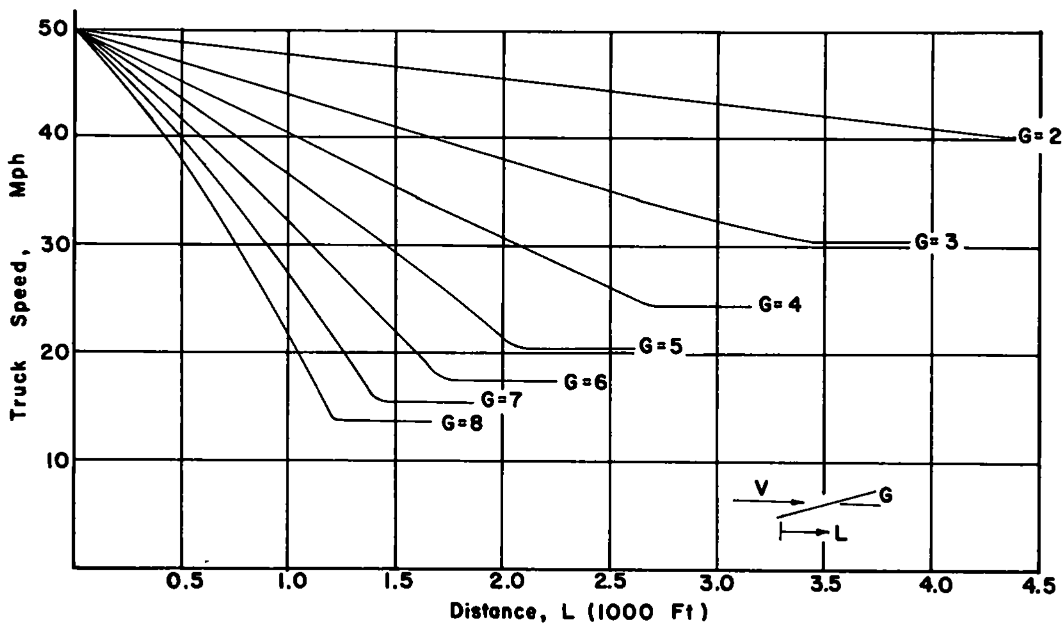

Figure 5. Velocity vs distance chart on uniform upgrades for trucks with GVW/BHPW = 300 and an entering speed of 50 mph.

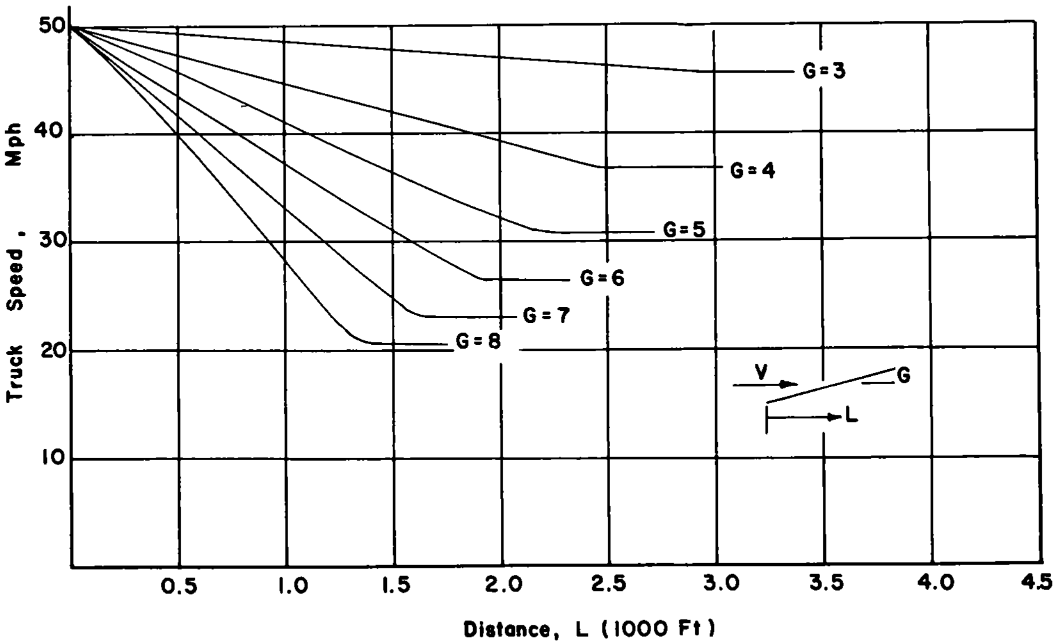

Figure 6. Velocity vs distance chart on uniform upgrades for trucks with GVW/BHPW = 200 and an entering speed of 50 mph.

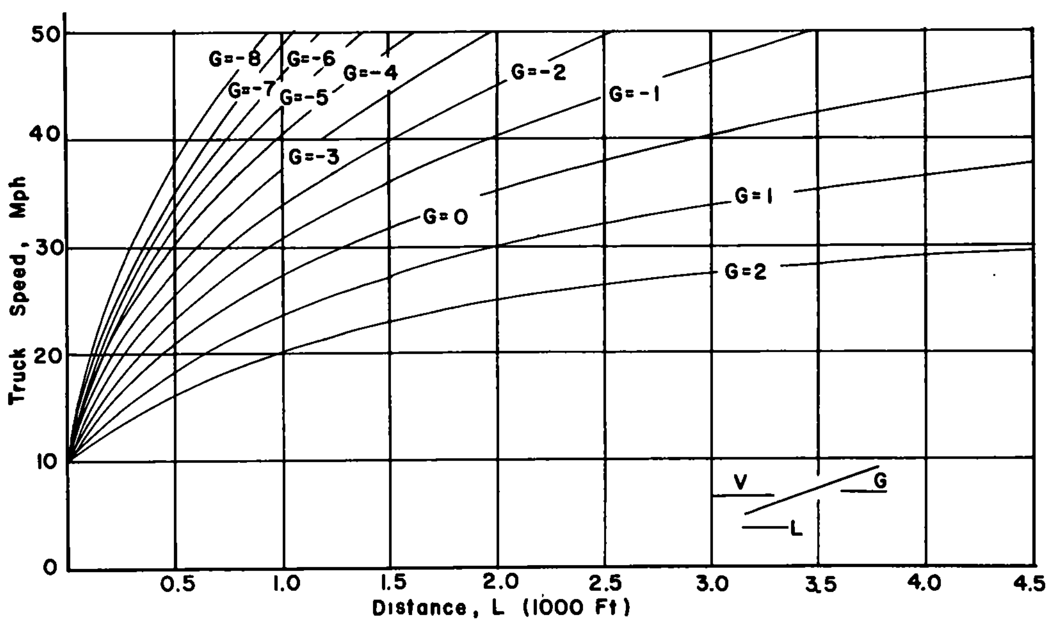

Figure 7. Velocity vs distance chart on uniform downgrades for trucks with GVW/BHPW = 400 and an entering speed of 10 mph.

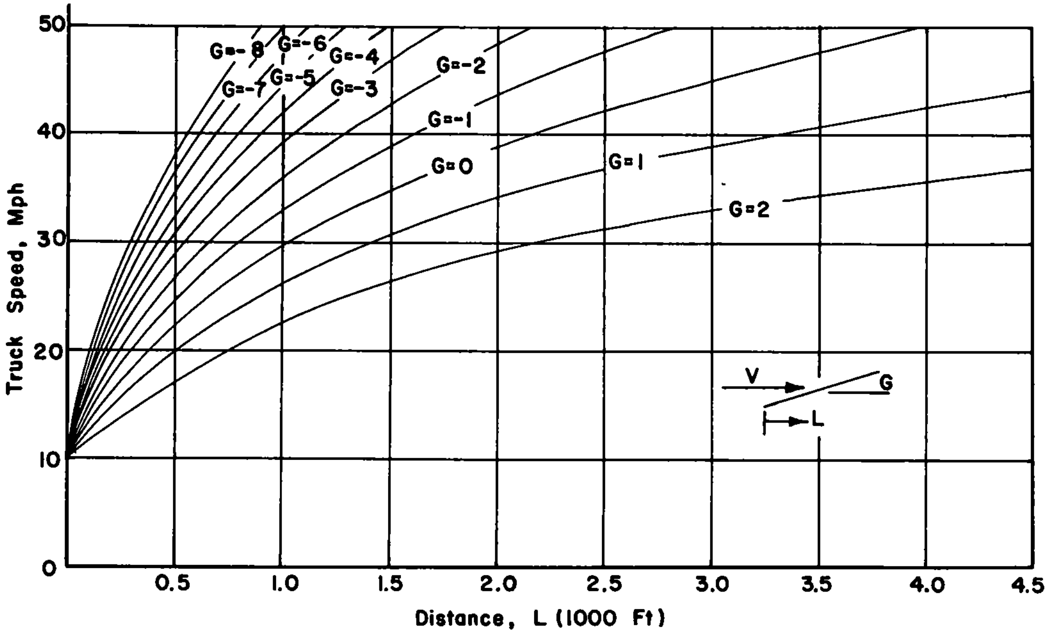

Figure 8. Velocity vs distance chart on uniform downgrades for trucks with GVW/BHPW = 300 and an entering speed of 10 mph.

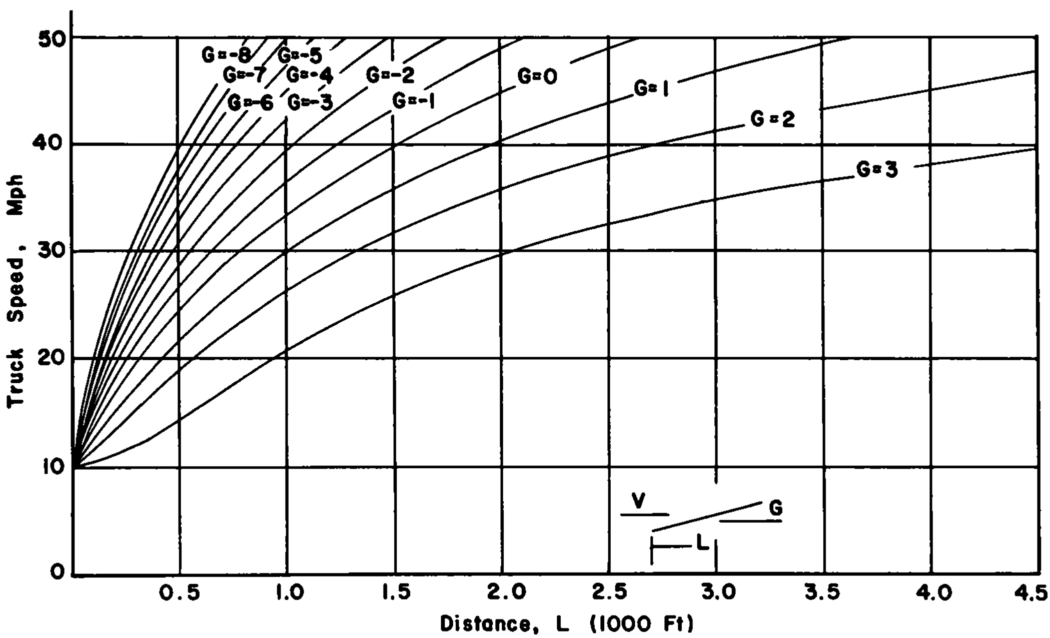

Figure 9. Velocity vs distance chart on uniform downgrades for trucks with GVW/BHPW = 200 and an entering speed of 10 mph.

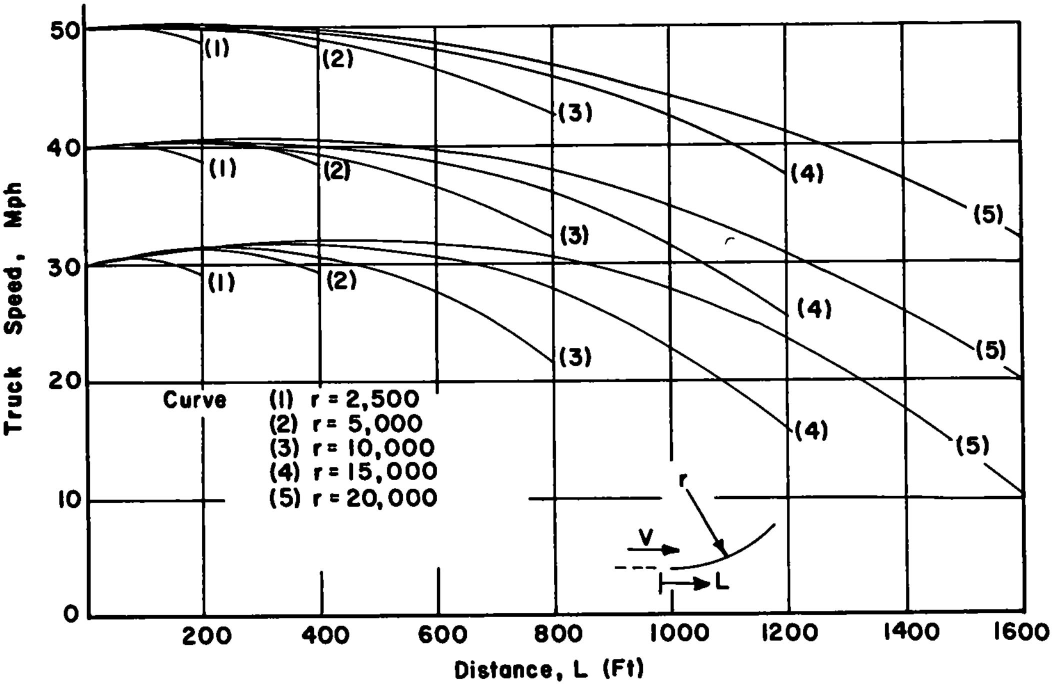

Figure 10. Velocity vs distance chart on vertical sag curves for trucks with GVW/BHPW = 400.

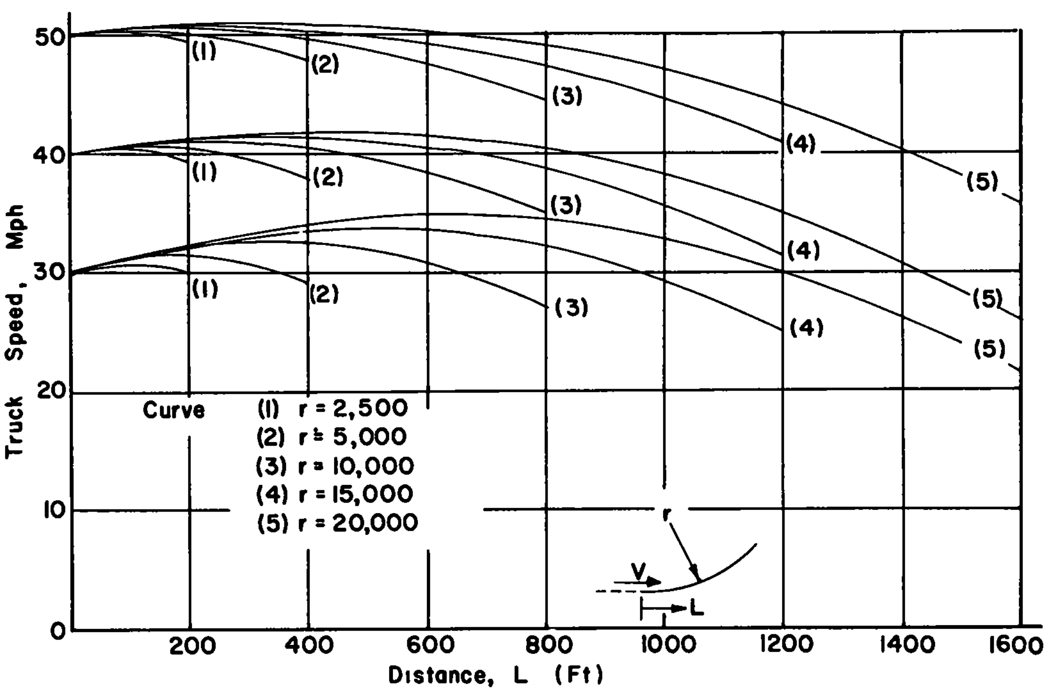

Figure 11. Velocity vs distance chart on vertical sag curves for trucks with GVW/BHPW = 300.

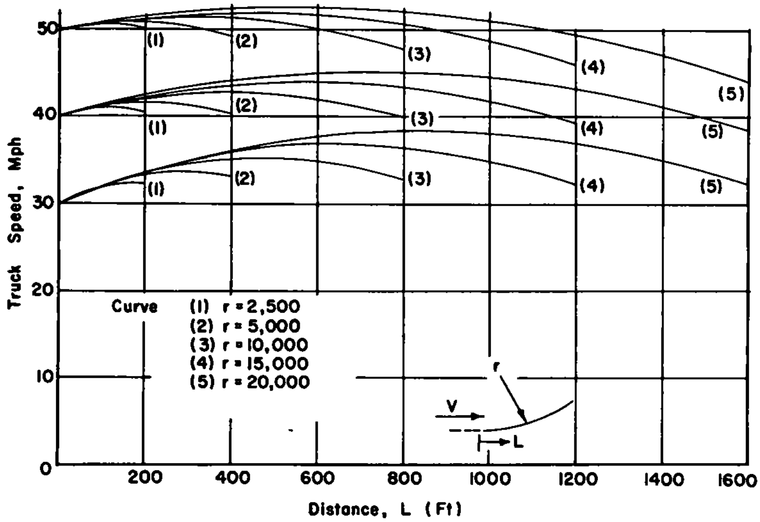

Figure 12. Velocity vs distance chart on vertical sag curves for trucks with GVW/BHPW = 200.

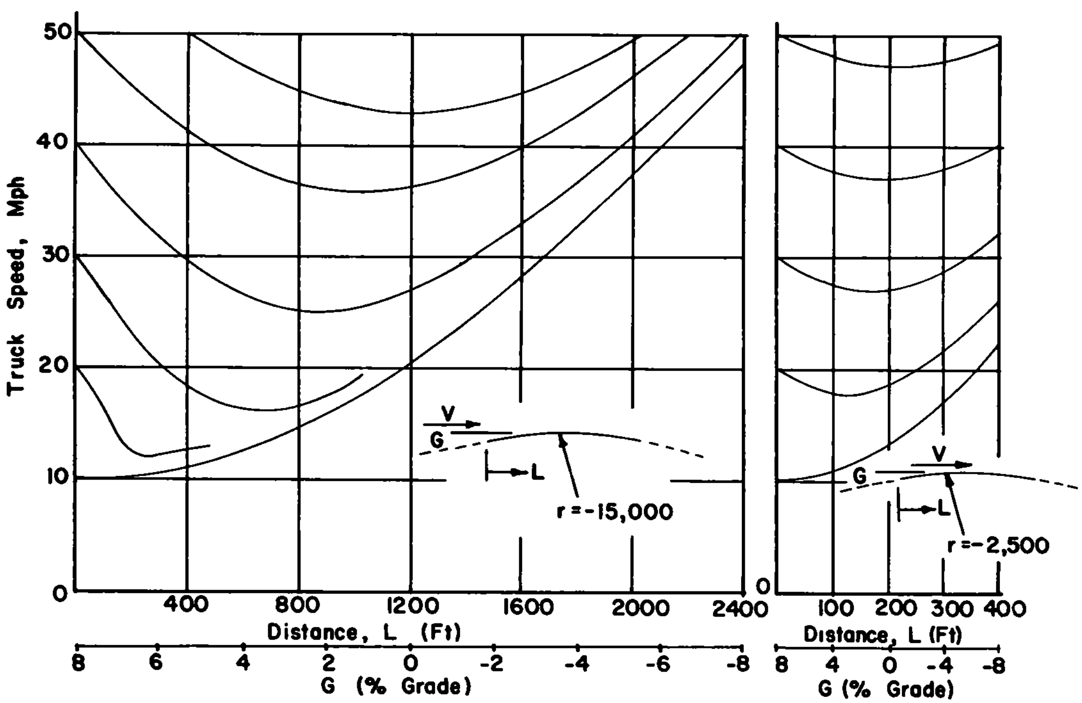

Figure 13. Velocity vs distance chart on vertical summit curves for trucks with GVW/BHPW = 400 and curve radii of 2,500 and 15,000 ft.

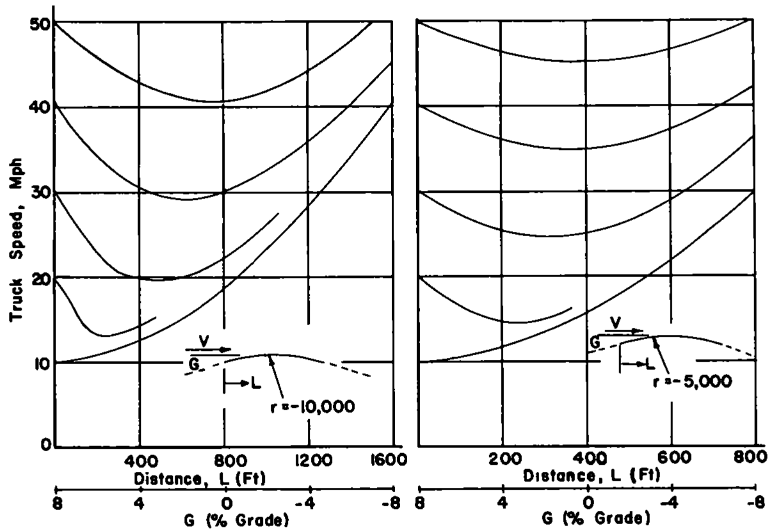

Figure 14. Velocity vs distance chart on vertical summit curves for trucks with GVW/BHPW = 400 and curve radii of 5,000 and 10,000 ft.

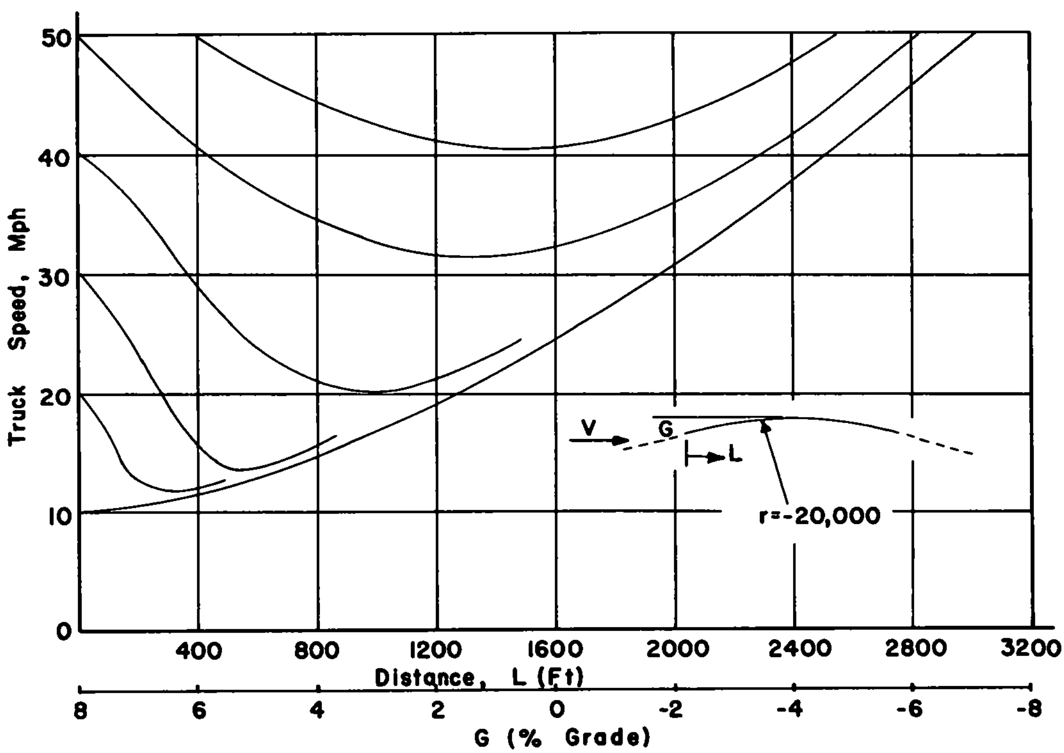

Figure 15. Velocity vs distance chart on vertical summit curves for trucks with GVW/BHPW = 400 and curve radius of 20,000 ft.

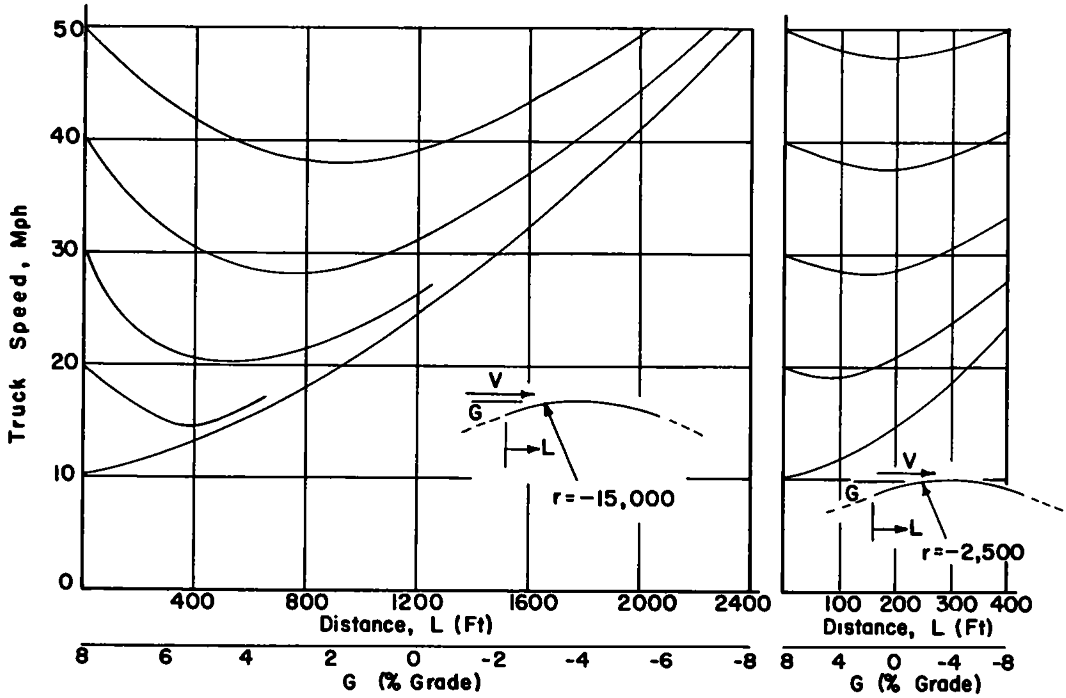

Figure 16. Velocity vs distance chart on vertical summit curves for trucks with GVW/BHPW = 300 and curve radii of 2,500 and 15,000 ft.

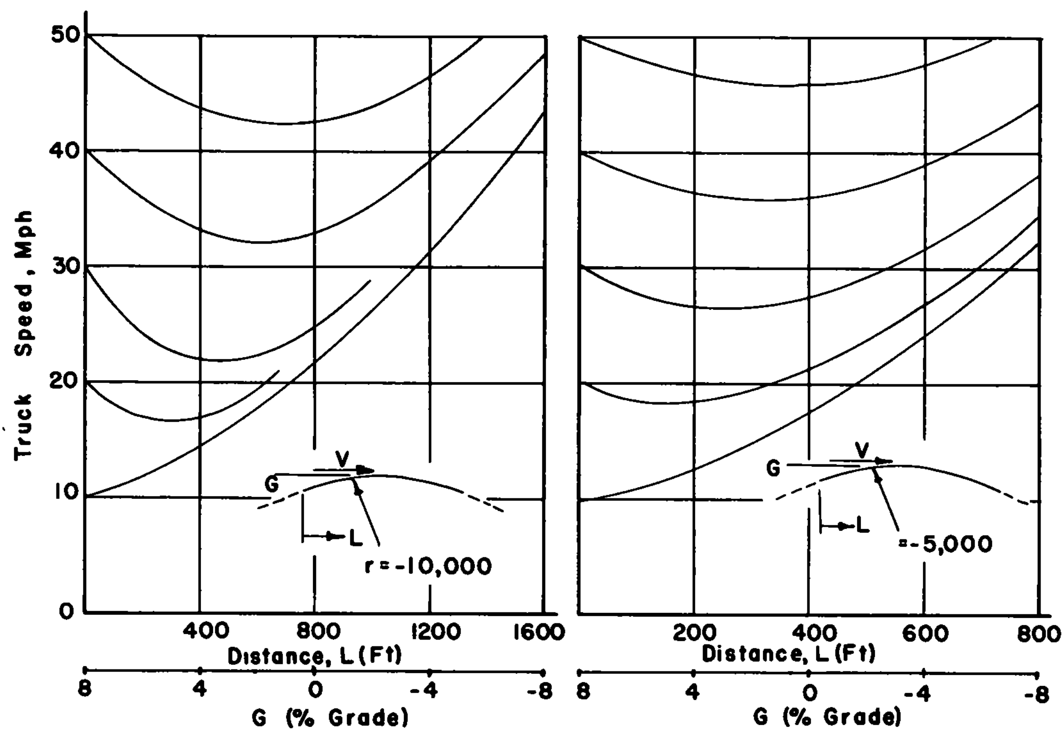

Figure 17. Velocity vs distance chart on vertical summit curves for trucks with GVW/BHPW = 300 and curve radii of 5,000 and 10,000 ft.

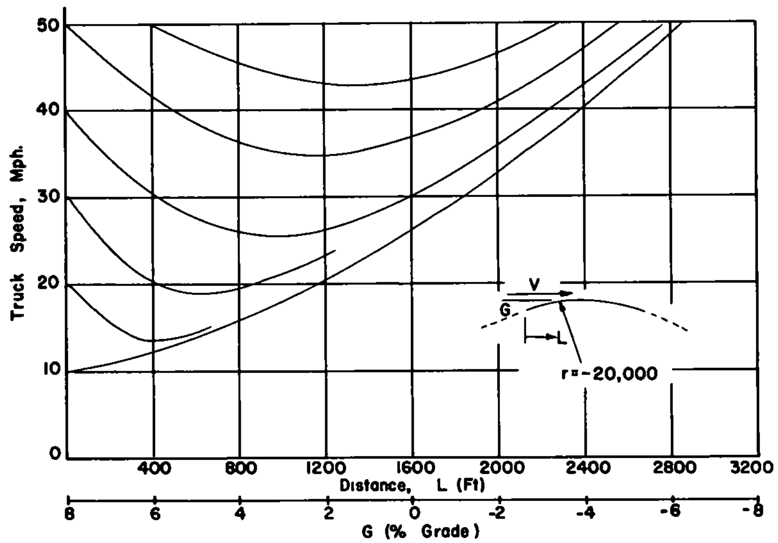

Figure 18. Velocity vs distance chart on vertical summit curves for trucks with GVW/BHPW = 300 and a curve radius of 20,000 ft.

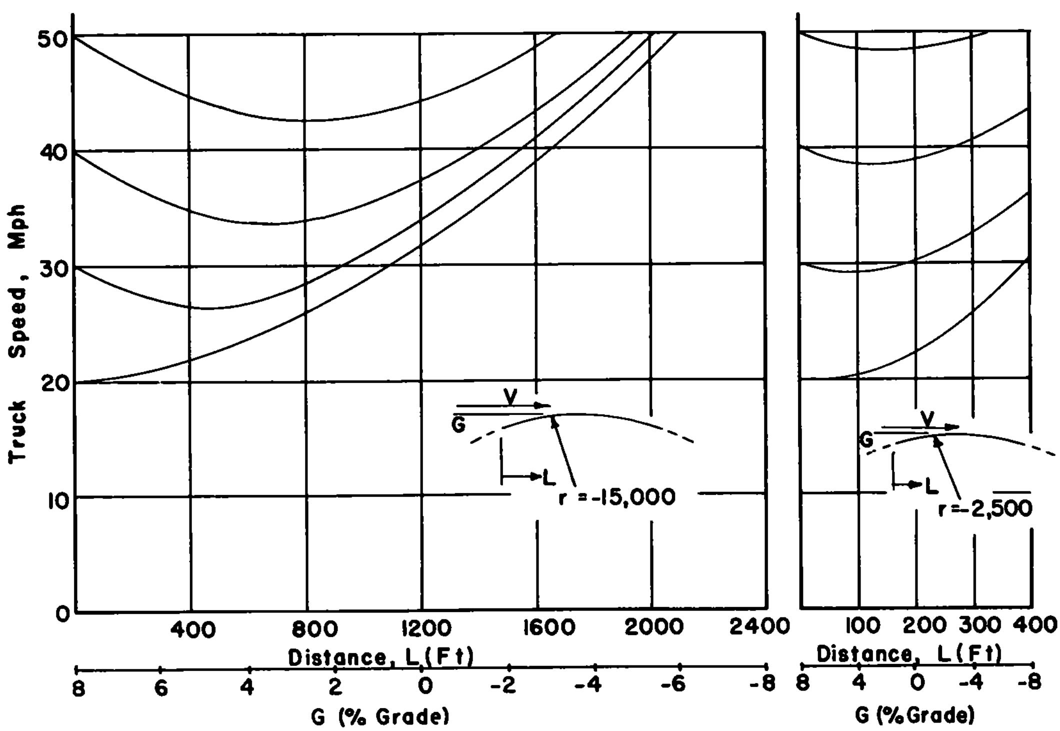

Figure 19. Velocity vs distance chart on vertical summit curves for trucks with GVW/BHPW = 200 and curve radii of 2,500 and 15,000 ft.

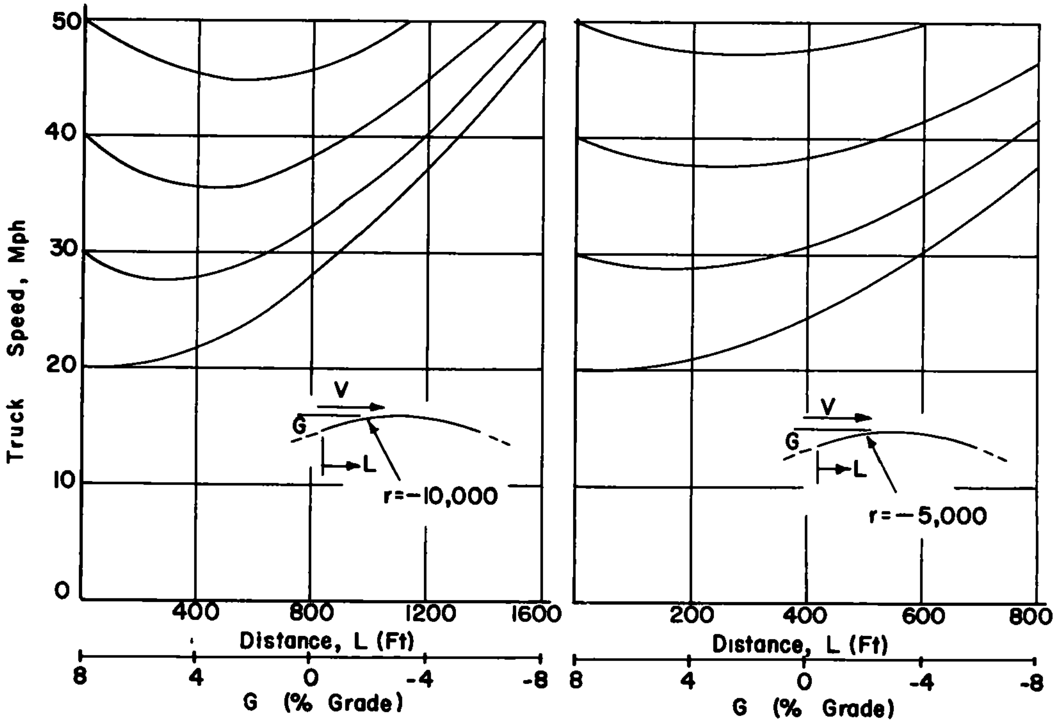

Figure 20. Velocity vs distance chart on vertical summit curves for trucks with GVW/BHPW = 200 and curve radii of 5,000 and 10,000 ft.

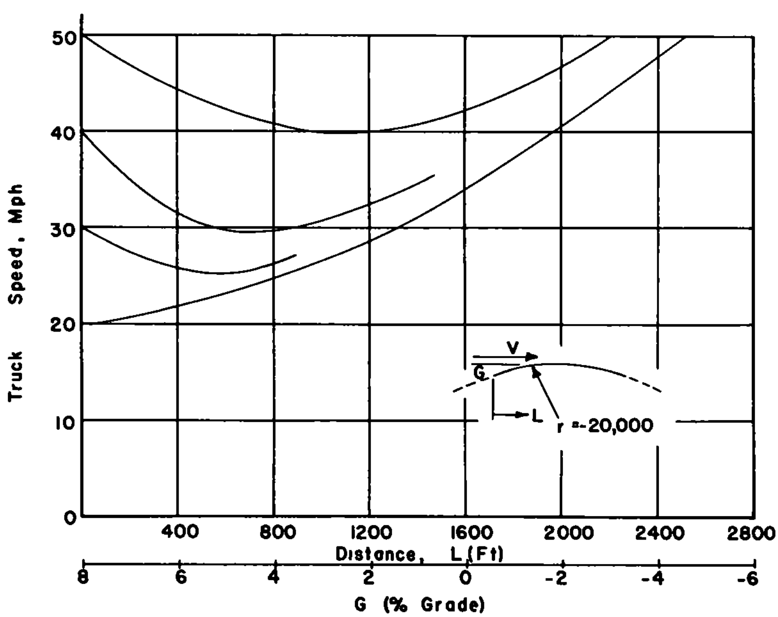

Figure 21. Velocity vs distance chart on vertical summit curves for trucks with GVW/BHPW = 200 and a curve radius of 20,000 ft.

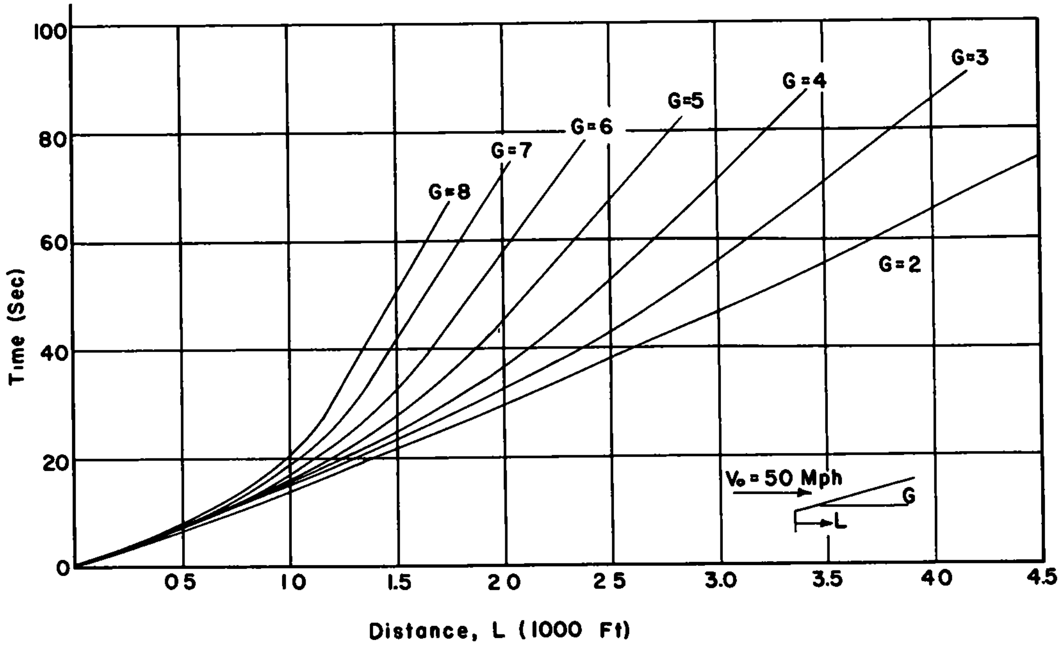

Figure 22. Travel time vs distance chart on uniform upgrades for trucks with GVW/BHPW = 400.

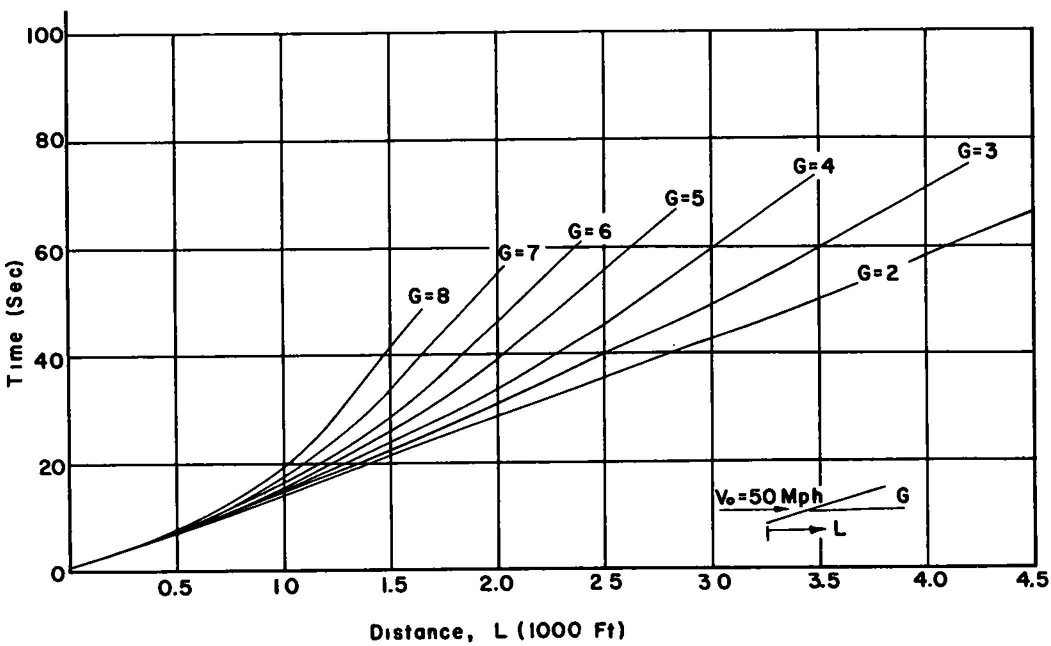

Figure 23. Travel time vs distance chart on uniform upgrades for trucks with GVW/BHPW = 300.

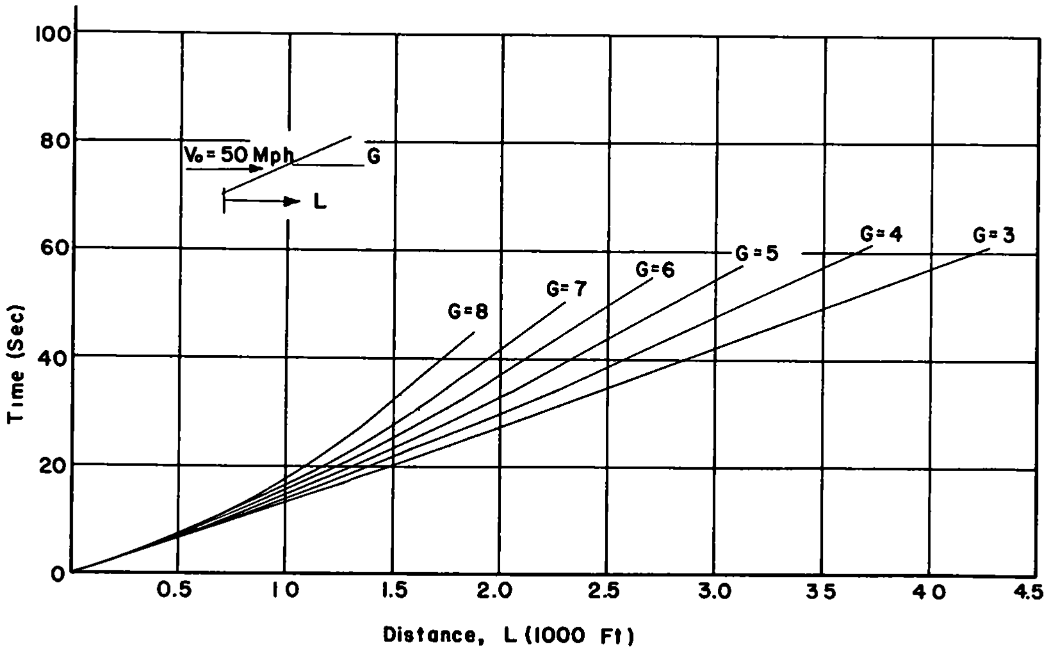

Figure 24. Travel time vs distance chart on uniform upgrades for trucks with GVW/BHPW = 200.

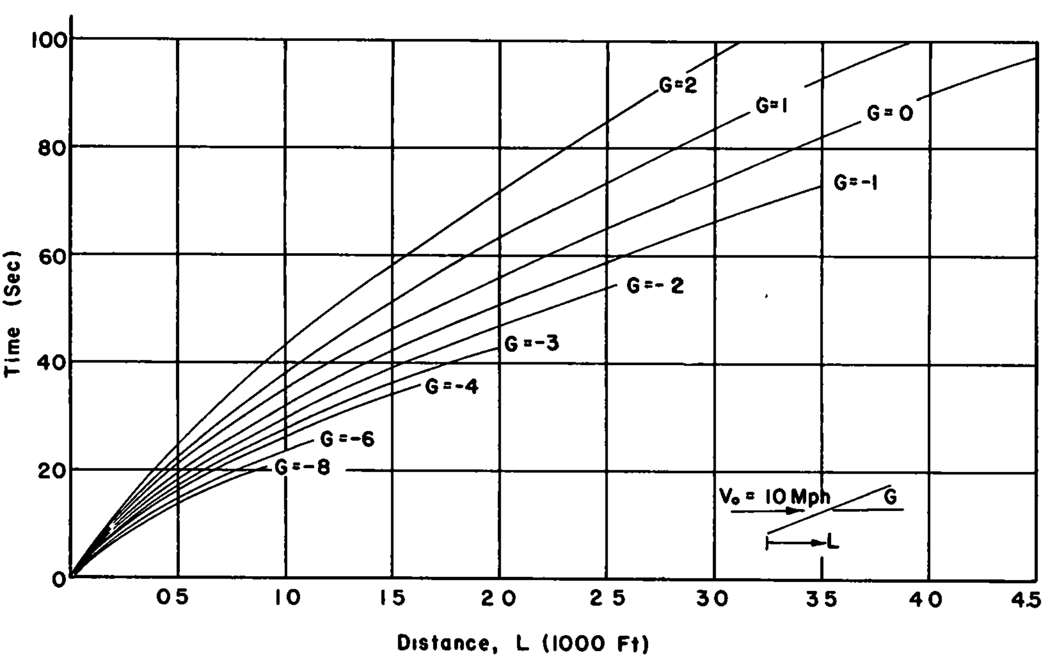

Figure 25. Travel time vs distance chart on uniform downgrades for trucks with GVW/BHPW = 400.

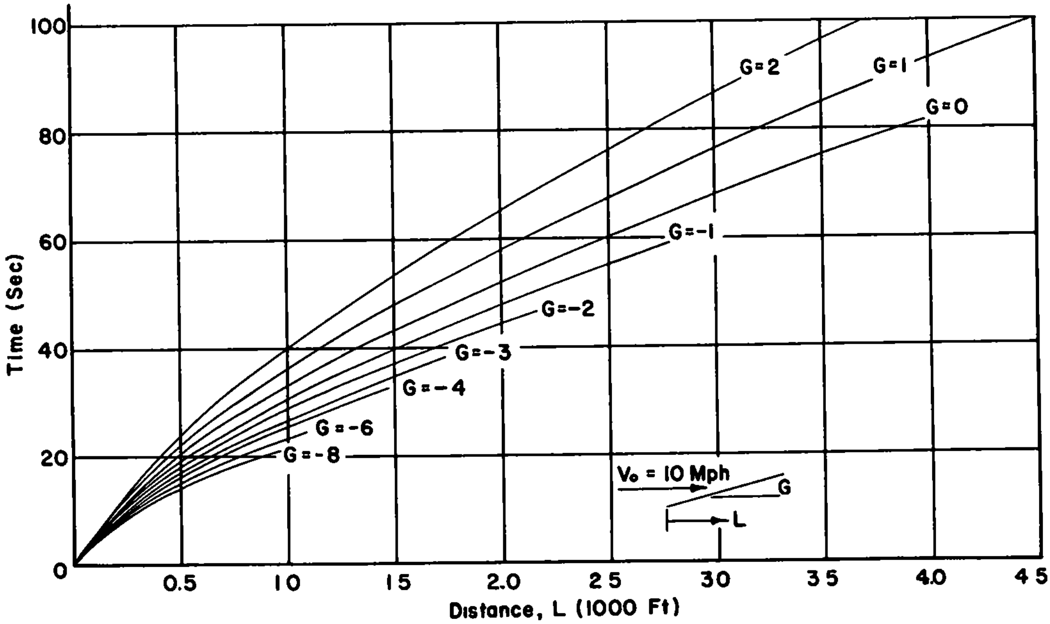

Figure 26. Travel time vs distance chart on uniform downgrades for trucks with GVW/BHPW = 300.

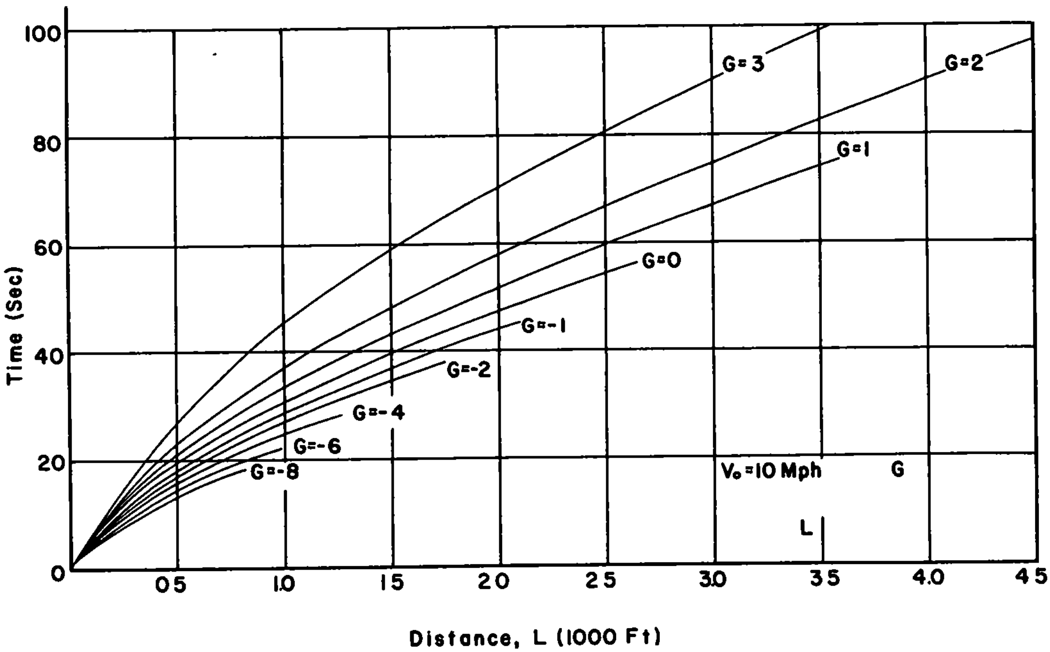

Figure 27. Travel time vs distance chart on uniform downgrades for trucks with GVW/BHPW = 200.

8. Figures 25 through 27 inclusive show vehicle travel time vs distance on uniform downgrades for values of $\frac{GVW}{BHPW}$ of 400, 300, and 200 for an entering velocity of 10 mph.

For uniform grades when the entering velocity is other than 10 or 50 mph the curves of items 7 and 8 are used by shifting the zero distance and time point to the distance for the actual entering velocity as obtained from the curves of items 1 or 2.

9. Figure 28 shows theoretical maximum sustained speed of a vehicle vs highway grade for vàlues of $\frac{GVW}{BHPW}$ or 400, 300, and 200.

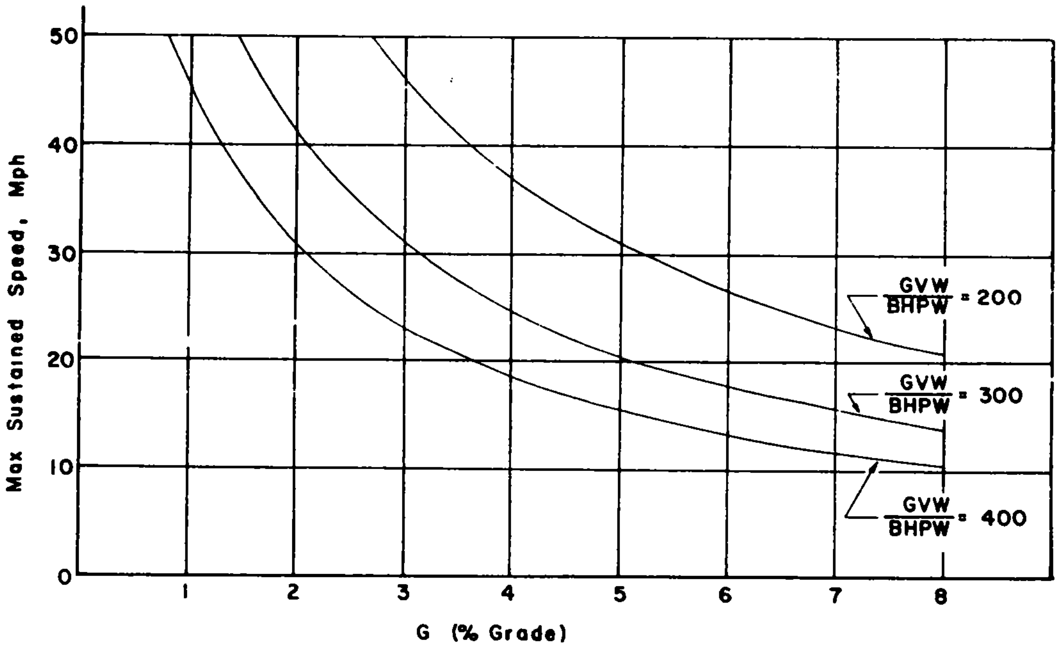

Figure 28. Effect of uniform grade on theoretical maximum sustained speeds of trucks.

To investigate whether the preceding calculated results bear any relation to the actual behavior of real trucks on real highways, several trucks were run over vertical highway curves and the speed vs time and distance history recorded. The properties of the truck were measured by the methods described in (1). The geometry of the vertical highway curve was obtained from surveys of the Washington State Highway Department. A comparison was then made between these measured results and the corresponding calculated results. An example of such a comparison is shown in Figure 29 for a sag curve and in Figure 30 for a summit curve. Comparisons of this type were carried out within the following ranges of values of vehicle and highway properties:

$\frac{GVW}{BHPW}$	= 200 to 400;
GVW	= 27,000 to 66,000 lb;
mph	= 10 to 50;
G	= + 6 to -6 percent;
r	= 15,000 to 18,333 ft; and
r	= infinity.

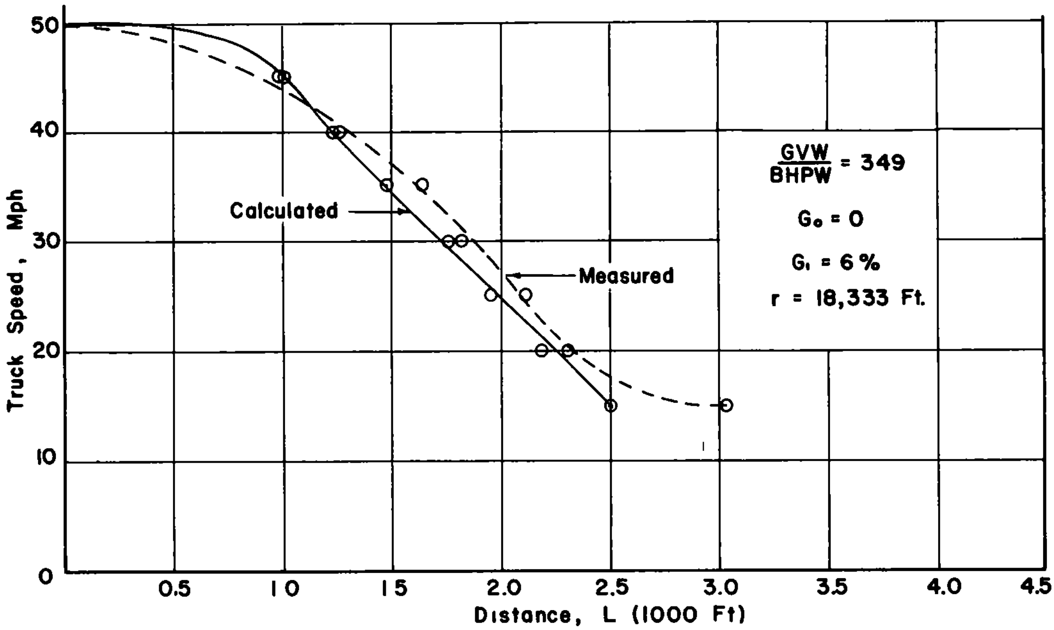

Figure 29. Comparison of calculated and measured truck velocity profiles on a sag curve.

The details of these experiments are given by Sawhill and Firey (3).

The results of these comparisons are summarized in Figure 31 showing the relation between calculated vehicle velocity and measured vehicle velocity. The calculated values are seen to agree satisfactorily with the measured values. In every case where the calculated and measured values disagreed by more than 2 mph the cause was traced to one of the following circumstances:

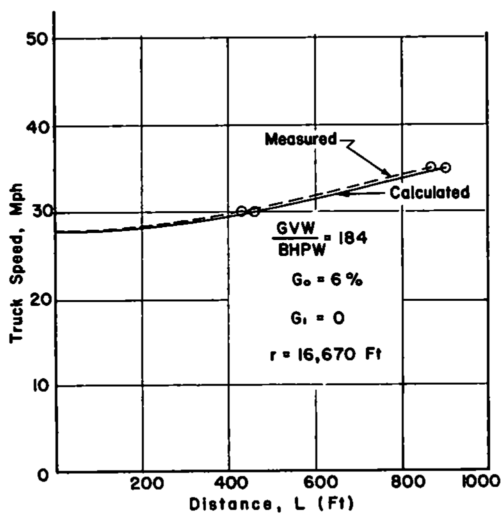

Figure 30. Comparison of calculated and measured truck velocity profiles on a summit curve.

1. In some of the sag curve experiments, the driver did not open the throttle wide until discernible deceleration occurred. The calculations necessarily assumed wide-open throttle to exist at the start of the curve, and in many cases the vehicle would then accelerate briefly until an appreciable grade exists.

2. In the experiments on uniform upgrades the theoretical maximum sustained speed is rarely achieved because the driver has available only a finite number of gear settings. As the maximum sustained speed is approached the driver will find himself either in too low a gear with F_0 slightly positive and the vehicle capable of being accelerated or in too high a gear with F_0 slightly negative and the vehicle slowing down. Most commonly the driver selects the next lower gear and operates the vehicle at maximum usable engine rpm, with slightly less than wide open throttle and at slightly less than theoretical maximum sustained speed.

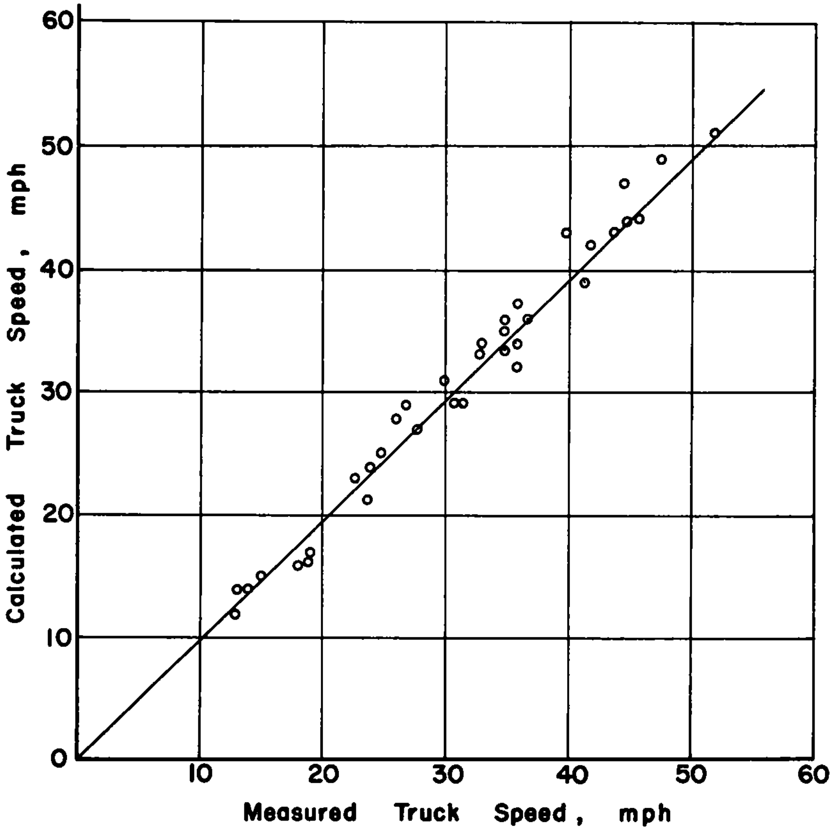

Figure 31. - Comparison of calculated and measured truck speeds on various vertical curves.

LIMITATIONS

The truck performance charts presented herein are not only limited to the ranges of truck and highway properties described previously but also subject to the following additional limitations:

1. Engine torque must be reasonably constant over the useable range of engine rpm at wide-open throttle.
2. The transmission characteristics must be such that the ratio of engine speed to vehicle speed is nearly constant in any one setting.
3. The highway surface must be of concrete or asphalt.
4. The rolling resistance characteristics of the truck must be reasonably close to the assumed relation for F_R.

Most naturally, aspirated truck engines and some supercharged engines produce nearly constant torque at wide-open throttle over the useable range of engine rpm. On supercharged engines, however, it is possible to achieve anything from a rising torque with increasing engine speed to a rising torque with decreasing engine speed. The charts presented herein do not apply to truck engines with these characteristics. The calculation method used can be applied to trucks equipped with such engines provided that wide-open throttle torque can be expressed as a function of engine rpm.

The usual geared transmission with friction clutch satisfies limitation 2 because engine speed and vehicle speed are directly related in any one gear setting. It is the hydraulic coupling and/or hydraulic torque converter transmission to which these charts are inapplicable.

Gravel or dirt surfaced roads greatly increase truck rolling resistance compared to asphalt or concrete surfaced roads which appear to be nearly equal in this respect. Hence the charts are not applicable to gravel or dirt surfaced roads.

The assumed relation for the rolling resistance force indicates the vehicle weight to be the only variable that suggests that tire hysteresis is a principal source of rolling resistance. As shown in (4), tire hysteresis losses vary markedly with tire construction and tire temperature as well as with tire loading. Hence, the assumed relation in F_R cannot be completely general. The extent to which the charts become inapplicable on this account is difficult to assess because quantitative data on the various factors influencing rolling resistance are not at present available. For this reason the charts should be used with reservations on level or nearly level roads where the rolling resistance force significantly affects truck performance.

APPLICATIONS

The charts of truck performance on highways may prove useful to highway designers and truck operators. A few examples of the use of the charts are presented here to illustrate possible applications.

Freeway Approach Ramp Example. — A large truck approaches the ramp shown in Figure 32 at an initial speed of 30 mph from an industrial area. This truck is eventually to merge with freeway traffic moving at 40 mph. It is desired to know how long an acceleration lane should be provided alongside the freeway so that the truck can reach a speed of 40 mph before merging into the freeway traffic. The design limiting truck is heavily loaded, therefore, a value of 400 for the ratio GVW/BHPW is used. Minimum vertical curve length to transition from the level industrial street to the 6 percent upramp to the freeway is 200 ft for a speed limit of 30 mph.

Reference to the scale at the bottom of Figures 13 and 14 show that to change from G = 0 to G = 6 percent the following are required:

r	L
2,500	150
5,000	300
10,000	600

For this example the radius of a vertical curve of 5,000 ft and length of 300 ft is used so that the design minimum of 200 is exceeded.

The length of constant 6 percent grade is 400 ft but the length of transition to the level freeway grade is 300 ft of 5,000-ft vertical curve radius to meet design standards. Curve 2 of Figure 10 shows truck speed to be 31 mph at point 2. Curve G = 6 of Figure 4 shows truck speed to be 20 mph at point 3. Figure 14 shows truck speed to be 15 mph at point 4. Figure 7 shows that the truck can reach a speed of 40 mph on the level freeway within a distance of 2,550 ft. This is the desired length of acceleration lane to be provided beyond point 4.

Truck Travel Time Example. — A truck operator wishes to ascertain the effect of engine power on truck travel time between points 1 and 9 on the 4-mi section of highway shown in Figure 33. The legal speed limit is 50 mph.

Figures 14 and 13 are used to determine the highway distances, which are found to be

1 to 2 = 300 ft
2 to 4 = 9,560 ft
4 to 5 = 900 ft
5 to 6 = 500 ft
6 to 8 = 9,760 ft
8 to 9 = 200 ft

The first analysis will assume an engine of low power and assume $\frac{GVW}{BHPW}$ to be 400.

Figure 10 shows truck speed to be 50 mph at point 2. Hence the travel time from point 1 to 2 becomes

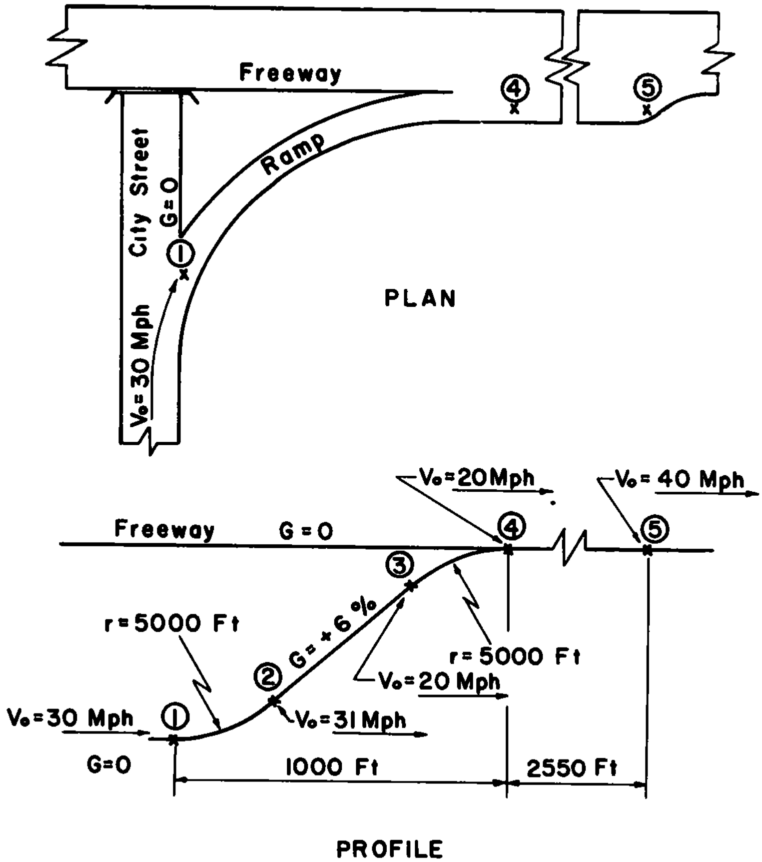

Figure 32. Highway profile for freeway approach ramp example.

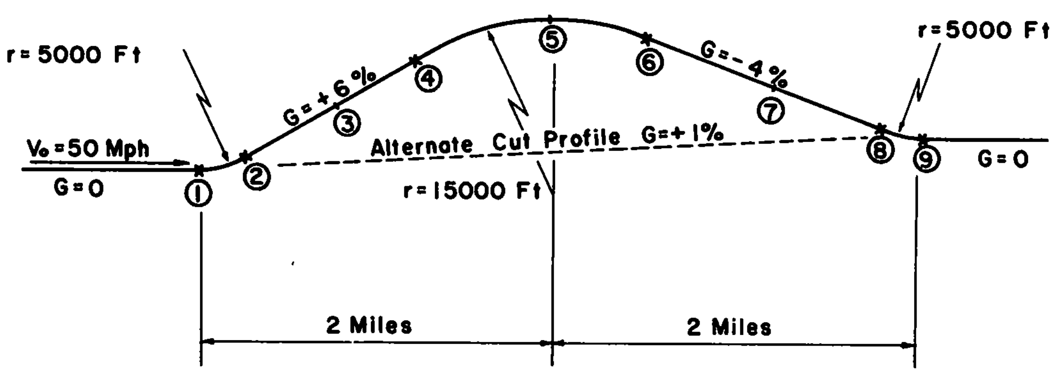

Figure 33. Highway profile for truck travel time and highway cut examples.

$$t_{1-2} = \frac{300(3,600)}{(50)(5,280)} = 4.1 \text{ sec}$$

Figure 4 shows that the truck will reach a maximum sustained speed of 13 mph at point 3 in a distance of 1,600 ft beyond point 2. Figure 22 shows that 32 sec will elapse between points 2 and 3.

The truck will continue at 13 mph up the uniform 6 percent grade from point 3 to 4 and the elapsed time becomes

$$t_{3-4} = \frac{(9,560 - 1,600)(3,600)}{(13)(5,280)} = 418 \text{ sec}$$

Figure 13 shows that truck speed will be 21 mph at point 5 and 34 mph at point 6. The elapsed time may be adequately approximated by assuming a linear variation of velocity between points 4 and 5 and between points 5 and 6:

$$t_{4-6} = \frac{(900)(3,600)(2)}{(13+21)(5,280)} + \frac{(500)(3,600)(2)}{(21+34)(5,280)} = 65 \text{ sec}$$

Figure 7 shows that the truck will reach a speed of 50 mph at point 7 after traveling a distance of 1,000 ft for an elapsed time calculated as

$$t_{6-7} = \frac{(1,000)(2)(3,600)}{(34+50)(5,280)} = 16.3 \text{ sec}$$

Presumably the truck will travel from point 7 to 9 at the legal speed limit of 50 mph and the elapsed time becomes

$$t_{7-9} = \frac{(9,760-1,000+200)(3,600)}{(50)\ (5,280)} = 123 \text{ sec}$$

The total elapsed time between points 1 and 9 is the sum of the elapsed times over the individual sections.

$$t_{1-9} = 658 \text{ sec for } \frac{\text{GVW}}{\text{BHPW}} = 400$$

Repeating the preceding steps for an engine of high power with $\frac{\text{GVW}}{\text{BHPW}}$ equal to 200,

$$t_{1-9} = 399 \text{ sec for } \frac{\text{GVW}}{\text{BHPW}} = 200$$

By comparing the cost of higher engine power with the value of shorter travel time a truck operator can select the most economic engine for trucks running over the hypothetical highway section of Figure 33.

Highway Cut Example. — The preceding truck travel time example can be extended to illustrate the use of the charts to estimate vehicle travel time savings resulting from highway cuts. What would the travel time be if the hill in Figure 33 were replaced with a cut of uniform grade?

The grade between points 1 and 9 turns out to be 1 percent on which trucks with GVW/BHPW equal to 200 can maintain the legal speed limit as shown in Figure 28, and the elapsed time becomes

$$t_{1-9} = \frac{4}{50} \times 3,600 = 288 \text{ sec for } \frac{\text{GVW}}{\text{BHPW}} = 200$$

For a value of $\frac{\text{GVW}}{\text{BHPW}}$ of 400, Figure 28 shows a maximum sustained speed of 45 mph on a 1 percent grade. The elapsed time then becomes approximately

$$t_{1-9} = \frac{4}{45} \times 3,600 = 320 \text{ sec for } \frac{\text{GVW}}{\text{BHPW}} = 400$$

The travel times for various smaller cuts can be calculated as in the preceding example and a comparison then made between the value of reduced vehicle travel time and the cost of highway cuts to determine the most economic depth of cut.

These examples represent rather simple highway sections for purposes of illustration only. The charts may also be used for several other types of calculation.

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1. "Truck Ability Prediction Procedure." Soc. Automotive Engineers, Recommended Practices TR82 (Aug. 1957).
2. Sawhill, R.B., and Firey, J.C., "Motor Transport Fuel Consumption Rates and Travel Time." HRB Bull. 276, 35-91 (1960).
3. Sawhill, R.B., and Firey, J.C., "Predicting Fuel Consumption and Travel Time of Motor Transport Vehicles." HRB Bull. 334, pp. 27-46 (1962).
4. Stiehler, R.D., Steel, M.N., Richey, G.G., Mandel, J., and Hobbs, R.H., "Power Loss and Operating Temperature of Tires." Jour. Res., Nat. Bur. Standards, C, 64C: No. 1 (Jan.-March 1960).