The Texas Climbing Lane Design Theory Compared with Some Road Test Results

by T. S. Huff* and F. H. Scrivner**

Synopsis: A simplified theory of the motion of heavy vehicles on grades is presented. A set of speed-distance curves computed from the theory and based on values of maximum sustained speeds observed in Arizona is given as the current basis for design of climbing lanes in Texas. Speed-distance curves representing the observed performance of a test vehicle on eleven grades are compared with the corresponding curves developed from the theory. Fair agreement was found and it was concluded that the simplified theory is accurate enough for use in the design of climbing lanes.

1. Theory

Consider a vehicle (Figure 1) of gross weight, W, travelling at a variable velocity, v, on a grade inclined at an angle, θ, with the horizontal, the value of θ being taken as positive if the vehicle is ascending and negative if it is descending. If g represents the acceleration of gravity and t the time, then, neglecting that part of the driving force required to impart angular acceleration to rotating parts, we may write the force equation, $\frac{W}{g}\frac{dv}{dt} = P - W \sin \theta$, where P, a variable, may be termed the net driving force acting on the vehicle. The above equation may be rewritten in the form

$$\frac{P}{W} = \frac{1}{g}\frac{dv}{dt} + \sin \theta \qquad (1)$$

The net driving force is the total traction exerted by the driving wheels against the road surface, less wind resistance and road surface resistance. Again neglecting inertial resistance to angular acceleration, it

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follows that if the truck is always operated at the highest possible speed and always within the range of engine r.p.m. recommended by the manufacturer, then the total driving force must be expressible, at least approximately, as a single valued function of the velocity only. Air resistance in still air is usually considered to be a function of the velocity only, and we shall assume that no wind exists. We shall also assume that the type and roughness of the pavement do not change and therefore, that the road surface resistance may be taken as constant, or at most as a function of velocity only. We therefore conclude that although the net driving force must satisfy Equation (1) involving the acceleration and the grade angle, it may also be expressed independently as some function of velocity only, since each of its components is a function of velocity only.

For example, if the truck operates at a known maximum sustained velocity on any grade, the numerical value of P/W corresponding to that velocity may be immediately calculated from Equation 1, which in this case reduces to $P/W = \sin \Theta$, and that magnitude of P/W will always exist at that velocity, at least approximately, regardless of the value of the acceleration. In Figure 2 we have plotted values of P/W computed in this way against corresponding values of the velocity, v, from basic data supplied mainly by W. E. Willey (1) in 1950, and applying to an average heavy vehicle operating on mountain grades in Arizona.

The points plotted in Figure 2 are connected by straight lines to form a continuous graph of P/W versus v. Each straight line segment extending from, say, v_n to v_{n+1}, may be represented by an equation of the form,

$$P/W = av + b \tag{2}$$

where v varies within the interval, v_n to v_{n+1}, and a and b are constant within the same interval.

From Equations 1 and 2 we may form a third equation, not containing P/W explicitly, which becomes the general motion equation for the vehicle, as follows:

$$\frac{dv}{dt} - gav + g\,(\sin\theta - b) = 0 \qquad (3)$$

where v is restricted to the velocity interval, v_n to v_{n+1}, and a and b are constant in the same interval.

We now denote the position of the vehicle at any instant by its coordinate, x, measured in the direction of motion from a stationary point on the grade behind the truck. We also stipulate that $x = t = 0$ when $v = v_o$, and that the grade angle, θ, is constant. Then the solution of Equation 3 may be written in the following form suitable for the construction of speed-distance and time-distance curves:

$$x = \frac{1}{a}\left[\frac{v-v_o}{g} + (\sin\theta - b)\,t\right] \qquad (4)$$

$$\text{when } t = \frac{1}{ag}\log\left(\frac{av + b - \sin\theta}{av_o + b - \sin\theta}\right)$$

and both v and v_o are restricted to the interval v_n to v_{n+1}. Thus, during the time, t, the velocity changes from v_o to v, the vehicle travels a distance x, and the ratio, net driving force/gross weight, changes in value from $(av_o + b)$ to $(av + b)$. (The logarithm is taken to the base, e).

In using Equations 4 for calculating the distance traveled or time consumed by a vehicle while it changes velocity over an interval greater than that for which a and b are constant, it is necessary to compute the increments of distance and time corresponding to each sub-interval of the type, v_o to v_n, v_n to v_{n+1}, and v_{n+1} to v, and to add these increments in order to obtain total distance and total time.

2. Texas Design Method

Figure 3 shows speed-distance curves computed from Equations 4, the value of the constants, a and b, having been taken from Figure 2. By interpolating between these curves, one may determine the approxmiate speed, in the range from 0 to 47 miles per hour, of Willey's (1) average heavy vehicle at any point on any series of successive grades ranging between minus 7% and plus 7%, provided the speed at one point on the series of grades is known. The upper limit of 47 m.p.h. was selected because that figure was the average speed of trucks on approximately level grades in Texas.

The curves of Figure 3 have been used in the design of climbing lanes in Texas since 1952. An example of the design procedure is given in the figure. Briefly, it consists in finding the point on an ascending grade where the speed drops to 30 m.p.h., and the next subsequent point where the speed has increased to 30 m.p.h. and the truck is accelerating. These two points form the limits of the tangent section of the climbing lane. Reversed curves, 525' in length, are added to each end of the tangent. Thus the design vehicle is removed from the general traffic stream at a speed somewhat greater than 30 m.p.h., and likewise is returned at a speed exceeding 30 m.p.h.

In using the chart for design purposes, vertical curves are generally ignored and speeds are usually taken from Figure 3 on the assumption that the vehicle travels in a straight line from one point of grade intersection to the next. Vertical curves can be broken up into straight line segments, of course, if the additional accuracy is considered worth while.

3. Road Test of a Heavy Vehicle

In December 1953 a road test was conducted by the Planning Survey of the

Texas Highway Department (2) on a section of Ranch to Market Road 93 in Travis and Burnet Counties west of Austin in an effort to provide data from which the theory being used in design of climbing lanes could be checked or corrected, if necessary. The vehicle used was an International Harvester R-195 two-axle truck-tractor (146 net horse power at sea-level) and a 33-foot Hobbs tandem-axle flat bed trailer, both loaned to the Department free of charge by the respective manufacturers. Table 1 gives essential data pertaining to the tractor. The trailer was loaded with steel piling, the gross weight of tractor and trailer being 57,180 pounds. (Figure 4)

In running the tests, pneumatic tubes, or detectors, which actuated electric switches when run over, were first stretched transverse to the highway at 100-foot intervals on a selected grade. Two instruments, an Esterline-Angus 20-pen graphic recorder with about 1/10 second accuracy (Figure 5) and an oscillograph and camera with tuning fork timer accurate to about 1/1000 second (Figure 6) recorded the time each of the four axles passed over the pneumatic tubes during the test.

Eleven grades ranging from 700 to 1500 feet in length, and from 0.16% to 7.62% in inclination, were used in the test.

In all test runs, the driver, an employee of the Department, attempted to maintain the highest possible speed while remaining within the range of engine r.p.m. recommended by the manufacturer and marked on the speedometer.

The test procedure was as follows:

UP-GRADE ACCELERATION RUNS: The driver approached the grade at the bottom at a very low speed (one or two miles per hour). When within three or four feet of the first detector, he accelerated as rapidly as possible and continued to accelerate until he had passed over the last detector at the top of the grade. If he had not reached maximum sustained speed at that time, he returned to the bottom of the grade and repeated the run, except that he approached the first detector at approximately the speed and in the gear he had previously passed the last detector. This procedure was followed until maximum sustained speed was attained.

UP-GRADE DECELERATION RUNS: The driver attempted to approach the grade at the bottom at a speed equal to or greater than 47 m.p.h. and attempted to reach the top at the highest possible velocity. If, after passing the last detector, his speed was still greater than maximum sustained speed, he returned to the bottom of the grade and repeated the run, except that he approached the first detector at approximately the speed and in the gear he had previously passed the last detector. The process was continued until the velocity on the grade was reduced to maximum sustained speed.

DOWN-GRADE ACCELERATION RUNS: At the top of the grade the driver approached the first detector at one or two m.p.h., then accelerated as rapidly as possible. If, on passing the last detector, he had not attained a speed of 47 m.p.h., he returned to the top of the grade, making his approach on the second down-grade run at the speed and in the gear he had previously passed the last detector, and again accelerated as rapidly as possible. The process was repeated until he attained a speed of at least 47 m.p.h. on the grade.

All told, there were 118 test runs of the types described above. (Figure 7) Both recording instruments performed well, but it was impractical to operate the oscillograph continuously during most test runs because the fast moving recording paper would be exhausted before the truck had finished the run.

4. Analysis of Road Test Results

Approximate values of velocities for use in plotting speed-distance curves representing the test runs were computed as follows from the basic data:

(a) From 20-pen recorder data: The velocity at the instant when the front axle of the vehicle was mid-way between two successive detectors was taken equal to the distance between detectors (100 feet) divided by the corresponding time interval.

(b) From oscillograph data: The velocity when the mid-point between the second and third axles was over a detector was taken equal to the distance between those axles (18.62 feet) divided by the corresponding time interval.

Accelerations for use in Equation (1) were computed from oscillograph data only, since such computations require more accurate data than velocity determinations. At low velocities, approximately simultaneous values of acceleration and velocity were computed from the time intervals between the passage of three successive axles over one detector. In order to convert the time data to accelerations, use was made of finite difference forms of the derivatives, d^2x/dt^2 and dx/dt. At higher velocities, time intervals between the passage of one axle over three successive detectors were used in the difference equations.

The approximate acceleration and the grade angle being known for a given instant, these values were substituted in Equation 1 for dv/dt and θ, respectively, and the numerical value of P/W was computed for that instant. Each computed value of P/W was then plotted against the corresponding velocity in

Figure 8, where the solid points represent instants when the acceleration was different from zero, and the circled points represent periods during which the truck was apparently traveling at maximum sustained speed, that is, when the acceleration was equal to zero. Ignoring areas of the graph where the scattering of points was too wide to indicate any consistency in the data, an average line was drawn through the remaining points. This line was taken to represent the graphical form of P/W expressed as a function of velocity only.

On the same graph values of sin θ were plotted against the corresponding maximum sustained speeds computed by a method proposed by the Society of Automotive Engineers (3). These values, plotted as points enclosed in triangles, are based entirely on the factors pertaining to the truck and test environment given in Table I.

(The reason for the wide scattering of points on Figure 8 is not known, but it might have been due in part to unavoidable variations in wind direction, wind velocity and driver behavior. Some of the scattering might also have resulted from the inherent inaccuracies encountered in the substitution of difference equations for differential equations. And some scattering could be expected because of variations in the force required to change the angular velocity of rotating parts while the truck accelerated at varying rates).

Next, from the graph of average values of P/W versus velocity (Figure 8), and by use of Equations 4, a set of three speed-distance curves (up-grade decelleration, up-grade acceleration, and down-grade acceleration) was plotted for each of the eleven test grades.

Finally, the 118 speed-distance surves (Figure 7) previously plotted directly from the observed data, (referred to hereafter as "test curves") were compared with the corresponding speed-distance curves computed by use of the graph of average values of P/W (referred to hereafter as "computed curves") in the following manner:

The computed curve, drawn on transparent tracing cloth, was placed over a corresponding test curve plotted to the same scale, and the velocity lines (horizontal lines) on the two graphs were matched. The computed curve was then moved horizontally, keeping the velocity lines matched, until it appeared to pass through the mid-point of the test curve. Then the test curve was traced on the cloth with the computed curve. If the curve so transferred coincided with the computed curve, then it could be concluded that, within the range of velocities covered by the test curve, the computed curve represented the test data well. On the other hand, the contrary was true if the test curve departed substantially from the computed curve. Figures 9 through 17 show these comparisons.

5. Comparison of Test Results with Theory

Although fair agreement frequently existed between the shapes of the speed-distance curves plotted directly from the data, (the solid lines of Figures 9 through 17) and the curves computed from the graph of average values of P/W (the dashed lines of figures 9 through 17), the following exceptions are noteworthy:

(a) On many runs, the test curves indicated some irregularity in the motion of the vehicle, apparently caused in part by gear shifting. This irregularity was especially noticeable on some of the up-grade deceleration runs at velocities approaching maximum sustained speed, when the vehicle frequently first slowed to two or three miles per hour below maximum sustained speed, and then accelerated.

(b) The observed maximum sustained speed was frequently from one to three m.p.h. greater than the speed shown on the computed curves. The reason for this discrepancy may be found by reference to Figure 8, where it can be seen that most of the circled points (which represent net driving force/gross weight at maximum sustained speed) lie above the line representing the average of all points. Thus, the net driving force acting at any sustained velocity was, on the average, greater than the net driving force acting at the same velocity when the vehicle was accelerating or decelerating. This apparent anomoly in vehicular performance might be explained by the fact that the driver, while rapidly accelerating or decelerating, had little time for searching out the best gear, whereas his sustained speed on any grade occurred only after he had had ample time to find the proper gear for that grade. In this connection it was also noted that the maximum sustained speeds computed for the test vehicle by the method recommended by the Society of Automotive Engineers (3) (see points enclosed in triangles in Figure 8) agreed rather well with the observed values (the circled points in Figure 8) except in the velocity range of about 14 ft./sec. to 30 ft./sec. (8.4 m.p.h. to 20.5 m.p.h.). In this range the values computed by the SAE method were somewhat greater than the observed values.

In spite of the exceptions noted above, the speed-distance curves computed from the graph of average values of the ratio, net driving force/gross weight (Figure 8) appeared to represent the average performance of the test vehicle fairly well. Therefore, Figure 18, which was made up by use of Figure 8 and Equations 4, for integral values of grade percentages, may be taken as a general summary of the average performance of the test vehicle. If detailed comparisons of Figure 18 are made with Figure 3 it will be seen that the test vehicle was generally slower than the design truck in current use in Texas.

6. Conclusions

(1) Inspection of the test curves of Figures 9 through 17 indicate that even under controlled conditions, the relation between the speed and the distance travelled by the average heavy vehicle handled by a driver of probably better than average skill may not always be consistent.

(2) The speed-distance curves computed on the assumption of a net driving force which varies only with velocity agreed fairly well with the corresponding curves plotted directly from test data, at least in those cases where the vehicular performance was consistent. Therefore it appears that the simplified theory (Equations 4) is sufficiently accurate for use in design of climbing lanes.

(3) The Society of Automotive Engineers has provided a method for computing maximum sustained speeds for any gross weight to horsepower ratio (3). Values so computed, if used in conjunction with the simplified theory of truck motion presented herein, should make it possible to predict, at least approximately, the behavior on grades of vehicles of any gross weight to horsepower ratio without resorting to full scale tests.

7. Acknowledgements

The following Department employees were especially helpful in conducting the road test: Reed Baker, K. G. Crawford, W. R. Welty, Hubert Henry, S. W. Adair and Gene Voltz. Miss Leah Moncure did the numerical work in connection with the reduction of the data and the preparation of the graphs.

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TABLE 1

DATA PERTAINING TO TEST VEHICLE AND

CONDITIONS OF OPERATION

1. Vehicle identification - Internation R-195 Tractor
2. Vehicle overall maximum dimensions (a) Height - 7.75' , (b) Width - 7.75'.
3. Total gross weight - 57,180 lbs.
4. Manufacturer's maximum gross vehicle weight rating - 50,000 lbs.
5. Gear ratios: (a) Transmission - 6.98, 3.57, 1.89, 1.00, 0.825 (overdrive). (b) Aux. Trans. - none. (c) Axle - 6.5, 8.86. (d) Total gear reductions - 61.84, 45.37, 31.63, 23.21, 16.75, 12.28, 8.86, 6.50, 7.31, 5.36.
6. Tire size - 10.00 x 20
7. Net engine power at sea level - 146 hp. at 2600 rpm.[a]
8. Altitude - 950 ft.
9. Road service type and condition - Bituminous, good.

[a]Brake horsepower - 162 at 2800 r.p.m.

References

(1) "Uphill Truck Speeds", by William E. Willey, Roads and Streets, January 1950, p. 52. See also, "Uphill Speeds of Trucks", Highway Research Board Proceedings, 1949, p. 304; and "Survey of Downhill Speeds of Trucks on Mountain Grades", Highway Research Board Proceedings, 1950, p. 322, both by Willey.

(2) "Texas Highways", Texas Highway Department, Austin, Texas, January, 1954, p. 14.

(3) "Truck Ability Prediction Procedure", Second Edition, SP-82, Society of Automotive Engineers, Inc., 29 West 39th Street, New York 18, New York.

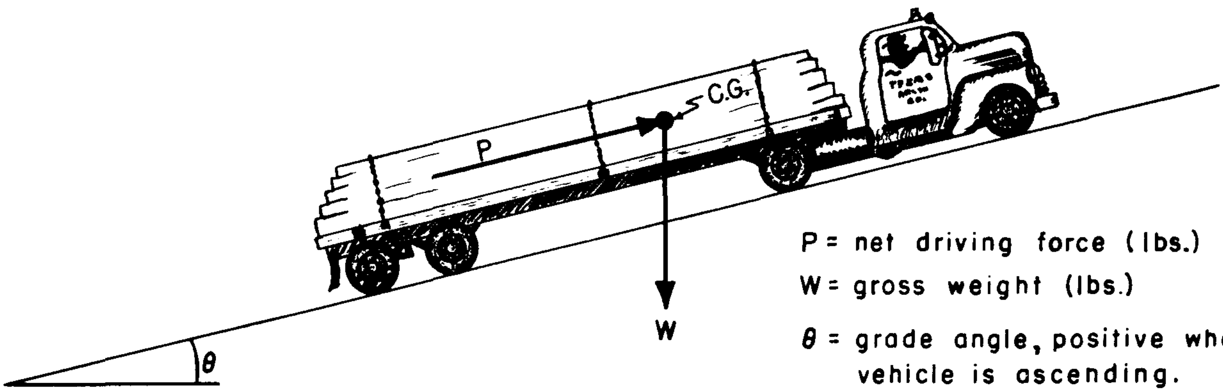
Caption List

Figure 4: Vehicle used in road test. Truck-tractor is over a pneumatic detector.

Figure 5: Twenty-pen graphic recorder measured time required for truck to travel the 100-foot distance between pneumatic detectors.

Figure 6: Oscillograph and camera, in portable dark room, recorded time each axle passed over pneumatic detector.

(Captions for all other figures appear on the drawings)



P = net driving force (lbs.)

W = gross weight (lbs.)

θ = grade angle, positive when vehicle is ascending.

Mass X Acceleration = Force,

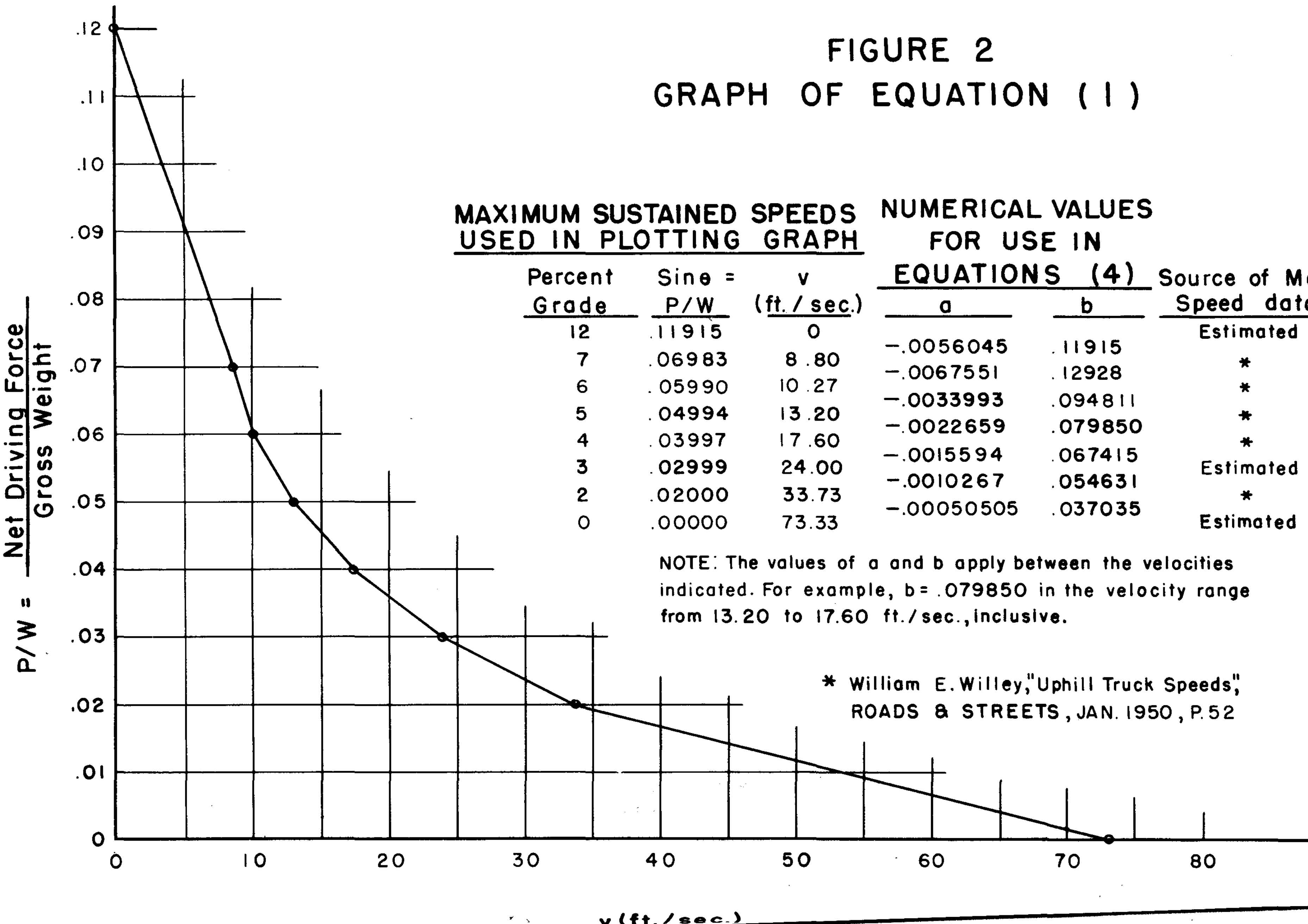
or $\frac{W}{g} \frac{dv}{dt} = P - W \sin \theta$,

Where v = velocity (ft./sec.), and
t = time (sec.).

(The additional driving force required to accelerate rotating parts is neglected.)

FIGURE 1

FIGURE 2
GRAPH OF EQUATION (1)



MAXIMUM SUSTAINED SPEEDS USED IN PLOTTING GRAPH

Percent Grade	Sine = P/W	v (ft./sec.)
12	.11915	0
7	.06983	8.80
6	.05990	10.27
5	.04994	13.20
4	.03997	17.60
3	.02999	24.00
2	.02000	33.73
0	.00000	73.33

NUMERICAL VALUES FOR USE IN EQUATIONS (4)

a	b
−.0056045	.11915
−.0067551	.12928
−.0033993	.094811
−.0022659	.079850
−.0015594	.067415
−.0010267	.054631
−.00050505	.037035

Source of Max. Speed data
Estimated
*
*
*
*
Estimated
*
Estimated

NOTE: The values of a and b apply between the velocities indicated. For example, b = .079850 in the velocity range from 13.20 to 17.60 ft./sec., inclusive.

* William E. Willey, "Uphill Truck Speeds", ROADS & STREETS, JAN. 1950, P. 52

EXAMPLE OF USE OF CURVES

ashed lines on graph indicate steps taken in
inding proper location for climbing lane shown
n sketch.)

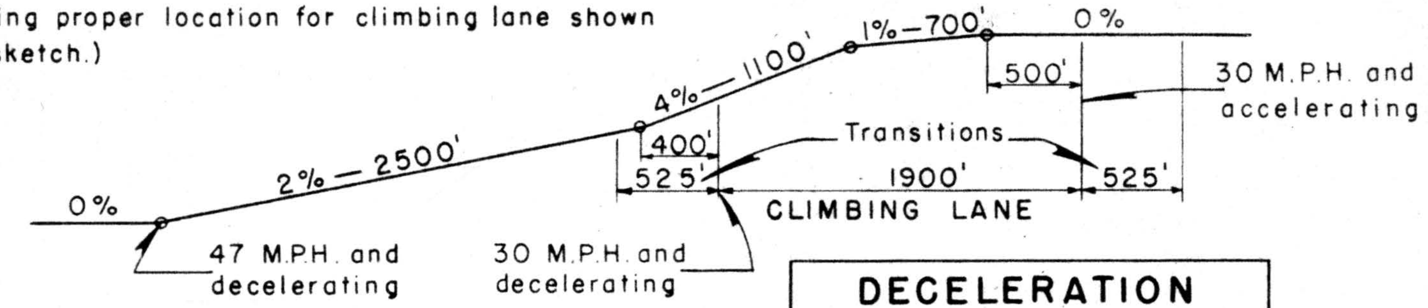


FIGURE 3

SPEED-DISTANCE CURVES

ESTIMATED FOR
A TYPICAL HEAVY TRUCK
OPERATING ON VARIOUS GRADES

CLAS
CLAS
CLAS
CLAS

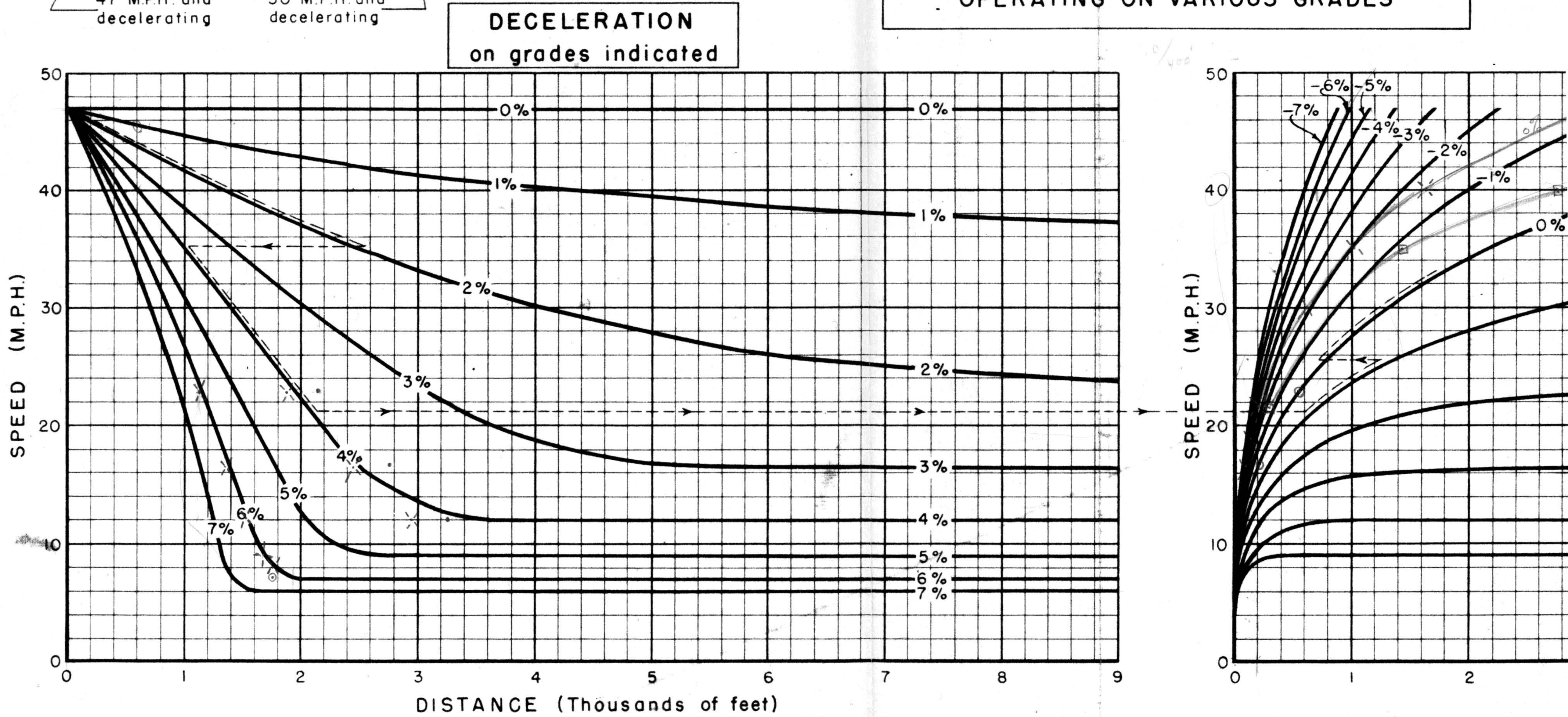


FIGURE 3

SPEED-DISTANCE CURVES

ESTIMATED FOR
A TYPICAL HEAVY TRUCK
OPERATING ON VARIOUS GRADES

WARRANTS FOR CLIMBING LANES

CLASS B HIGHWAYS — Provide climbing lane and parking shoulder.

CLASS C HIGHWAYS — Desirable treatment: same as for CLASS B HIGHWAYS. Minimum treatment: convert shoulder to climbing lane.

CLASS D HIGHWAYS — Make studies to determine feasibility of converting shoulder to a climbing lane, taking into account:
(1) construction costs and,
(2) volume of heavy trucks.

CLASS E HIGHWAYS — Climbing lanes not considered necessary.

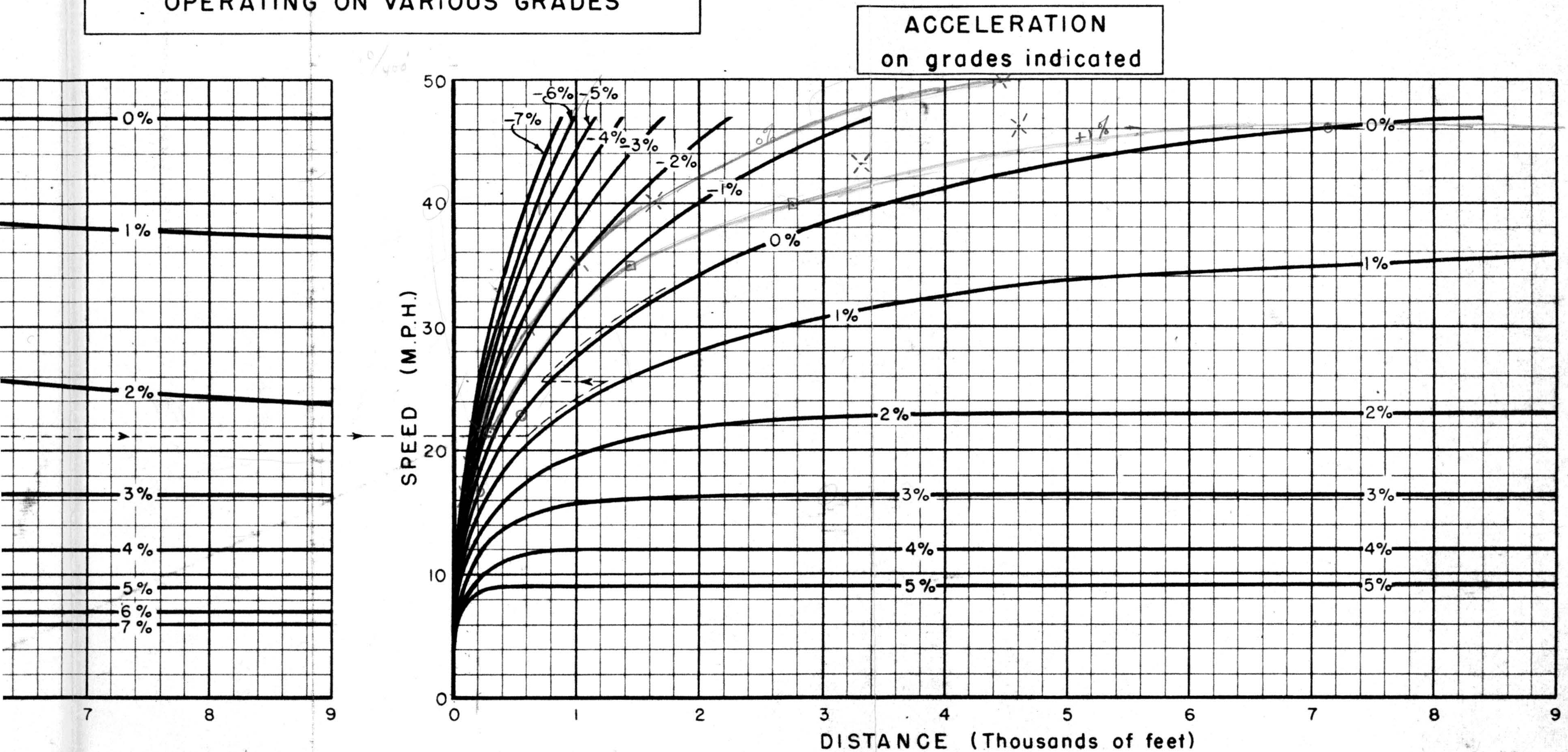


Fig. 4

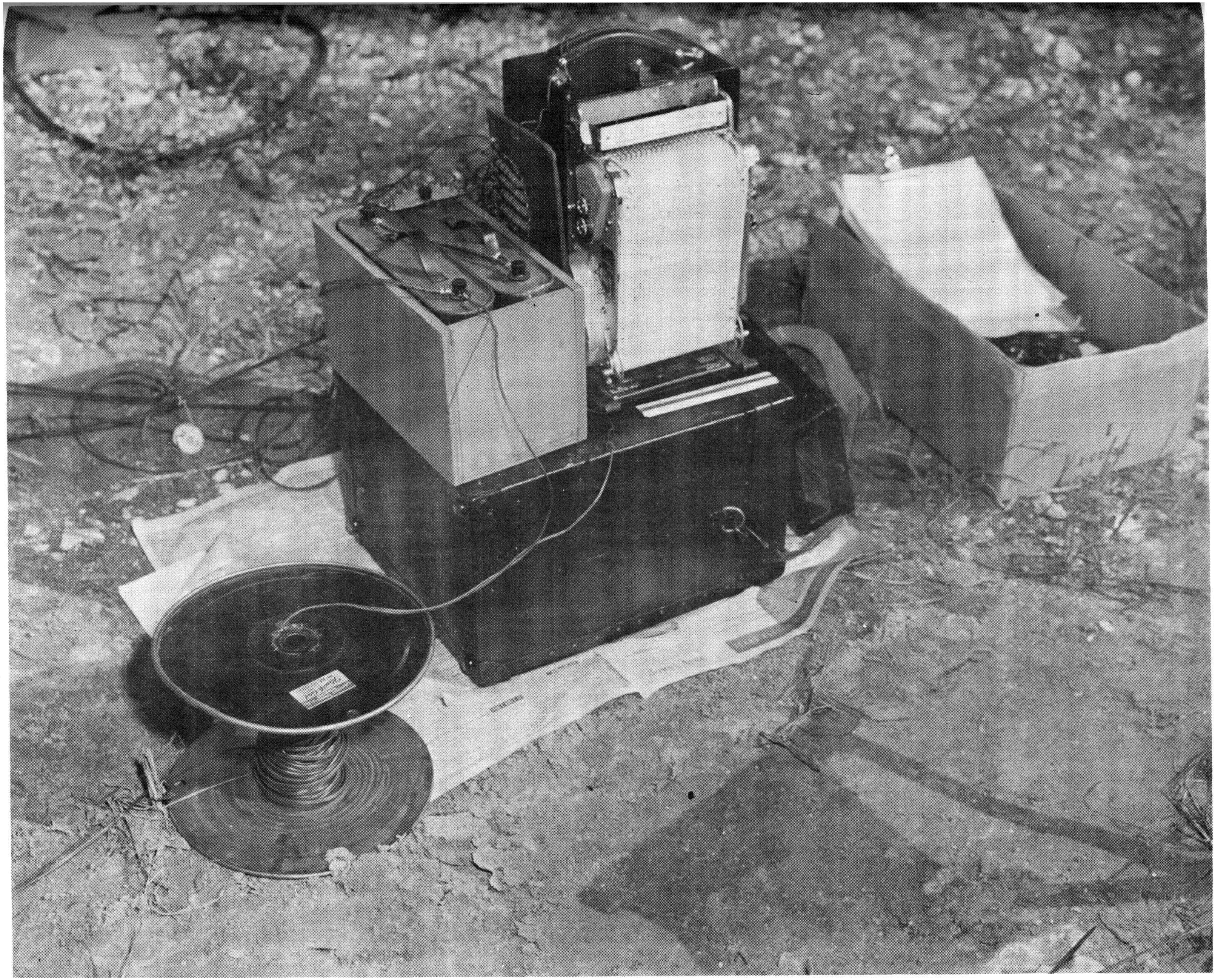


Fig. 6

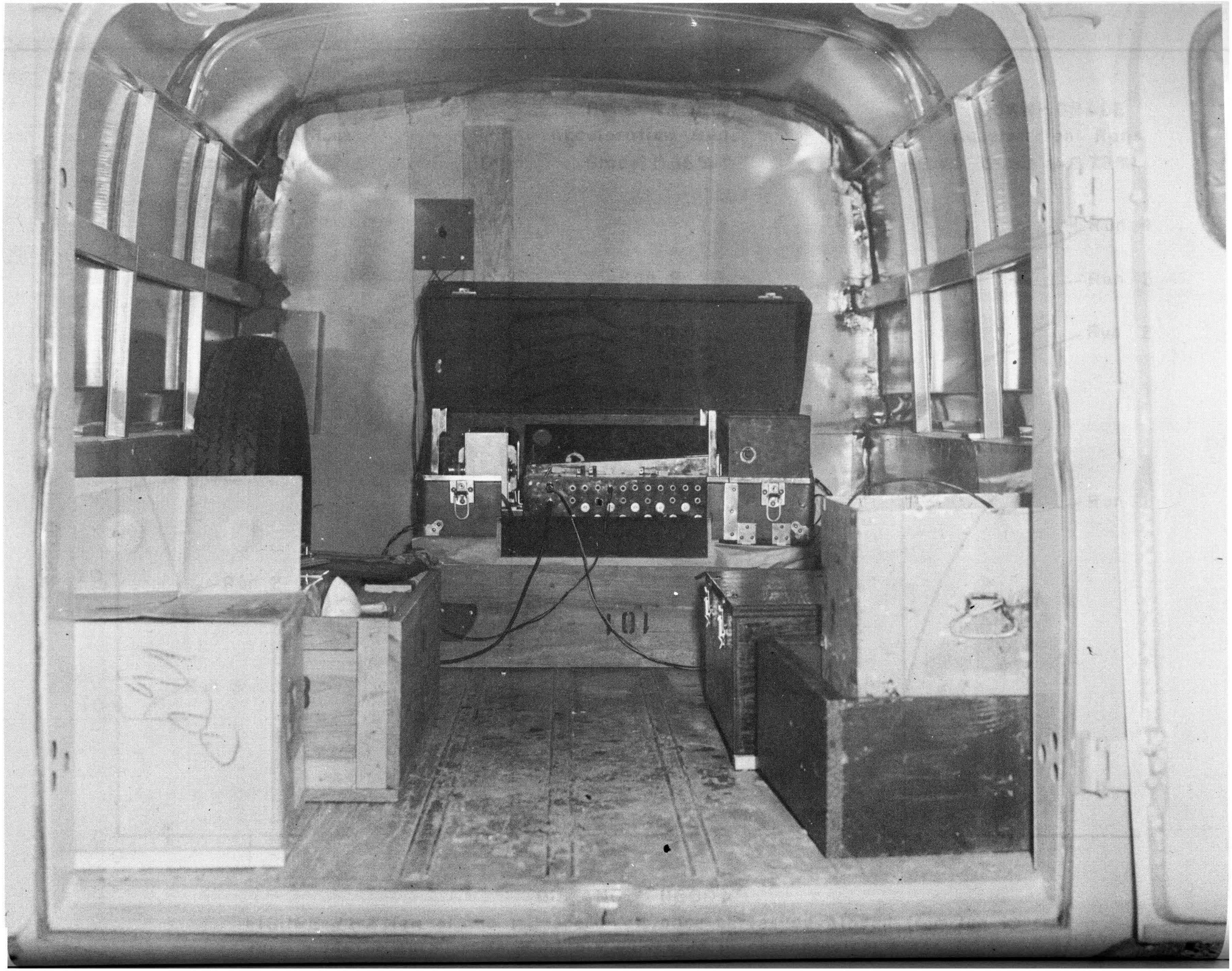


Fig. 6

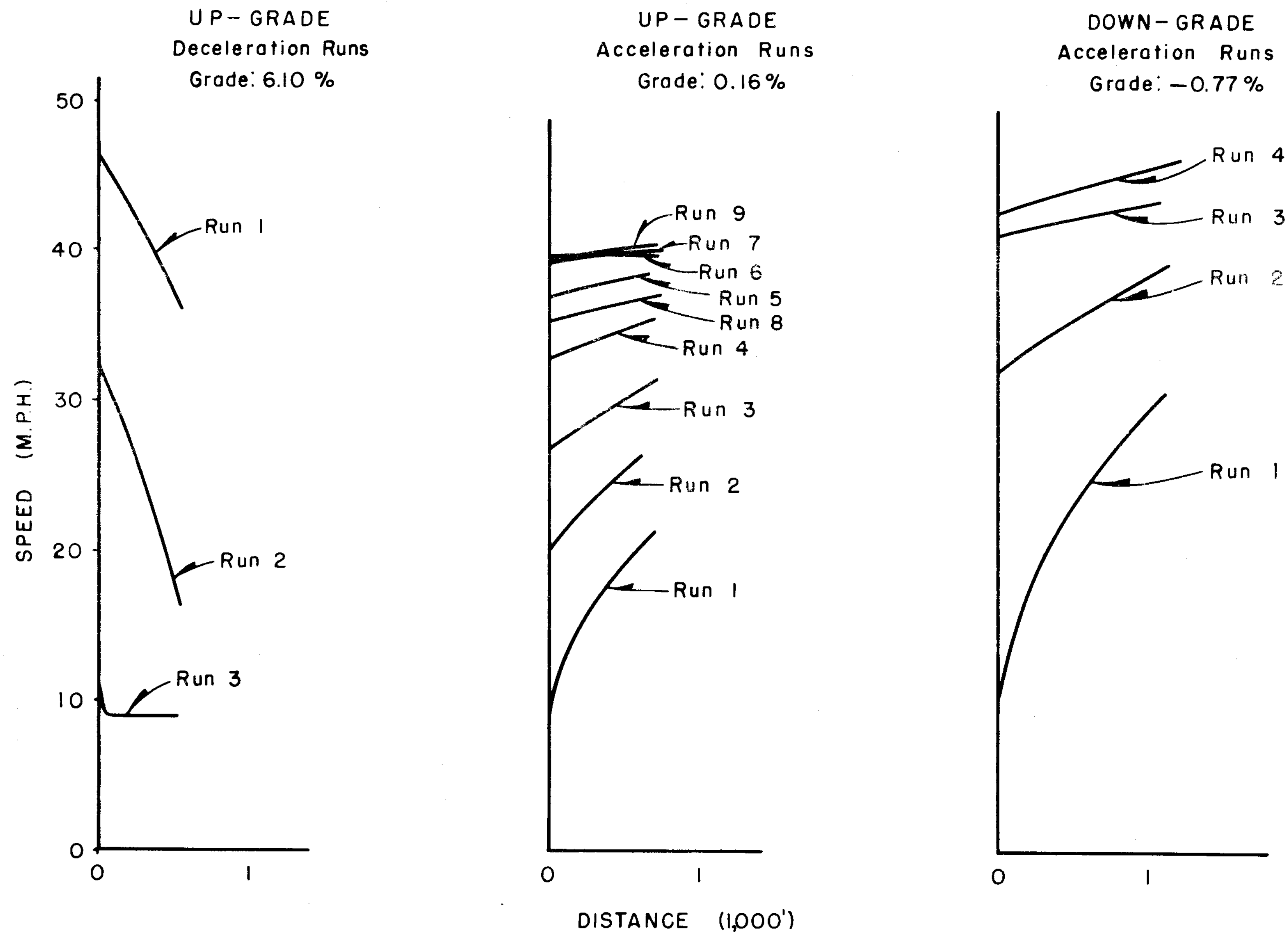


FIGURE 7: A few of the 118 speed-distance curves developed from the several runs made on each grade. Runs are numbered in chronological order.

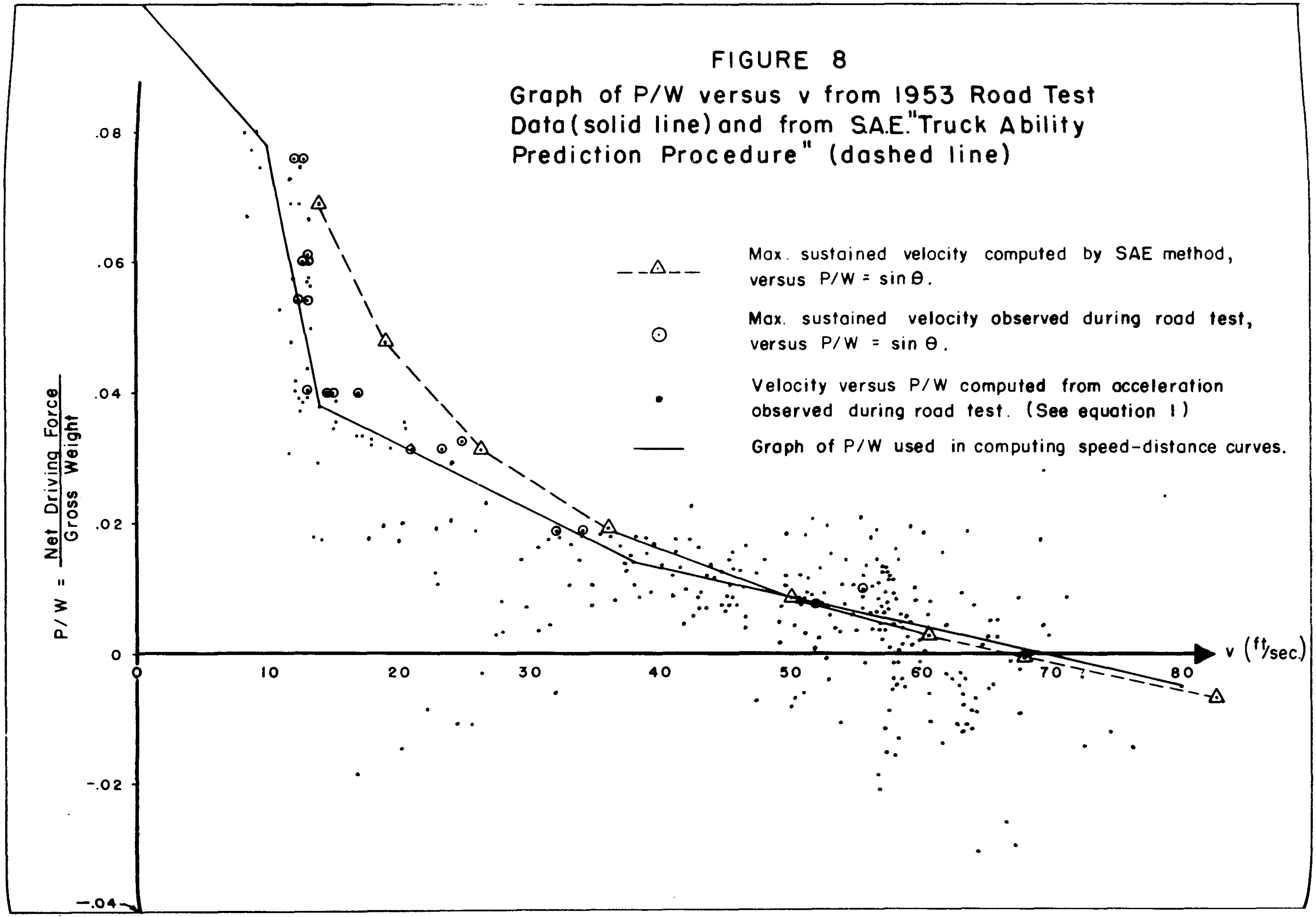
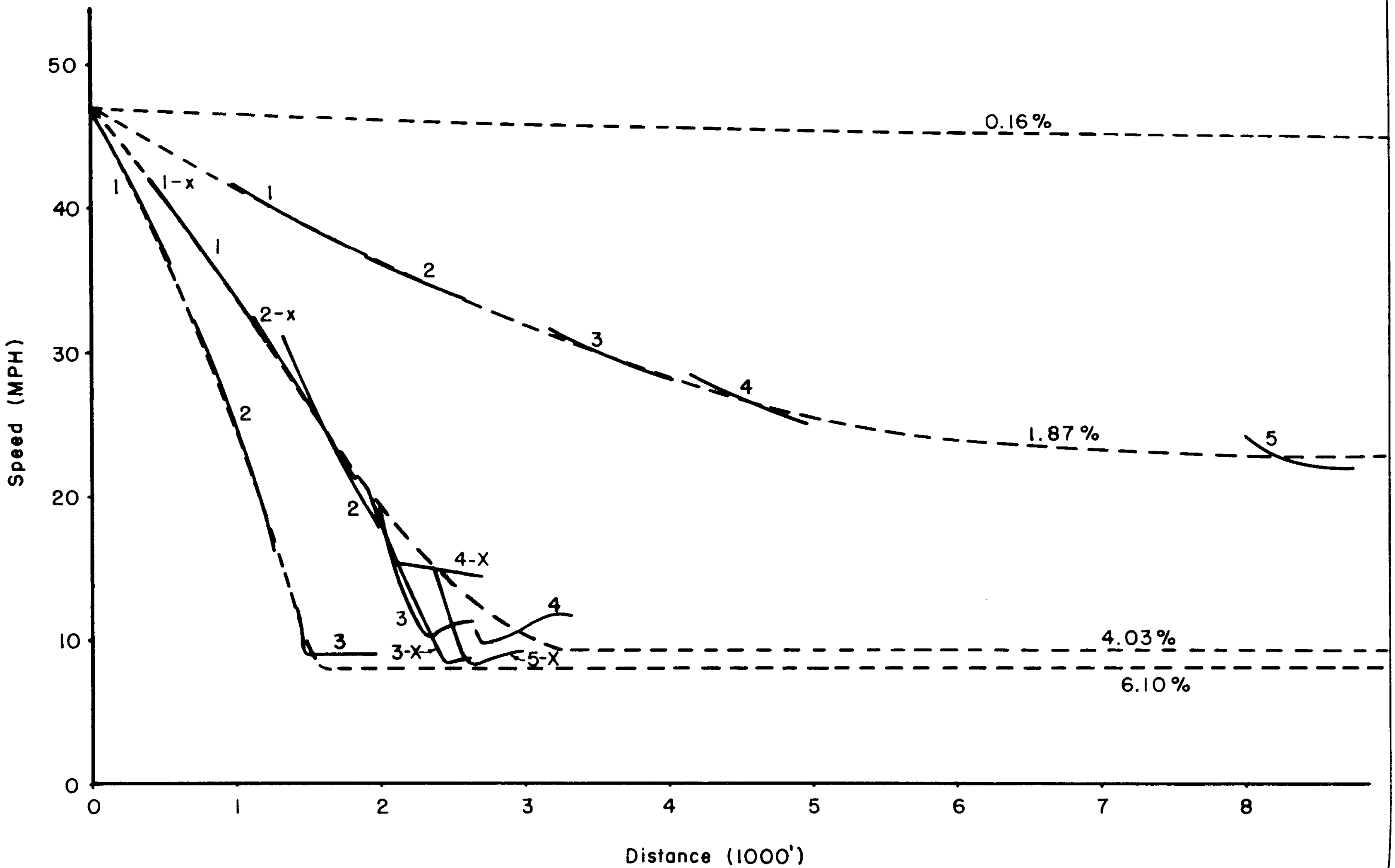
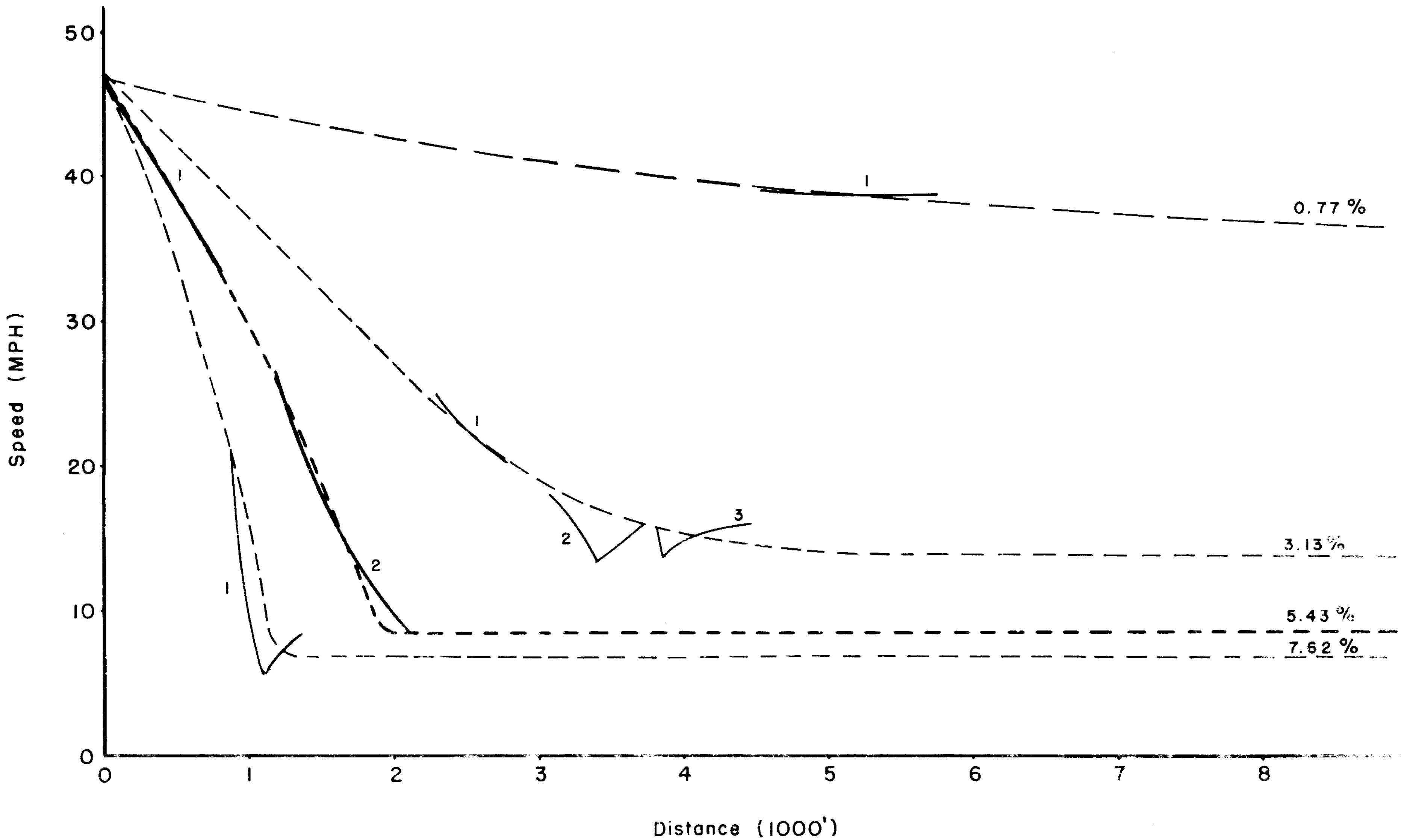


FIGURE 8
Graph of P/W versus v from 1953 Road Test Data (solid line) and from S.A.E. "Truck Ability Prediction Procedure" (dashed line)
Max. sustained velocity computed by SAE method, versus P/W = sin θ.
Max. sustained velocity observed during road test, versus P/W = sin θ.
Velocity versus P/W computed from acceleration observed during road test. (See equation 1)
Graph of P/W used in computing speed-distance curves.
P/W = Net Driving Force / Gross Weight
v (ft/sec.)
.08
.06
.04
.02
0
-.02
-.04
0
10
20
30
40
50
60
70
80



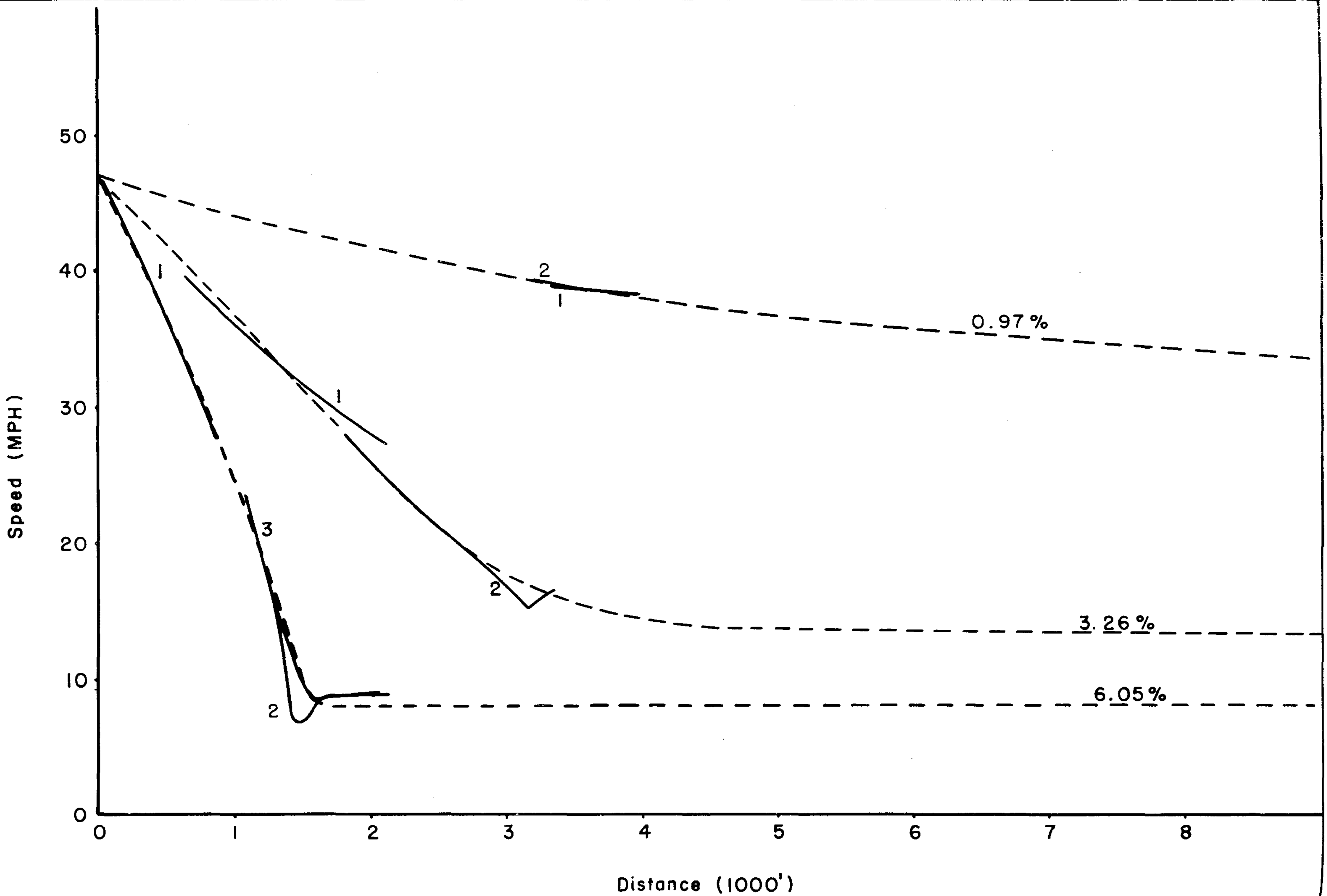
Speed (MPH)
50
40
30
20
10
0
0.16%
1.87%
4.03%
6.10%
1
1-x
1
2
3
4
5
1
2-x
2
2
4-X
3
4
3
3-X
5-X
0
1
2
3
4
5
6
7
8
Distance (1000')

Fig. 9



Speed (MPH)
50
40
30
20
10
0
Distance (1000')
0
1
2
3
4
5
6
7
8
0.77 %
3.13 %
5.43 %
7.62 %
1
1
2
3
1
2
1

Fig. 10



Speed (MPH)
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
Distance (1000')
1
2
3
0.97%
3.26%
6.05%

Fig. 11

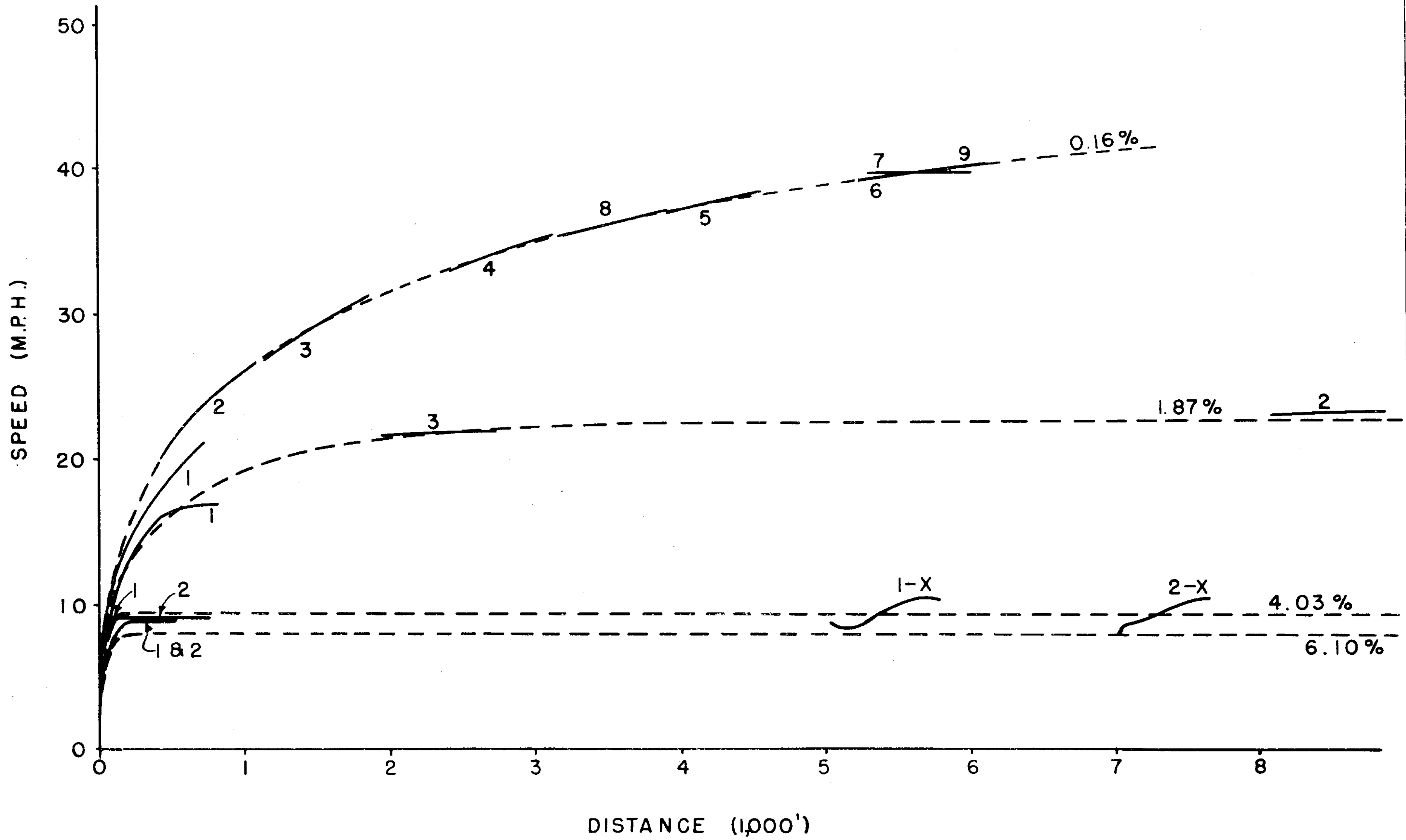
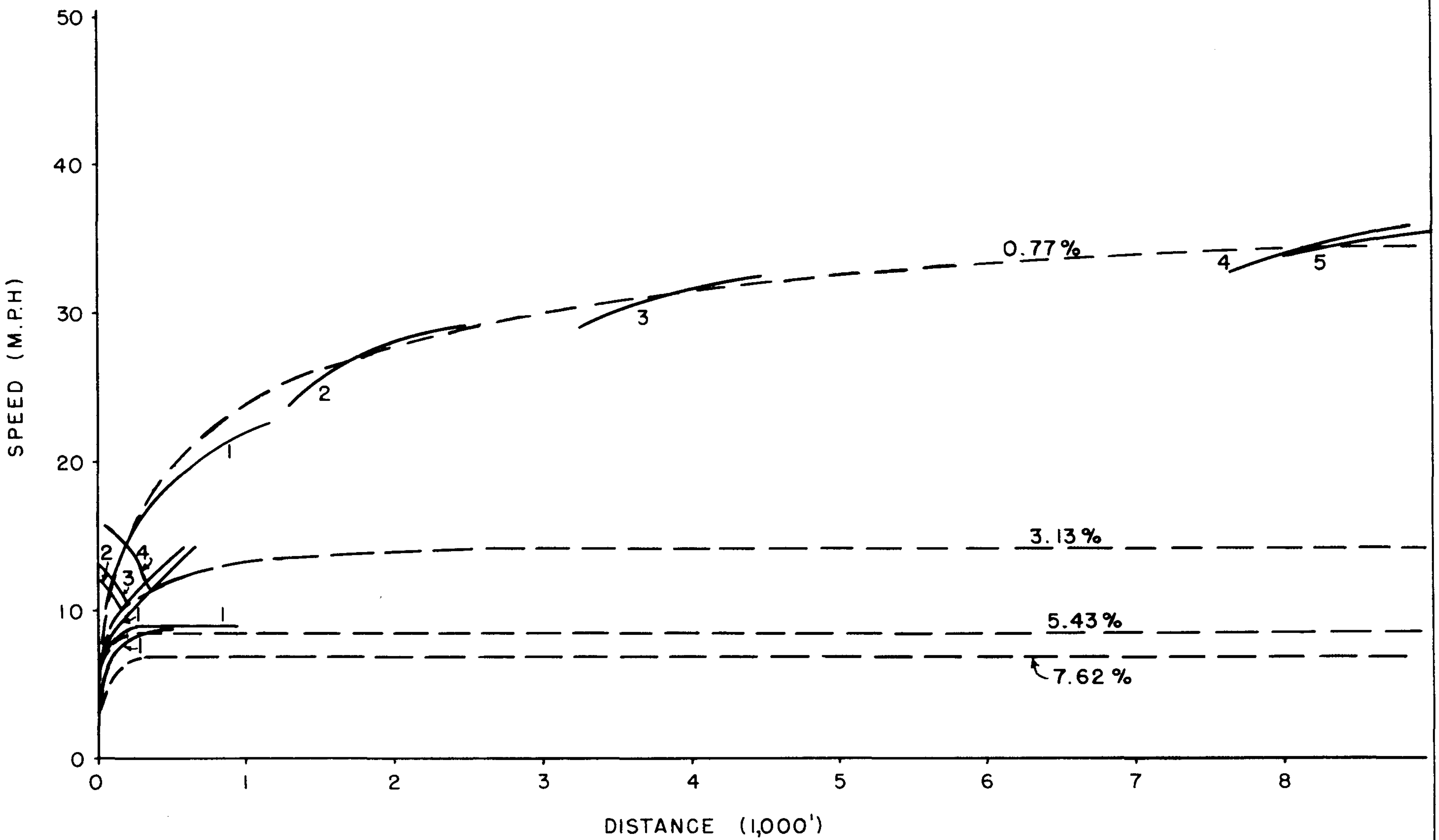
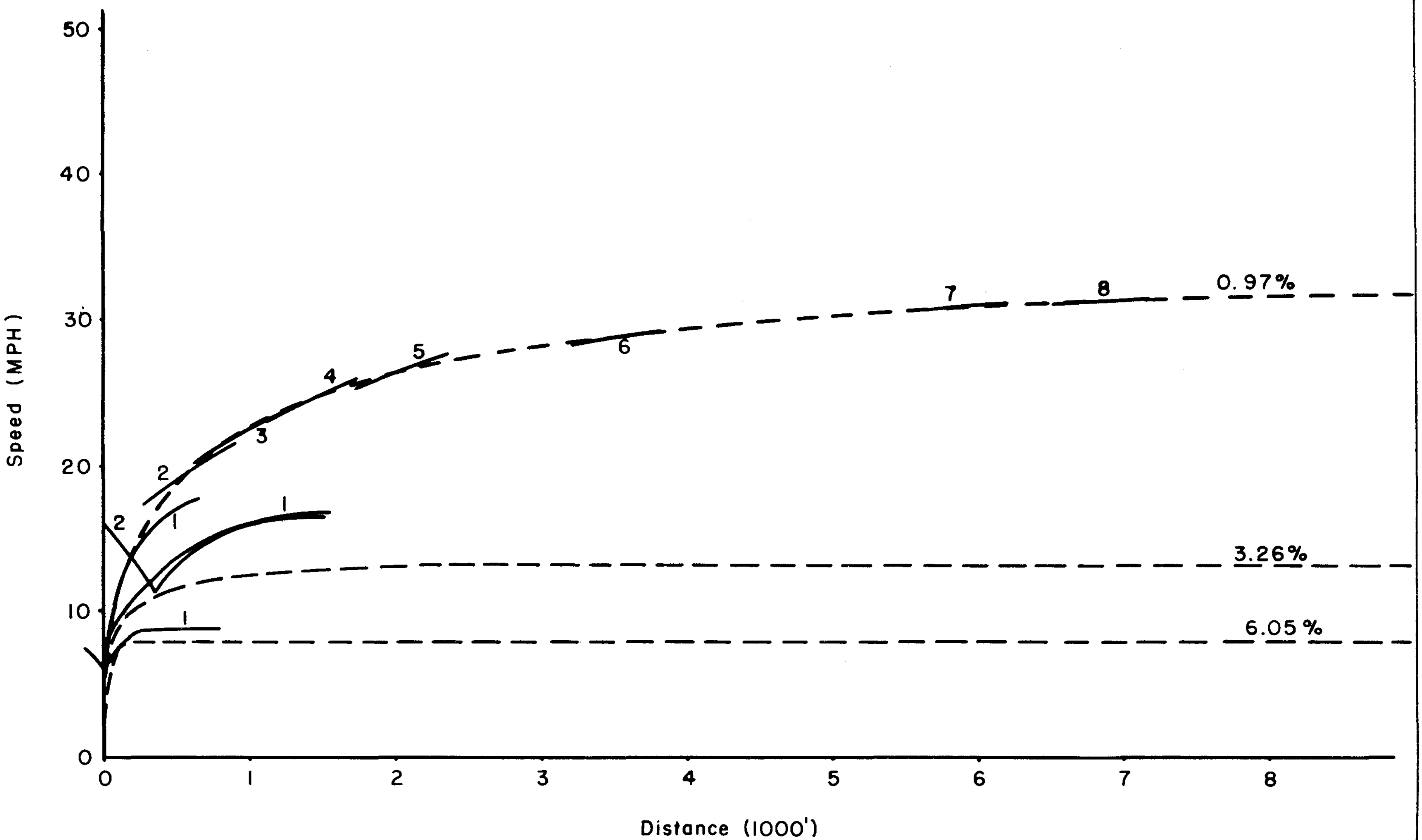

SPEED (M.P.H.)
DISTANCE (1,000')
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8
0.16%
1.87%
4.03%
6.10%
1-X
2-X
1&2
1
2
3
4
5
6
7
8
9

Fig. 12



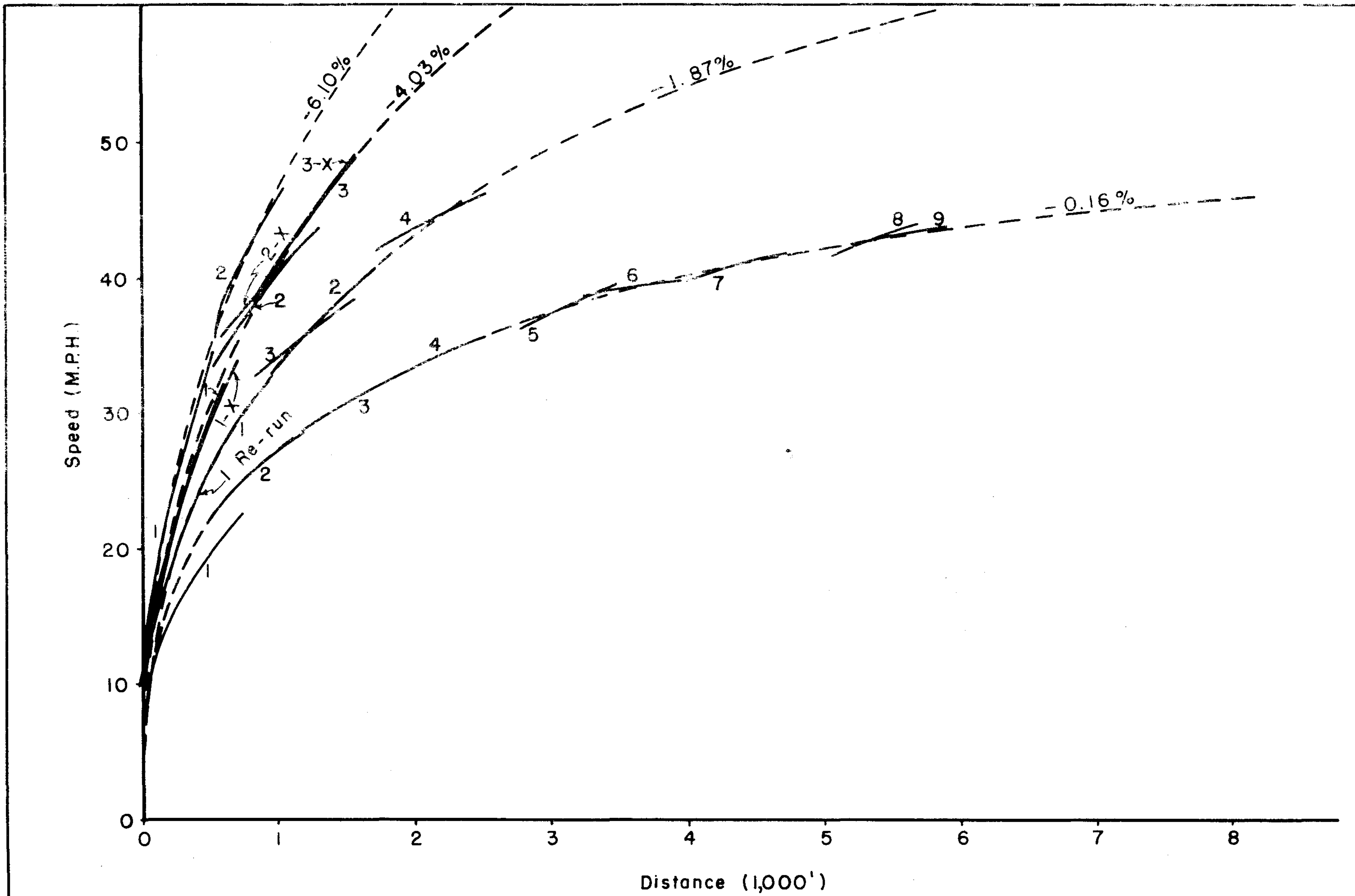
50
40
30
20
10
0
SPEED (M.P.H)
0
1
2
3
4
5
6
7
8
DISTANCE (1,000')
0.77%
3.13%
5.43%
7.62%
1
2
3
4
5

Fig. 13



Speed (MPH)
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
Distance (1000')
0.97%
3.26%
6.05%
1
2
3
4
5
6
7
8

Fig. 14



-6.10%
-4.03%
-1.87%
-0.16%
3-X
2-X
1-X
1 Re-run
Speed (M.P.H.)
Distance (1,000')
0
10
20
30
40
50
1
2
3
4
5
6
7
8
9

Fig. 15

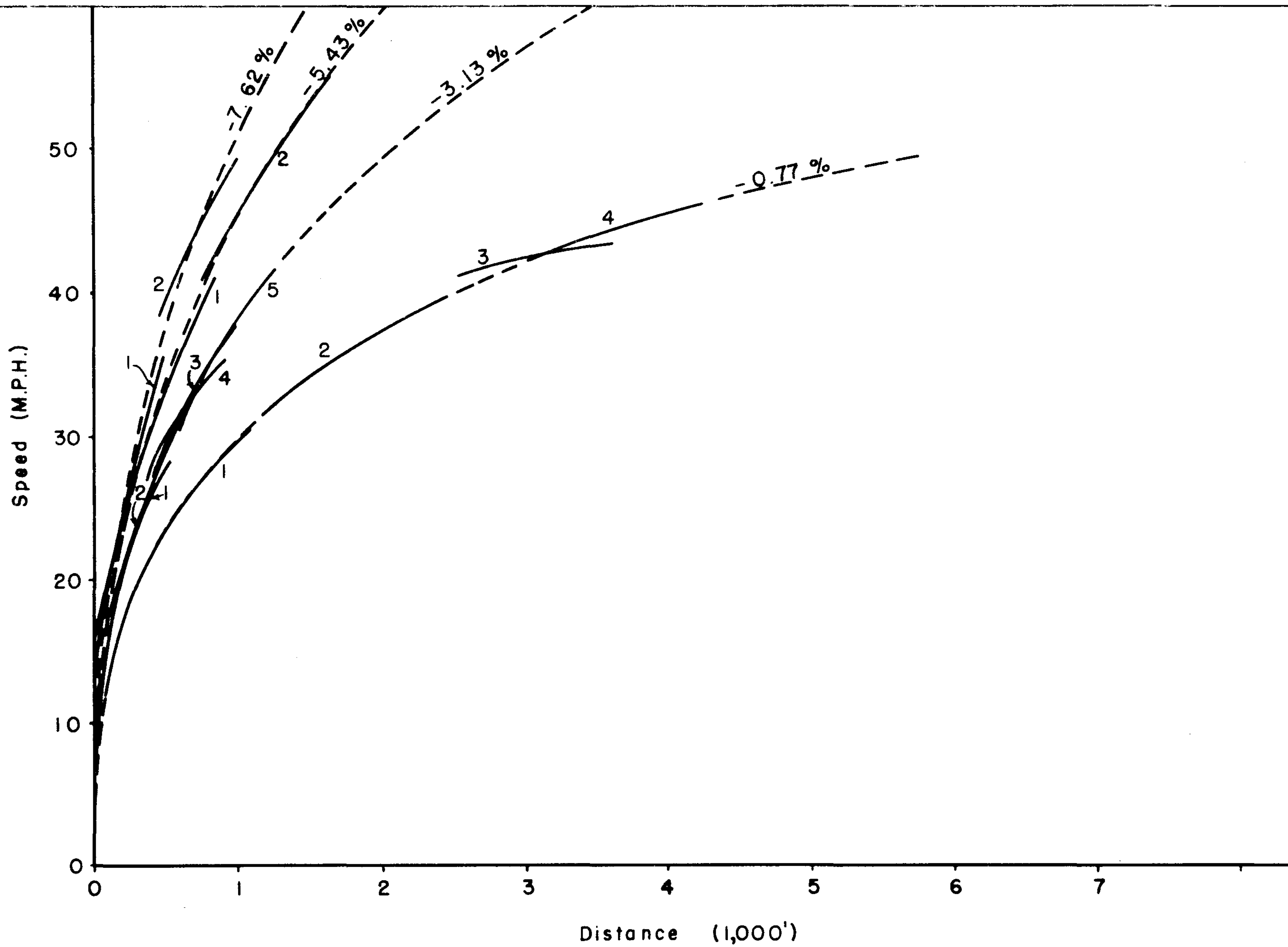
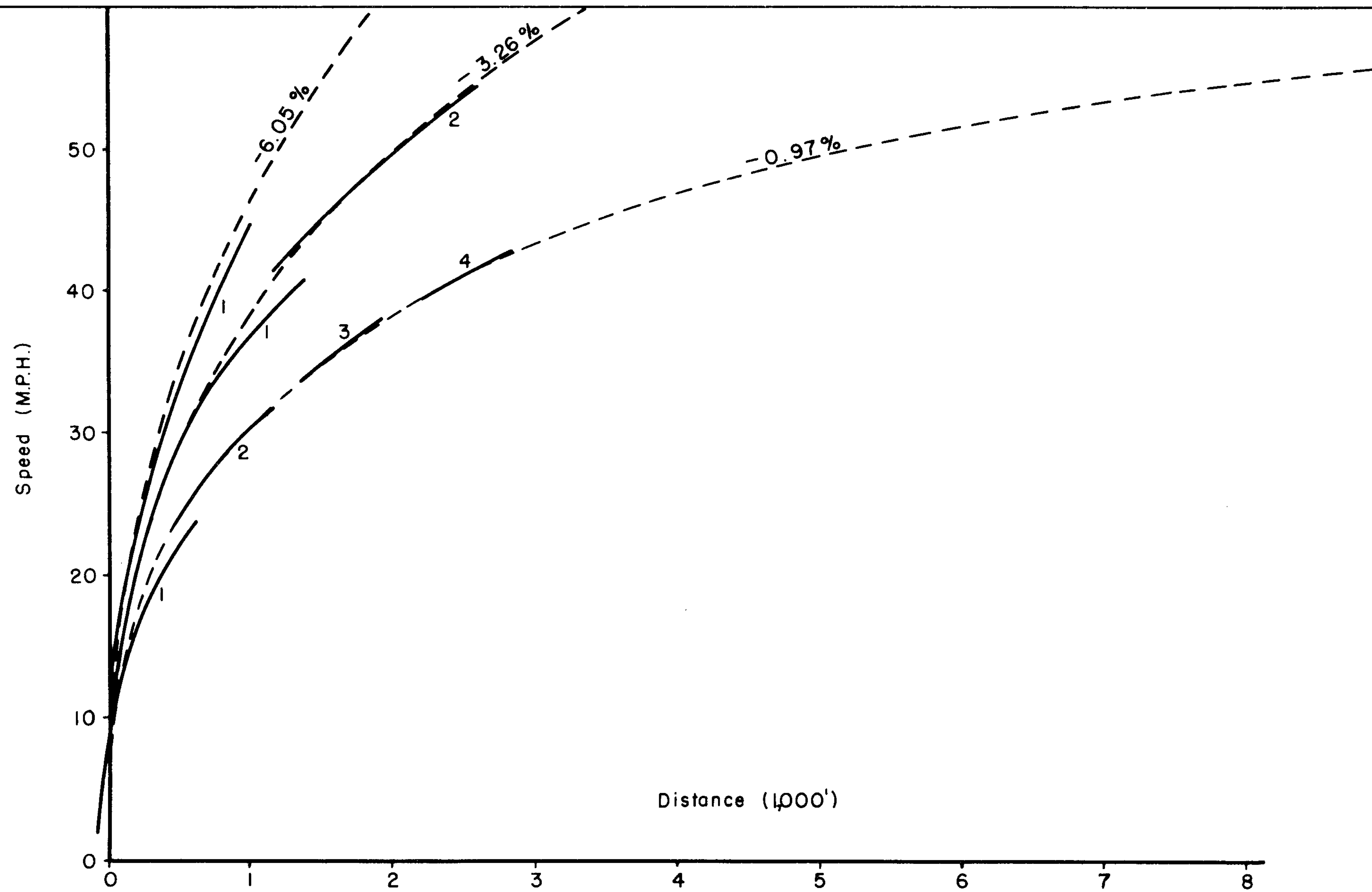

-7.62 %
-5.43 %
-3.13 %
-0.77 %
Speed (M.P.H.)
Distance (1,000')
0
10
20
30
40
50
1
2
3
4
5
6
7

Fig. 16



-6.05 %
-3.26 %
-0.97 %
1
1
1
2
2
3
4
Speed (M.P.H.)
Distance (1,000')
0
10
20
30
40
50
0
1
2
3
4
5
6
7
8

Fig. 17

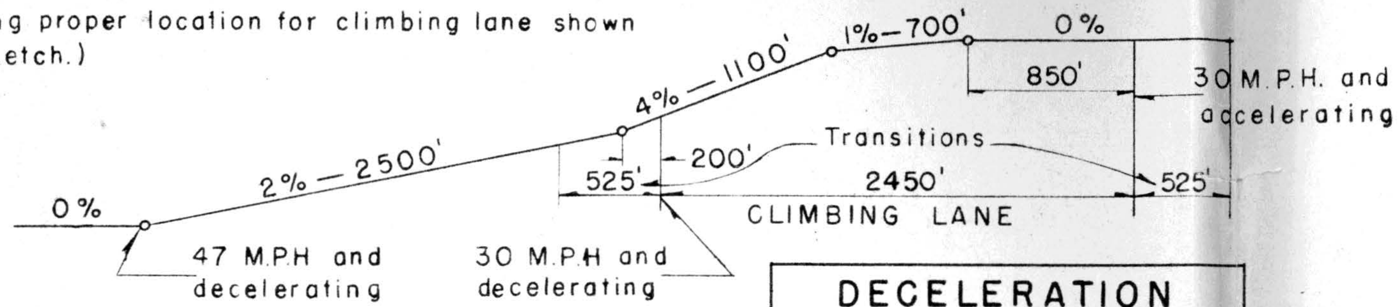
FIGURE 18

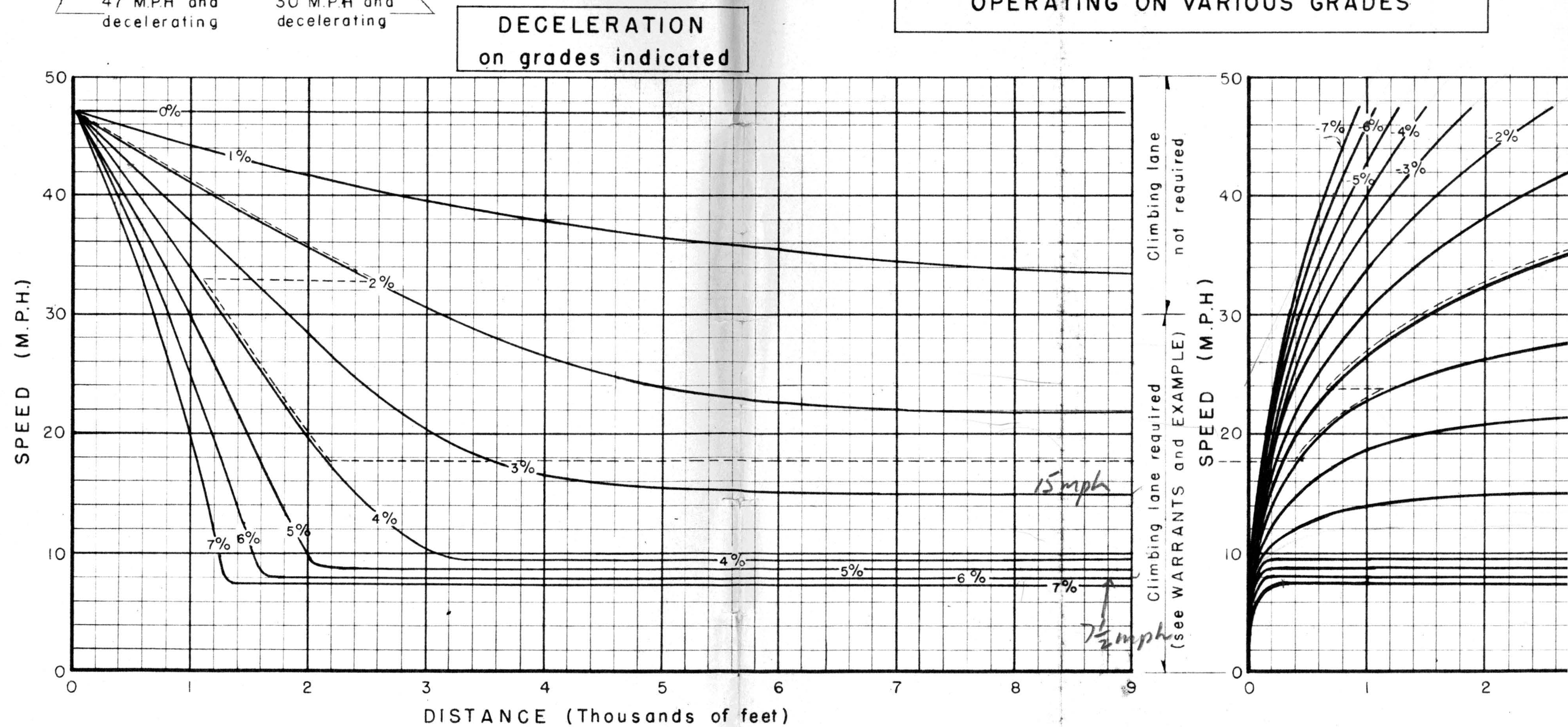
SPEED-DISTANCE CURVES

FROM ROAD TEST OF
A TYPICAL HEAVY TRUCK
OPERATING ON VARIOUS GRADES

EXAMPLE OF USE OF CURVES

(Dashed lines on graph indicate steps taken in finding proper location for climbing lane shown on sketch.)





Trim Line

. and
ating

FIGURE 18

SPEED-DISTANCE CURVES

FROM ROAD TEST OF
A TYPICAL HEAVY TRUCK
OPERATING ON VARIOUS GRADES