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RETARDERS FOR HEAVY VEHICLES: EVALUATION OF PERFORMANCE CHARACTERISTICS AND IN-SERVICE COSTS

Phase I - Technical Report

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16. Abstract

The potential benefits to be derived from retarder use in heavy truck applications are evaluated in terms of (1) productivity gains due to decreased trip time, (2) cost savings due to decreased brake wear and maintenance, and (3) safety enhancement due to reduced probability of a runaway accident. The physical factors influencing downhill speed control are described and analyzed. The characteristics of currently available retarders are discussed. An assessment of the retarder market and its future potential is presented. An examination of available accident information is employed in developing safety performance analyses of heavy vehicles on downgrade sections of highways. The results of these various studies are applied in summarizing the items that prospective buyers of retarders need to know in order to estimate the cost benefits to be obtained from various levels of retarder power.

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Ms. Barbara Edstrom of HSRI gathered and organized the extensive summary of state information presented in Appendix D.

The rate of return analysis was prepared by Mr. Gary Hu of HSRI and graphs were made by Ms. Barbara Edstrom.

This manuscript was typed by Ms. Jeannette Nafe. The figures were prepared by Mr. Gary Hu.

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1.0 INTRODUCTION

This document presents results from the first phase of a two-phase project, entitled "Retarders for Heavy Vehicles: Evaluation of Performance Characteristics and In-Service Costs," being performed by the Highway Safety Research Institute (HSRI) of The University of Michigan on behalf of the National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation.

The work in Phase I has been conducted in three tasks directed at (1) characterizing the current use of retarders, (2) analysing the safety performance of heavy trucks, particularly with regard to "run-away" accidents, and (3) developing calculation procedures that can form the technical basis of a recommended practice for retarder performance evaluation, selection, and use. This report organizes and utilizes findings from these three initial tasks to provide an assessment of the potential for deriving operational, cost, and safety benefits from the use of retarders.

In the next two sections, entitled "Characterization and Analysis of Retarder Use" and "Safety Performance Analysis," background information is furnished on the following subjects: the physics of downhill retardation; descriptions of currently marketed retarders; the retarder market; legal, social, and subjective factors having a bearing on the use of retarders; the extent of downhill runaway problem; countermeasures for the downhill runaway problem; and methods for estimating the reduction of accident costs through the use of retarders.

Section 4 addresses the potential for reducing trip time, brake lining wear, and accident costs through the expanded use of retarders. Section 5 presents a discussion of the data and information needed for making an objective decision on whether to purchase a retarder. Preliminary conclusions and recommendations, derived from the on-going Phase I work, are presented in Section 6. Detailed information and data covering accident, economic, and vehicle-usage factors, plus equations pertaining to brake temperature are included in several appendices.

2.0 CHARACTERIZATION AND ANALYSIS OF RETARDER USE

The focus of this section centers on the use of retarders for providing braking capabilities in addition to those supplied by the foundation brakes of heavy vehicles. Traditionally, the retarder has been viewed primarily as a safety device for heavy trucks. Nevertheless, efforts are being made currently to emphasize the cost savings, due to reduced brake wear, that can be obtained by using a retarder rather than the foundation brakes for speed reductions requiring moderately low levels of braking torque. This section addresses the application of retarders both in the downhill braking situation and in efforts to economize on the costs of trucking.

2.1 Physical Specifications of Retardation Capabilities Sufficient for Downhill Speed Control

The control of heavy trucks during steep mountain descents is a safety problem that highway departments, truck drivers, fleet owners, brake and retarder manufacturers, and agencies of the federal government have addressed in various ways. For example, highway departments have built run-off ramps or provided "sand piles" for stopping heavy runaway trucks at selected sites [1].* To prevent brake fade and subsequent loss of speed control, drivers of heavy vehicles have learned to proceed down steep grades at moderate speed and in an appropriately low gear. Safety-conscious fleet owners have established maintenance and inspection programs to ensure proper brake adjustment. Equipment manufacturers have developed (1) economical, fade-resistant brakes and (2) auxiliary braking devices (retarders) for supplementing the foundation brakes. The federal government has supported work aimed at developing a "Grade Severity Rating System" [2] that would employ road signs to inform drivers of (1) the severity of an approaching hill and (2) safe operating speeds, depending upon the weight of the vehicle. The evidence from accident studies (see Section 3) and records of run-off ramp usage indicates the existence of a significant

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*References included in square brackets are listed in Section 7.0.

truck runaway problem and thereby provides a safety-oriented justification for all efforts aimed at reducing the truck runaway problem.

Given the premise that a downgrade descent problem exists, the purpose of this section is to use physical principles and engineering methods to identify the retarding capability necessary for preventing a specific vehicle from accelerating on a particular highway grade.

The total retarding capability of a vehicle comes from a number of sources in addition to the foundation brakes and the retarder (if a retarder is installed). This situation is illustrated in Figure 2.1 which is a free-body diagram of a tractor-trailer combination making a constant-speed descent on a road whose grade, in percent, is given by 100 tan θ. For constant speed, the gravitational propelling force, W sin θ, is balanced by all of the forces resisting forward motion. With the drive wheels coupled to the engine, the forces resisting forward motion are

(1) aerodynamic drag,

(2) tire rolling resistance,

(3) retarding force at the drive wheels deriving from the torque created by the engine with throttle closed, F_{xeng}, and

(4) braking forces, F_{xbi}, created at each braked wheel by means of a mechanical friction brake and/or a retarder.

If we assume that a retarder is not provided and that, at a given line pressure, all brakes are generating an equal amount of brake torque,* the laws of physics yield the following expression for the horsepower that must be continuously absorbed by a single brake, viz.:

$$HP_{\substack{single\\brake}} = \frac{1}{n}\left[\left(W \sin \theta - F_{x_{RR}} - F_{x_{aero}}\right)\frac{V}{375} - HP_E\right] \qquad (1)$$

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*In practice, this does not occur because the push-out pressures may vary from brake to brake, and the torque per unit line pressure may be set differently on each axle, and brake adjustment may vary from brake to brake.

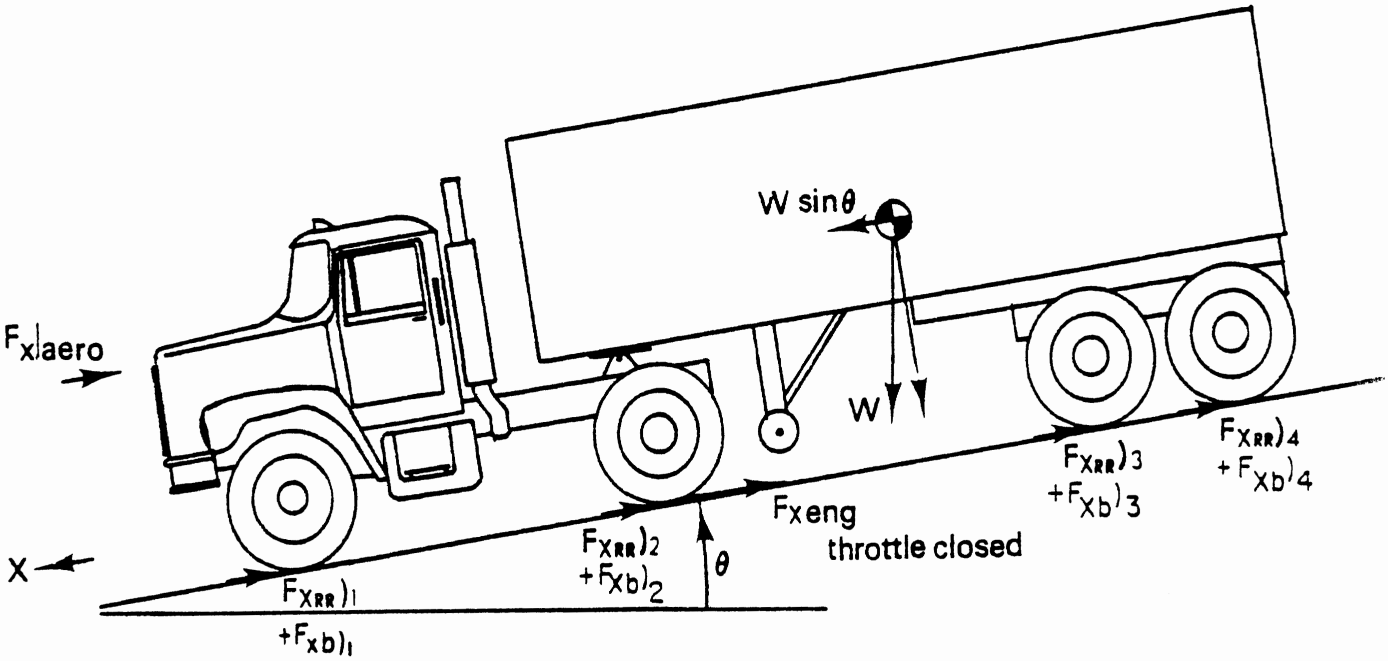

Figure 2.1. Free-body diagram of a four-axle tractor-trailer descending a grade at constant speed.

where

n = number of braked wheels

$F_{x_{RR}}$ = tire rolling resistance summed over all wheels, lb

$F_{x_{aero}}$ = aerodynamic drag force, lb

HP_E = horsepower absorbed by the engine with the throttle closed

V = speed of descent, mph

W = total weight of the combination vehicle, lb

θ = angle of the road plane with respect to the horizontal

Clearly, the horsepower to be absorbed by a single brake will increase:

(1) as the number of operational or installed brakes decreases

(2) with increased speed of descent

(3) with increased total weight

(4) with increased grade angle

(5) with decreased rolling resistance of the tires

(6) with decreased aerodynamic resistance

(7) as the horsepower that can be absorbed by the installed engine decreases

Accordingly, Equation (1) shows that existing plans to make trucking more fuel efficient by:

(1) increasing the total weight,

(2) reducing (a) the rolling resistance of tires and (b) aerodynamic drag, and

(3) reducing the internal losses in the engine

will require that each brake absorb more horsepower on a given grade at a given speed. If additional sources of retardation are not utilized, it can be anticipated that the trends to make trucking more fuel efficient will require that trucks descend grades at lower speeds to keep the horsepower absorbed by the mechanical friction brake within acceptable limits. It follows that trucking productivity will decrease in mountainous areas and that the potential for brake overheating and fade in long descents will likewise increase.

In order to reduce the above discussion to a quantitative basis, Equation (1) can be expanded to reflect the properties of both past and present-day (or future) trucks. Typical expressions for the retarding power provided by aerodynamic drag and rolling resistance are as follows:

$$HP_A = \frac{C_W \, AV^3 \, C_A}{375} \qquad (2)$$

where

HP_A is the horsepower absorbed through aerodynamic drag

A is the frontal area of the vehicle in ft^2

V is the velocity in mph

C_W is a drag coefficient (approximately 0.002)

and C_A is a coefficient representing the influence of drag reduction devices (C_A = .09 to 0.75 for various drag reduction improvements)

$$HP_{RR} = \frac{C_{RR} \, WV \, C_T}{375} \qquad (3)$$

where

HP_{RR} is the horsepower absorbed by rolling resistance

C_{RR} describes the tire/road interface (C_{RR} = 0.012 is a representative value for good roads)

C_T describes the tire construction (C_T = 1.0 for bias tires, C_T = 0.7 for radial tires)

W is the vehicle weight (GVW) in lbs.

With respect to engine friction, a standard 290 hp engine produced in 1974 absorbed approximately 113 hp including the effects of driveline efficiency and accessory power, while a 300 hp engine produced in 1980 will absorb approximately 75 hp under the same conditions [3]. Figure 2.2 has been constructed to illustrate representative magnitudes for these sources of "natural" retardation for an 80,000-lb vehicle operated at velocities from 10 to 60 mph. (The values plotted in Figure 2.2 are tabulated in Table 2.1.) Examination of these typical results indicates that fuel economy measures may reduce a vehicle's natural retardation by approximately 100 hp at 55 mph.

In addition, these results (Figure 2.2 and Table 2.1) show that the contributions of engine friction, aerodynamic drag, and rolling resistance are approximately equal at 55 mph, although the importance of aerodynamic drag reduces dramatically at lower speeds.

The influence of natural retardation on the power balance needed to maintain constant velocity on a downgrade is summarized by the following equation:

$$HP_{B/R} = HP_H - HP_N \tag{4}$$

where

$HP_{B/R}$ is the required braking/retarder horsepower

HP_H is the power supplied by the downgrade

and

$$HP_N = HP_E + HP_{RR} + HP_A \tag{5}$$

The horsepower of a particular downgrade, θ, is linearly related to the vehicle speed by the following equation:

$$HP_H = \frac{W \theta V}{375} \tag{6}$$

(where $\theta \approx \sin \theta$ for highway grades).

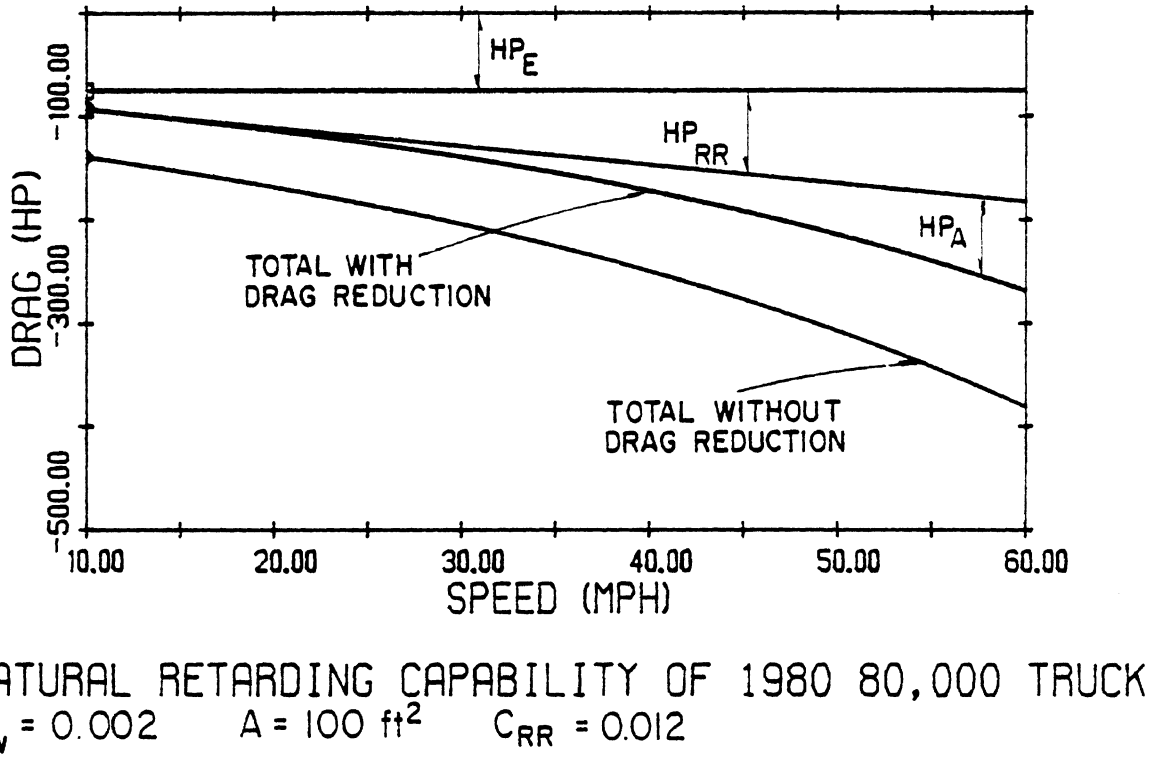

Figure 2.2. Magnitude of the sources of natural retardation.

Table 2.1. Sources of Natural Retardation

V_{mph}	Aerodynamic HP_A ($C_A = 0.75$)	Rolling Resistance HP_{RR} ($C_T = 0.7$)	Engine HP_E	Total With Fuel Saving Devices	Total Without Fuel Saving Devices	ΔHP
10	0	18	75	93	140	47
20	3	36	75	114	168	54
30	11	54	75	140	204	64
40	26	71	75	172	249	77
50	50	90	75	215	307	88
60	86	108	75	269	381	112

Example results from applying Equations (4), (5), and (6) to grades ranging from 2 percent to 10 percent are presented in Figure 2.3. This figure graphically illustrates the influence of natural retardation on the required braking and/or retarder horsepower for the example vehicle used in constructing Figure 2.2. In this case, for velocities above 30 mph the required braking/retarder horsepower, $HP_{B/R}$, happens to be approximately equivalent to the horsepower on a grade that is 2 percent less than the actual grade. As indicated in Figure 2.3, the natural retardation of this example vehicle is sufficiently large for preventing runaway on all grades less than or equal to 2 percent.

If the example vehicle were not equipped with radial tires, aerodynamic aids, and a low-friction engine, the natural retardation would have been enough for holding velocity on a grade of approximately 3 percent rather than on the 2-percent grade shown in Figure 2.3. Hence, the reduction in natural retardation due to fuel economy measures (roughly 100 hp) has approximately the same influence as operating on grades that are effectively 1 percent steeper than they are for a comparable vehicle without fuel economy improvements.

Now consider the use of a retarder to absorb the required braking/retarder horsepower.

For the purposes of this discussion,* retarders will be divided into two major categories, either "driveline" or "engine speed" retarders. A driveline retarder applies torque to a rotating element connected to the wheels without an intervening transmission. As the name implies, an engine speed retarder operates on the engine side of the transmission. The engine speed retarder produces a braking force at the wheels only when the transmission is in gear.

Since the horsepower capability of a driveline retarder is independent of engine speed, the determination of the downgrade performance of a vehicle equipped with this type of retarder is easy to

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*Detailed discussions of the features of various types of currently available retarders are presented in the next section.

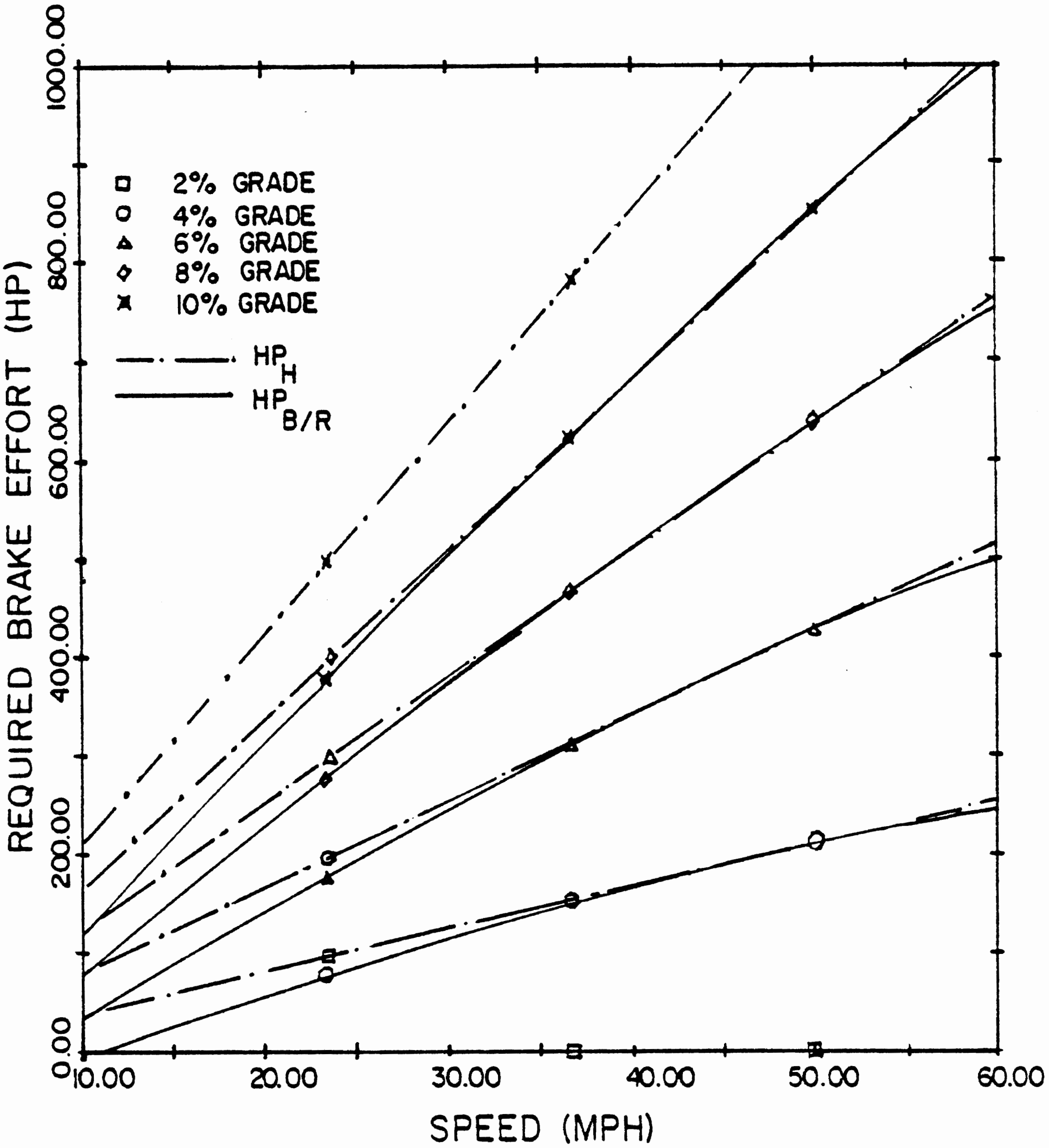


Figure 2.3. Required braking power.

explain. As indicated by Equation (6), the weight and forward velocity of the vehicle plus the slope of the grade are the important factors contributing to the horsepower of a given hill, i.e., HP_H. Given information on the natural retardation, the maximum vehicle weight, the slope of the steepest downgrade along the route, and an acceptable velocity on the steepest downgrade, the required retarding horsepower can be readily determined. A driveline retarder that can absorb this amount of required horsepower will maintain the desired velocity on the steepest hill to be encountered.

The characteristics of retarder horsepower as a function of speed can have an influence on the type of equilibrium that exists at a selected maximum speed. Figure 2.4 contains two examples illustrating a stable and an unstable equilibrium. In both examples, the required braking horsepower curve for a 6 percent grade (from Figure 2.3) represents the steepest hill to be considered. Also, in both examples, 40 mph is selected as the acceptable speed. In the first example, operation above 40 mph will result in surplus braking power tending to slow the vehicle to 40 mph, while operation at less than 40 mph will result in a deficiency of braking power causing the vehicle speed to increase towards 40 mph. Thus a stable equilibrium is achieved at 40 mph. In example 2, 40 mph is an unstable operating condition—above 40 mph the grade is sufficient to cause the vehicle to speed up, below 40 mph the retarder will reduce vehicle speed. If vehicle speed is less than 40 mph, the driver could cycle the retarder on and off to increase speed, but if the speed ever got above 40 mph, the retarder could not control speed and the foundation brakes would have to be used to reduce speed to 40 mph. Clearly, the retarder with an unstable equilibrium requires driver control actions that are not necessary in the stable equilibrium situation.

For an engine speed retarder, the selection of adequate retarder horsepower is easily demonstrated graphically. Figure 2.5 shows the power versus velocity characteristics of a hypothetical engine speed retarder superimposed on the 6 percent grade curve from Figure 2.3.

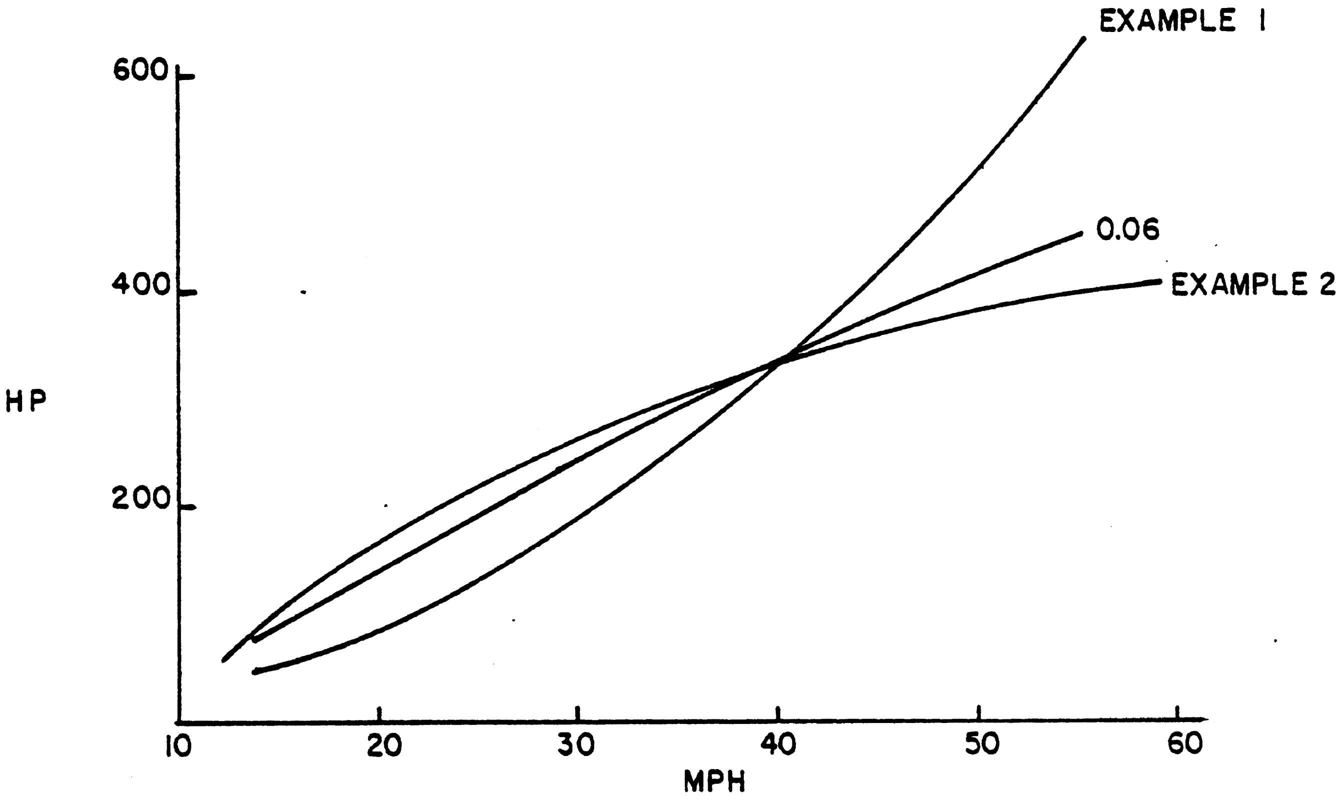


Figure 2.4. Examples of stable and unstable equilibrium.

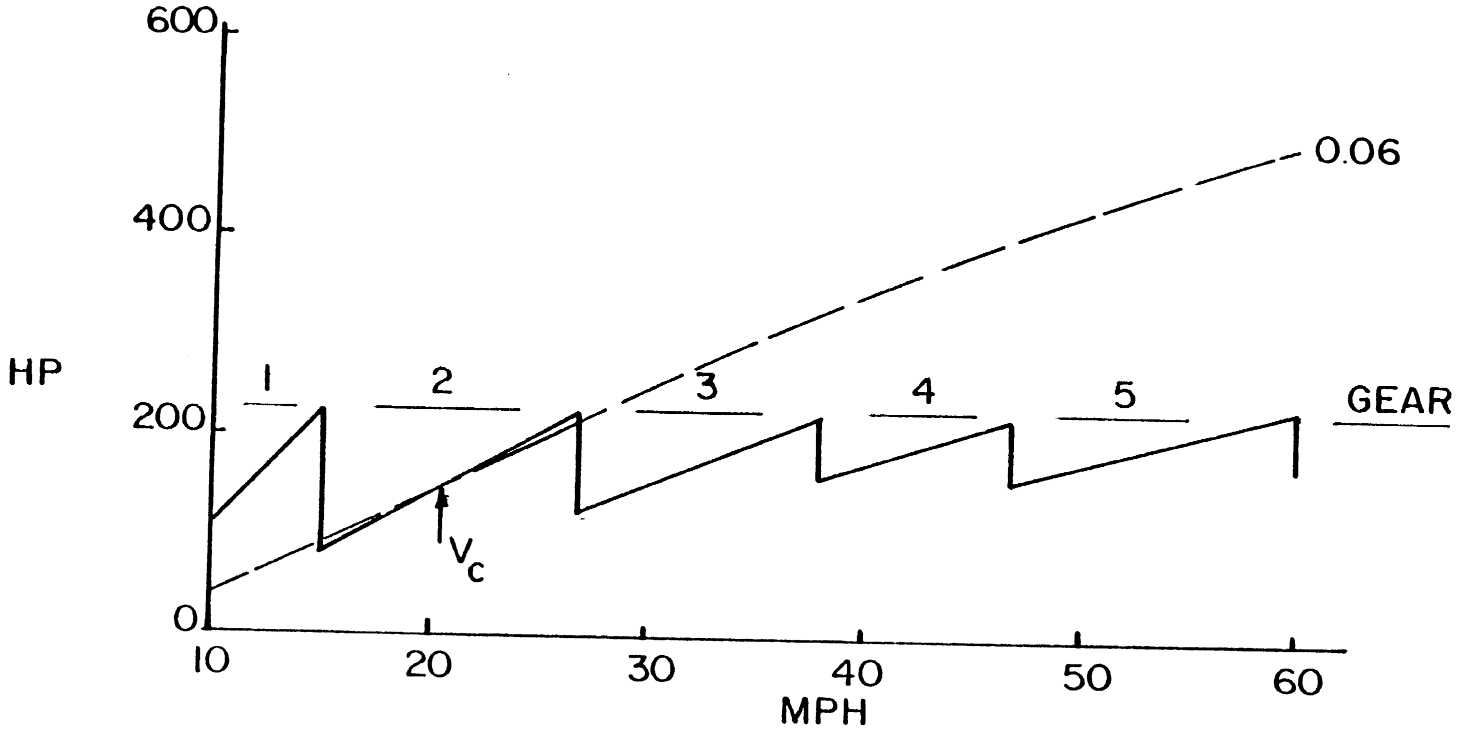


Figure 2.5. Control speed, V_c, for an engine speed retarder.

The retarding horsepower is shown to fall off with engine speed in each gear range. For the example shown in Figure 2.5, the equilibrium speed is approximately 20 mph in second gear. This speed, V_C, occurs at a stable equilibrium condition.

If 20 mph were not fast enough to be acceptable, one could consider (1) a different transmission with a more favorable set of speed ranges for its gears, (2) a higher horsepower retarder, or (3) the use of the foundation brakes in addition to the retarder.

Although discussions with personnel from retarder manufacturing companies have indicated that they specify retarders capable of maintaining speed control without utilizing the foundation brakes, it is of interest to consider the use of foundation brakes for maintaining speed control with and without the aid of a retarder. For a number of years highway engineers have been interested in this problem and in devising schemes of rating downhill sections of road to aid truck drivers. This interest has led to the development of a proposed grade severity rating system based on brake temperature [2]. The proposed rating system represents a trade-off between the desire to travel rapidly and the need to prevent overheating the brakes to the point where they can no longer supply the torque required to control vehicle speed. The following discussion examines the implications of restricting brake temperature to be at, or below, a specified maximum value.

Appendix A contains an analysis of the brake temperature changes taking place during a constant velocity descent on a fixed grade of given length. The basic result obtained in Appendix A for the maximum temperature (which occurs at the bottom of the hill) is expressed by the following equation:

$$Q_f = Q_0 \, e^{-L/V\tau} + \left(\frac{HP_B}{h(V)} + Q_a \right) \left(1 - e^{-L/V\tau} \right) \qquad (7)$$

where

Q_f is the final brake temperature

Q_o	is the initial brake temperature at the top of the grade
L	is the length of the grade
V	is the velocity
τ	is the thermal time constant of the brakes
HP_B	is the horsepower input to the brakes (i.e., the absorbed horsepower)
$h(V)$	is a cooling coefficient that is a function of velocity
Q_a	is the ambient temperature

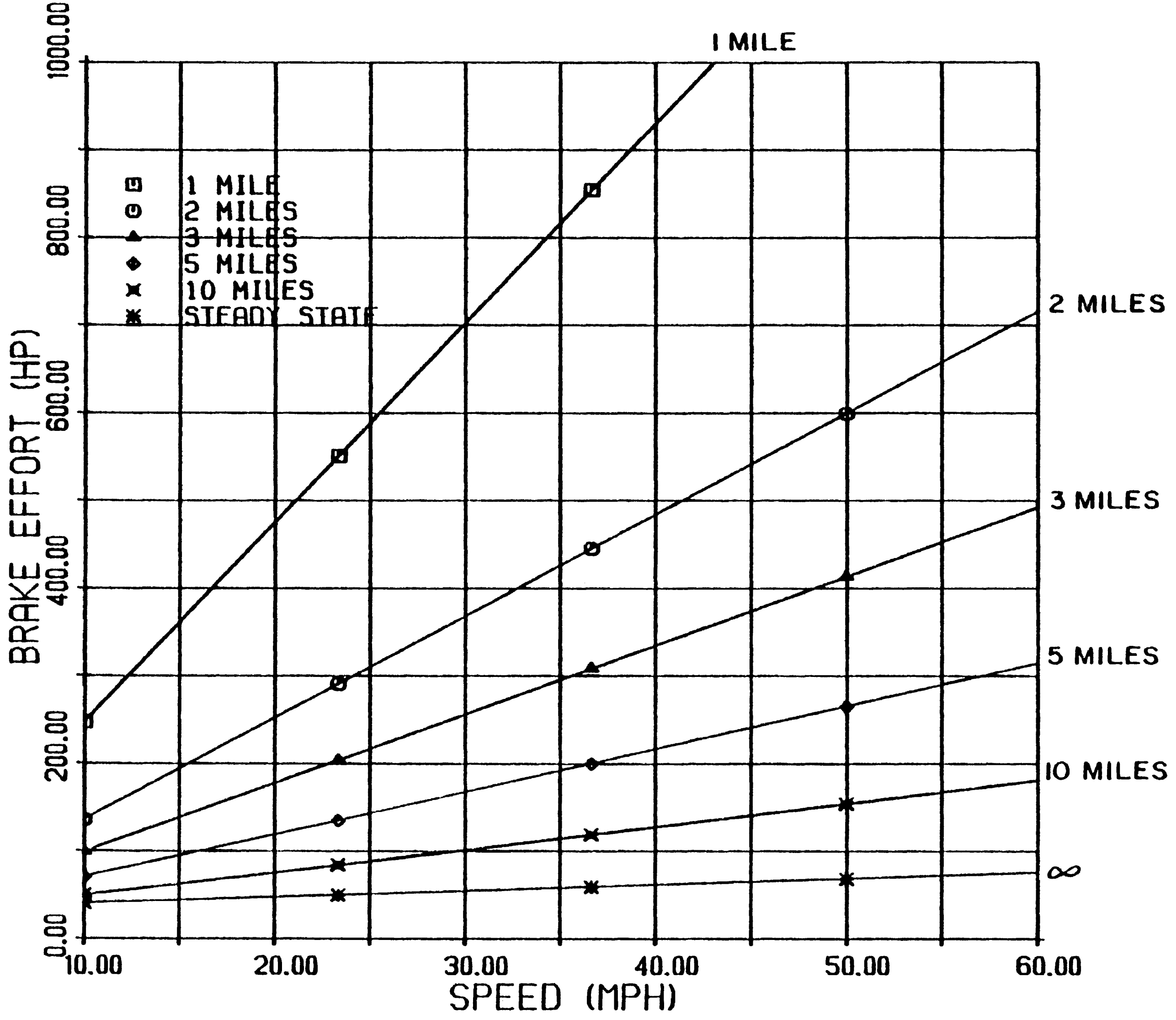
Note that $L/V = t_f$, the length of time required to descend the grade.

In order to emphasize the influence of the length of grade, and control velocity, V_c, on the horsepower that the brakes can absorb without exceeding the temperature boundary, Q_f, Equation (7) can be restated (rearranged) as follows:

$$HP_B = \left[\left(\frac{Q_f - Q_o \, e^{-L/V_c\tau}}{1 - e^{-L/V_c\tau}} \right) - Q_a \quad h(V_c) \right] \tag{8}$$

Figure 2.6 presents the results of applying Equation (8) to various length grades over the range of velocities from 10 to 60 mph. This figure shows the horsepower that the brakes can absorb without violating the temperature constraint for the five-axle, tractor-semitrailer vehicle studied in [2].

Equations (4) and (8) form a set of simultaneous equations for HP_B and V_c with the independent variables being L and θ. (An example graphical solution of these equations can be obtained by (1) superimposing Figures 2.3 and 2.6 and (2) reading off the velocity and horsepower at points corresponding to known (selected) grades, θ, and lengths of grade, L.) The solution of these equations for a hill specified by a grade, θ, and a length of grade, L, consists of the



$Q_o = 150° F \quad Q_a = 90° F \quad Q_f = 425°F$

Figure 2.6. Brake capabilities based on a maximum temperature.

safe descent speed, V_C, and the amount of brake horsepower, HP_B, required for descending that hill at the safe speed. ("Safe speed" means that speed for which Q_f, the final temperature, will not exceed the selected maximum temperature (e.g., 425°F for drum-type brakes). In fact, using the approach described, Q_f will equal the selected maximum temperature, thereby providing the minimum time (maximum velocity) solution.)

A typical solution for the safe descent speed as a function of grade and grade length can be used to develop an understanding of the implications of setting a temperature limit. Figure 2.7 has been generated using the vehicle and brake parameters employed in constructing Figures 2.3 and 2.6. As illustrated in Figure 2.7, the allowable speed on a steep grade has a rather abrupt transition between being almost independent of length for long grades to being a very sensitive function of length in the region near the minimum length at speeds approaching 55 mph. For example, on a 6-percent grade ($\theta = 0.06$ radians) the vehicle can be operated at 55 mph if the grade is 2.9 miles long. However, if the grade is 3.0 miles long, the safe speed is 36 mph, and, if the grade is 5.0 miles long, the safe speed is 16 mph. For steeper grades this trend is even more accentuated. On an 8-percent grade, a change in length from 1.9 to 2.0 miles reduces the safe speed from 55 mph to 28 mph. These results indicate that for steep grades there is a sharply defined critical length above which the allowable speed of descent falls rapidly from 55 mph to below 20 mph.

Further insight into the meaning of setting a brake temperature limit can be derived from looking at graphically obtained solutions for horsepower and control speed on grades of 6 and 8 percent and at grade lengths of 2 and 3 miles, as portrayed in Figures 2.3 and 2.6, respectively. The appropriate curves from Figures 2.3 and 2.6 are displayed in Figure 2.8. The lower pair of curves (one for a 6 percent grade and the other for a length of 3 miles) are seen to merge at 40 mph and remain very nearly equal up to 60 mph. In this speed range, the increase in required braking horsepower due to increased speed on the grade is nearly matched by (1) the higher convective heat

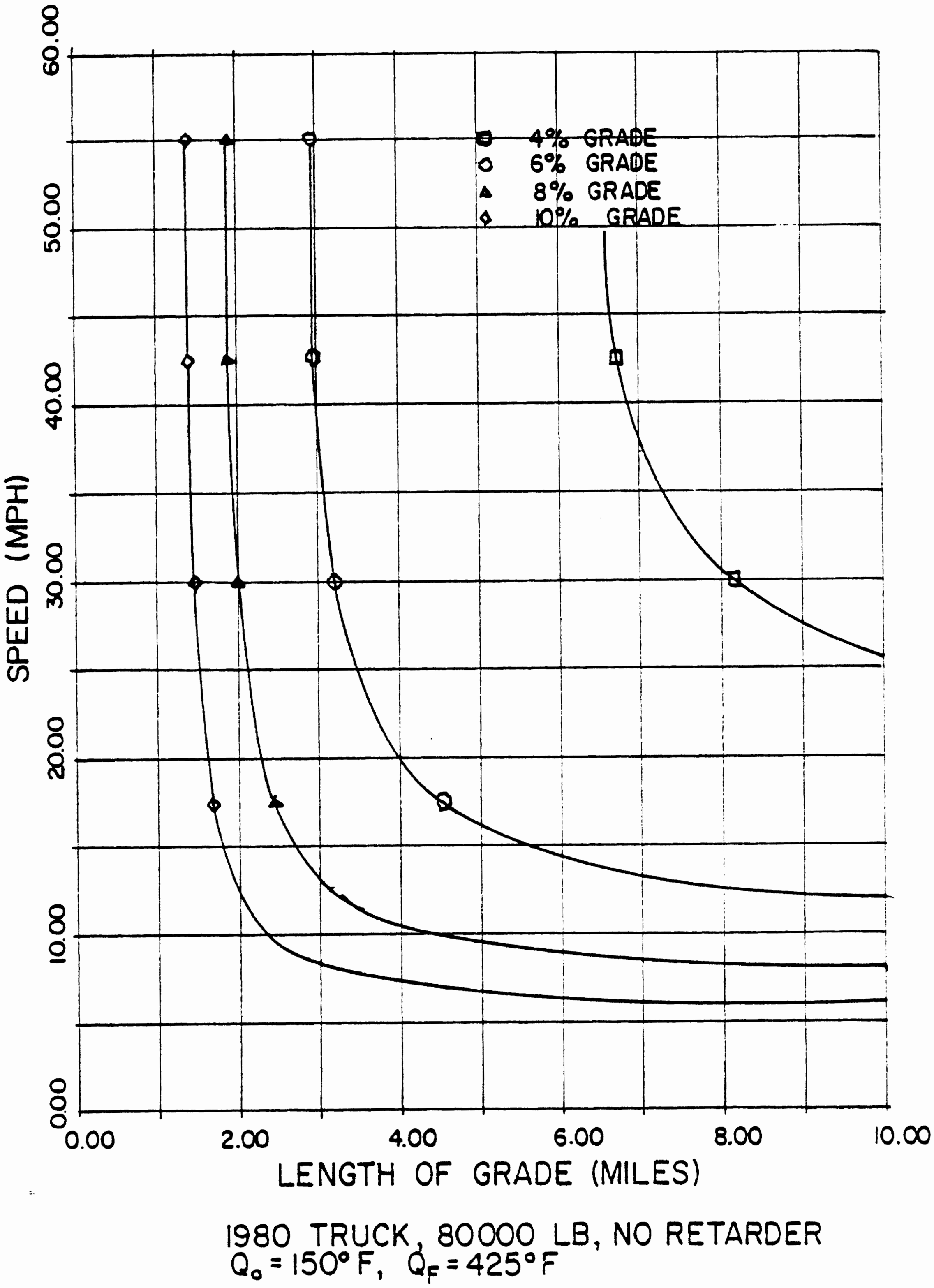


Figure 2.7. Allowable speed versus length of grade for various grades.

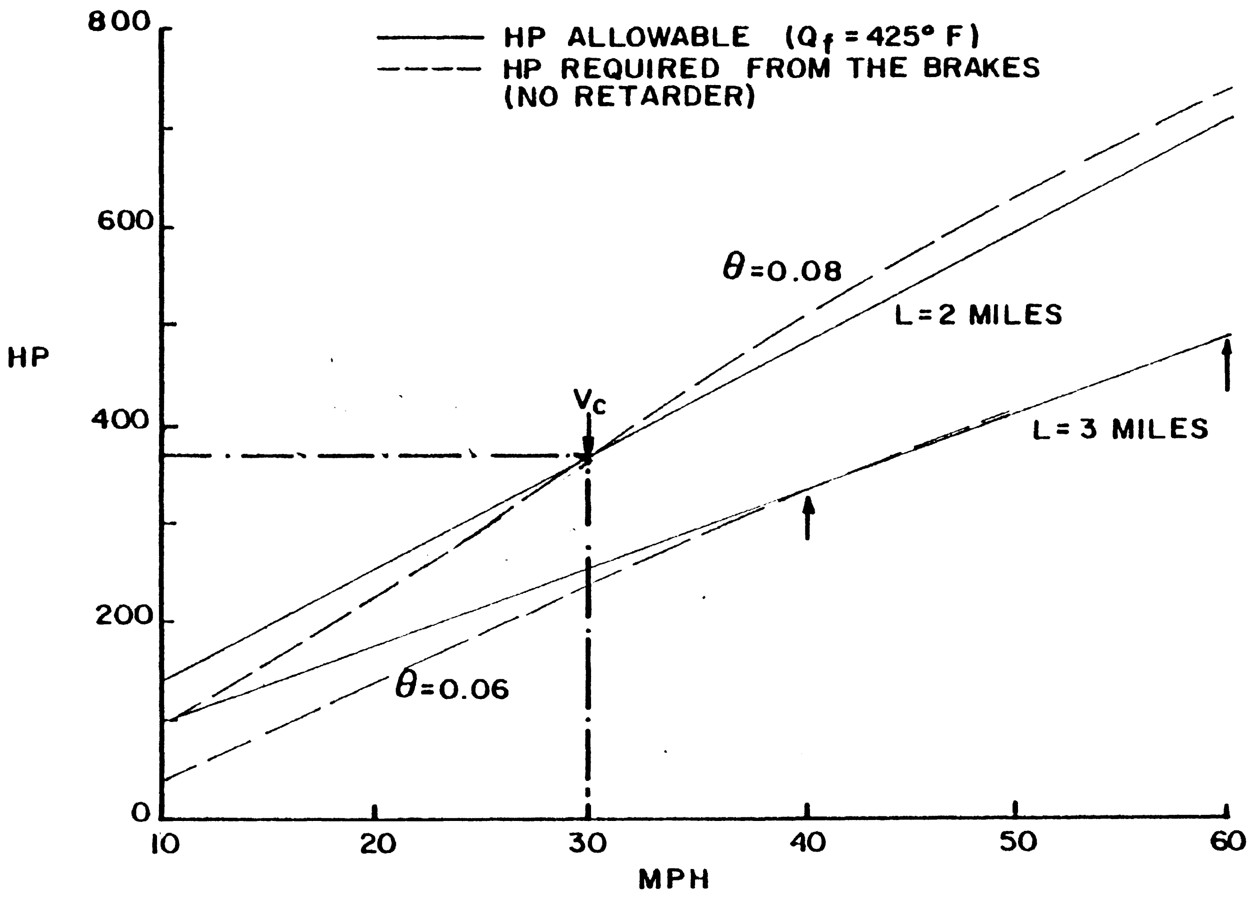


Figure 2.8. Graphical solutions for control speed and absorbed horsepower.

transfer and (2) the shorter time on the grade as speed increases. Clearly, small changes in length or grade can make large changes in the control speed in this case.

The upper pair of curves (for θ = 8 percent and L = 2 miles) intersect at a control speed of approximately 30 mph with an accompanying requirement for the brakes to absorb approximately 370 horsepower. The solution at 30 mph and 370 horsepower is a point of unstable "equilibrium" in the sense that if the speed exceeds 30 mph, there is no inherent mechanism to force the vehicle's speed back to 30 mph without exceeding the temperature boundary. However, for speeds up to 35 mph, an additional 10 horsepower of braking effort would be enough to cause the velocity to fall off towards 30 mph (the equilibrium point for a final temperature of 425°F). Hence, even if the vehicle speed did approach 35 mph and some slight additional braking were required to reduce speed, the final temperature would not necessarily exceed 425°F by a significant amount. Thus, it appears that small errors (on the order of 2 or 3 mph) in controlling speed will not lead to excessive temperatures.

However, a major difficulty associated with setting a temperature limit is the slowness of the process of cooling the foundation brakes. The length of time for cooling a brake from 425°F to 150°F (e.g., as might be considered in a grade severity rating system [2]) is on the order of 40 minutes, depending upon vehicle speed. For mountainous regions with closely spaced downgrades, the distance between applications of the brakes may not be far enough to allow the brakes to cool to 150°F. This point is illustrated in Figure 2.9, which was constructed using Equation (7) with $HP_B \equiv 0$. As shown in the figure, the example vehicle would have to travel 39 miles at 60 mph or 26 miles at 30 mph (without applying the brakes) to cool the brakes from 425°F to 150°F.* For a mountainous region with downgrades spaced approximately 7 to 10 miles apart, Figure 2.9 indicates that once the

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*Two competing factors influence these results: (1) slower speed means longer cooling time and (2) higher speed provides a higher cooling rate. In this case, the slower speed yields the shorter distance.

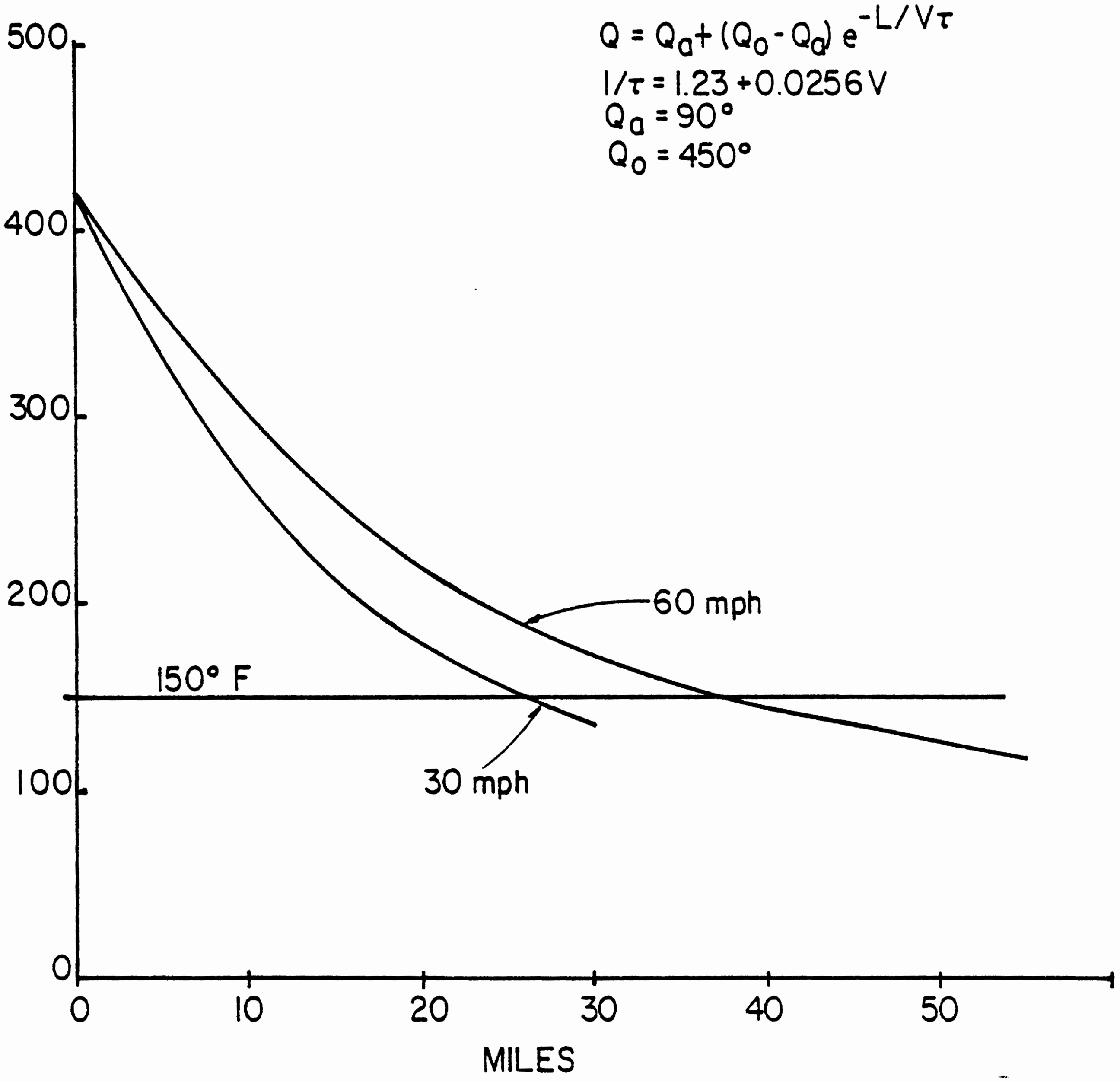

Figure 2.9. Miles to reach 150°F.

brakes are heated to 425°F, they will cool only to approximately 300°F for speeds in the range from 30 to 60 mph.

The initial brake temperature at the top of a downgrade is an important parameter in determining the control speed for descending the grade without exceeding the temperature limit. Specifically, a change from Q_0 = 150°F to Q_0 = 300°F has a large influence on the selected control speed, as shown in Figure 2.10. At 55 mph, for example, the allowable lengths of grade for various grades are shown in Table 2.2. Given that the driver may be unaware of brake temperature, the potential for an erroneous choice of speed for various length grades appears to be a hazard in mountainous areas unless the driver is able to follow carefully determined control speed information.

Table 2.2. Length of Grade, L, in Miles for V_c = 55 mph for Two Initial Brake Temperatures and Four Grades.

Q_0 °F \ θ Percent	4%	6%	8%	10%
150	6.6	2.9	1.9	1.4
300	3.3	1.4	0.9	0.7

Clearly, if both the foundation brakes and a retarder are used for downhill speed control, then speeds of descent faster than those applicable to operation with the brakes alone can be allowed without absorbing too much power in the foundation brakes. For example, Figure 2.11 indicates that a vehicle equipped with a retarder producing 200 hp over the normal influence of engine drag can operate at 55 mph on 4 percent grades up to at least 10 miles long without exceeding a brake temperature limit of 425°F even if the initial brake temperature at the top of the hill were 300°F. On a 6-percent grade that is 10 miles long, the control speed is shown to be 34 mph in Figure 2.11. In comparison, the results for a comparable vehicle using the foundation brakes alone (see Figure 2.10) are (1) 3.3 miles at 55 mph on a 4-percent grade and (2) a control speed of 11 mph on a 6-percent grade that

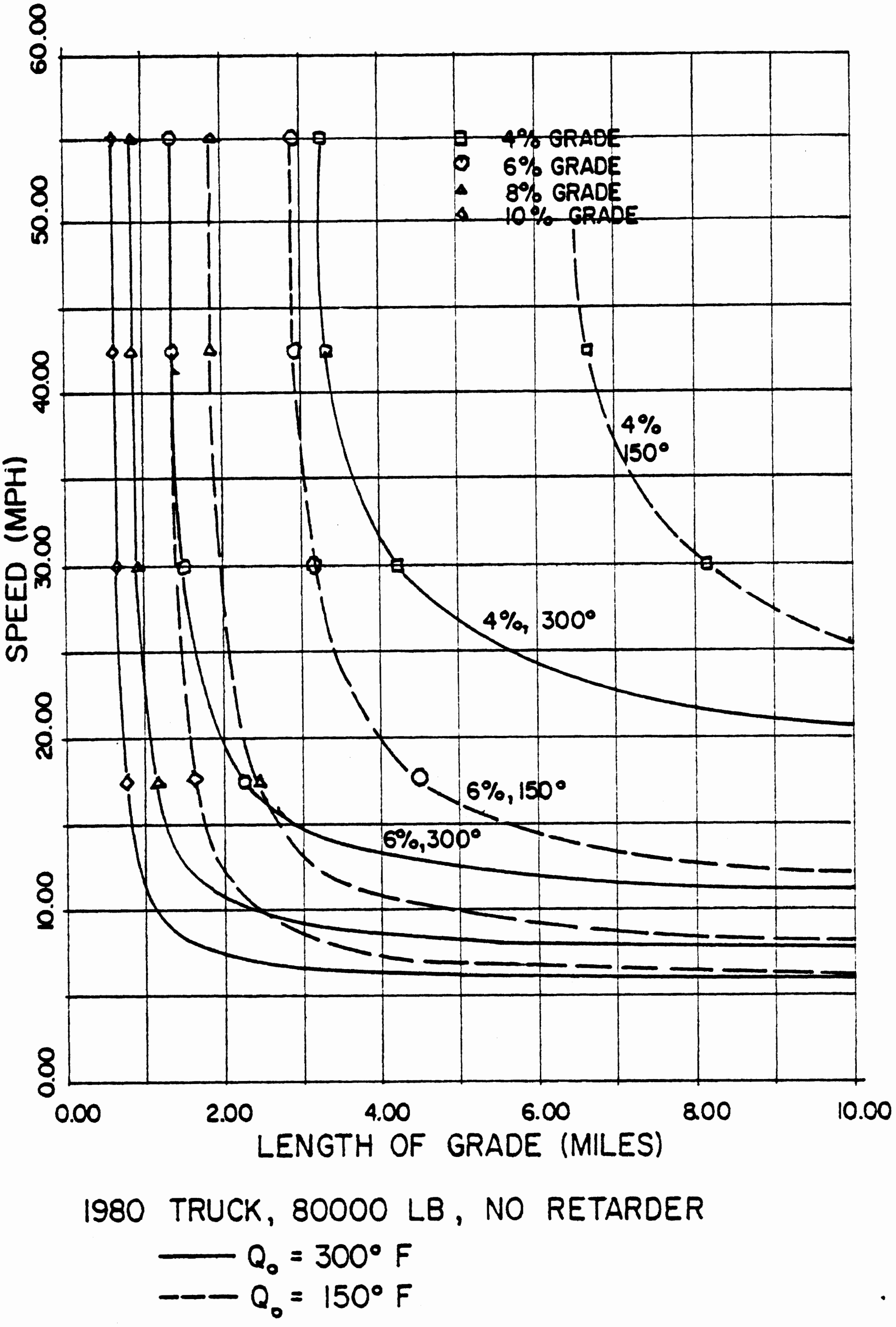

Figure 2.10. Influence of initial brake temperature on control speed.

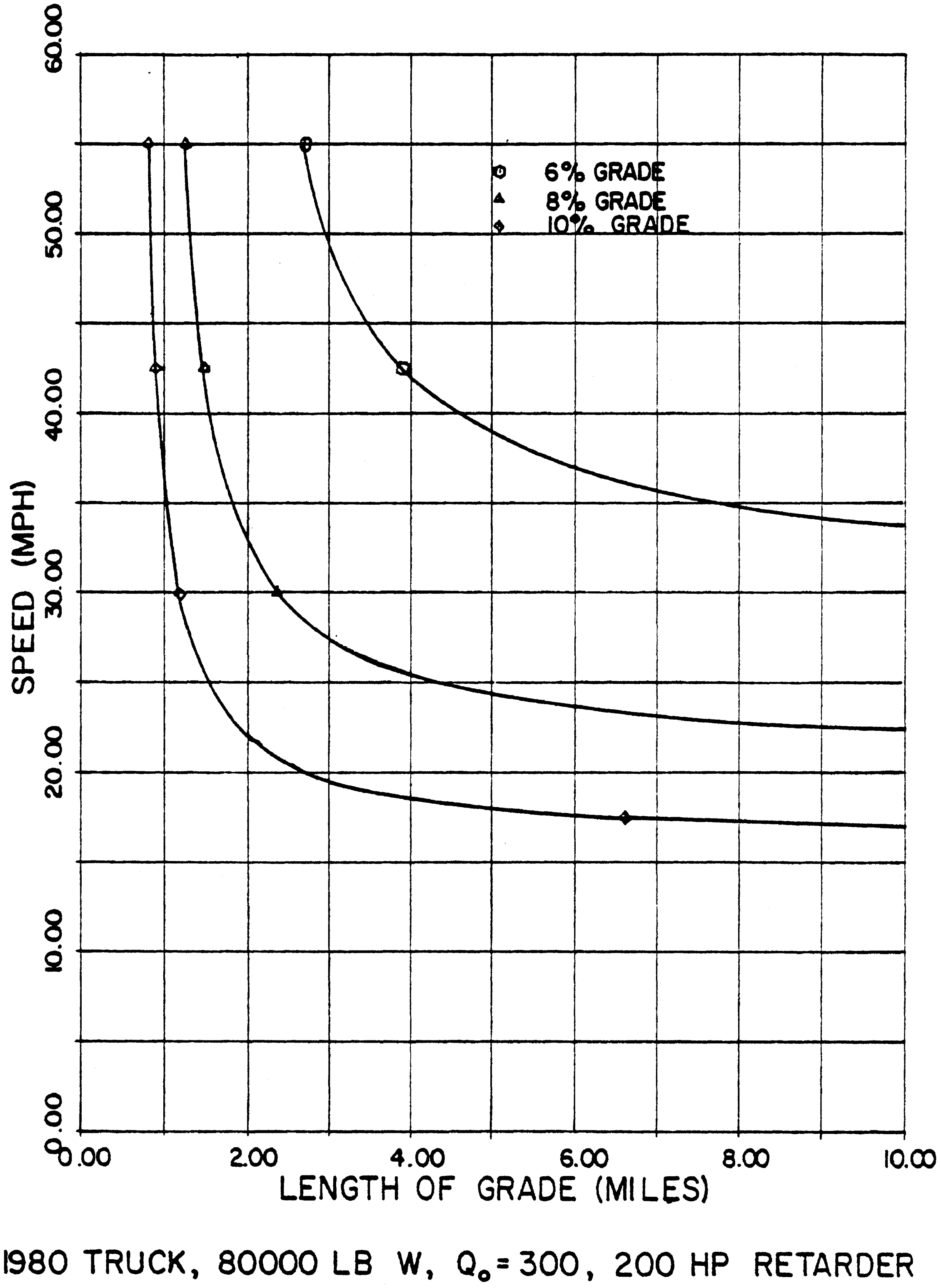

Figure 2.11. Results for combined use of a retarder and the brakes.

is 10 miles long. Although the combined use of both the retarder and the foundation brakes has the disadvantage of not reserving the foundation brakes for emergency situations, the combined use is very effective in increasing speed and may well represent the actions of drivers that are pressed for time.*

2.2 Technical Descriptions of Retarder Operation

Retarders can be classified into four generic groups, based on the mechanical designs used to generate a retarding torque and then dissipate the resulting heat. Even though individual manufacturers may have unique approaches in their retarder designs, there is a commonality among all of the retarders in any one of the four generic groups. Hence, properties shared by most retarders in a group are described below in terms of how they function, how they are used, and other possible effects they have on performance besides their primary function of slowing the vehicle without involving the foundation brakes. The discussions are concerned mainly with performance, so descriptions of the hardware configurations are minimal. Table 2.3 summarizes the operational behavior of each of the four groups, while specifications for particular retarders are listed in Tables 2.4 and 2.5, which also note unique features of particular retarders. All retarders operate by producing a torque about one of the rotating components in the vehicle (the engine crankshaft, driveline, etc.) that acts to retard the forward motion of the vehicle. In the process, kinetic energy is converted to heat. Because different types of retarders are attached to different rotating components, different torque levels are needed for the different devices to provide equivalent retardation levels. For this reason, retarder performance is generally specified in terms of horsepower, which is the rate that the kinetic energy of a vehicle is converted to heat. The relationship between horsepower, torque, and rotational speed is:

$$P = \eta \cdot \tau \cdot 1.90 \times 10^{-4} \qquad (9)$$

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*In practice, drivers would need to be very familiar (or well informed) with regard to the route, the weight of their vehicles plus load, and thermal properties of the vehicle's brake system in order to operate safely while using both the foundation brakes and the retarder to minimize time.

TABLE 2.3

Operational Behavior of Generic Retarder Groups

	Engine Brake	Exhaust Brake	Electric Retarder	Hydraulic Retarder
Source of Retarding Torque	Compressing air	Compressing air	Inducing Eddy Currents	Shearing of Fluids
Heat Dissipation	Engine Cooling System and Exhaust System	Engine Cooling System and Exhaust System	Forced air	Engine Cooling System or Separate Liquid Heat Exchanger
Torque Location	Engine	Engine	Driveline, Trailer Axle	Engine, Driveline, or Trailer Axle
Typical Capacity (relative to engine)	60-100%	30-70%	50-150%	50-150%
Applications	Diesel Engines Used in U.S.A.	4-Stroke Engines	Commercial and Off-Road Vehicles	Commercial, Off-Road Vehicles
Means for Modulating Retardation	Gear Selection, Vary No. of Cylinders	Gear Selection, Adjust Orifice Size	Vary No. of Energized Coils	Vary Amount of Fluid and Pressure
Power-RPM Relation (Moderate to High RPM)	Linear	Linear	Linear	Cubic
Theoretical Power Limitation	Engine Size, RPM Rating, Compression Stroke	Engine Size, RPM Rating, Valve Spring Size <u>or</u> Back-Pressure Limit	Retarder Size <u>or</u> Drive Line Torque Rating	Retarder Size <u>or</u> Drive Line Rating
Typical Response Times	0.1-0.2 second	0.2-2 seconds	0.1-0.2 second	0.3-2 second
Noise	"Popping" noise at normal engine sound level	Low-Frequency rumbling at air inlet (normally asperated engines only	None	None
"Fade"	None	None	50% after 20 min.	None

TABLE 2.4

Specifications for Individual U.S.-made Retarders

Manufacturer	Model	Type	Applications	Power @2000 RPM	Weight (lb.)	Notes
Allison	Torque-matic	Hydraulic	Allison 750, 5000, 6000, 8000 transmissions (off-road vehicles)	over 300	N/A	a,s
	Brake Pressure		Allison HT700 series, CLBT 750 transmissions	550	200	a,g,s
	Retarder Opt.		Allison M-600 series transmission	300	130	a,s
Caterpillar	Brake Saver	Hydraulic	Caterpillar 3046 engine	360	500	b,g,h,j,n,o,p,t
			Caterpillar 3408 engine	450	500	b,g,h,j,n,o,p,t
Cummins	Rotary Engine Brake	Exhaust	Cummins NTC/Formula 300, 350, NTS-400 engines	200	10	b,g,h,j,w
Decelo-matic	Mountain Tamer	Exhaust	4-stroke Engines	N/A	N/A	g,t,x,y
Jacobs	20,25B,30E, 53A,59,71A, 92A,675,676, 677,K1150, C346,903A, 903B	Engine	Cummins V6-140, V6-155, V8-185,V8-210,V8-225, series NH,NT,903, and K (1150 CID only), Detroit Diesel series 53A,71, and 92, Mack series 673, 675,676,677, and 711, Caterpillar series 3406	N/A	N/A	b,g,i,t
	JE300	Electric	Commercial and off-road vehicles	165	345	c,g,i,u,v
	JE320			219	N/A	
	JE500			250	503	
	JE520			280	503	
	JE720			490	754	
	JE740			560	768	
	JE920			680	875	
Mack	Dynatard	Engine	Mack ENDT 676 engine	250	N/A	b,i,o,u
			Mack ENDI 865 engine	300	N/A	b,i,o,u
Williams Air Control	Blue Ox UM770,WM780	Exhaust	4-stroke Engines	N/A	20	g,h,i,t,x

NOTES FOR Tables 2.4 and 2.5:

a - Retarder can be (is) integrated into automatic transmissions.
b - Retarder is based on (or integrated into) individual engine design.
c - Retarder can be (is) attached to propeller shaft.
d - Retarder can be (is) attached directly to gearbox.
e - Retarder can be (is) attached directly to differential.
f - Retarder can be (is) attached to (or integrated with) axle.
g - Features adjustable retardation.
h - Pneumatically actuated.
i - Electrically actuated.
j - 2-second response time.
k - 0.5 second response time.
l - 0.3 second response time.
m - Employs internal gearing to reduce size of chamber.
n - Employs pressure regulator to maintain constant torque at high RPM levels.
o - Power rating is for maximum engine speed.
p - Uses engine oil.
q - Uses cooling system water.
r - Uses independent oil supply.
s - Uses transmission fluid.
t - Can be actuated by releasing throttle.
u - Can be actuated by lightly applying brake pedal.
v - Can be actuated by 5-position switch.
w - Employs servo-mechanism to maintain constant back pressure.
x - Is retro-fitted to exhaust system using standard pipe fittings.
y - Can cut-off fuel supply.
z - Rotor and stator consist of flat plates pressed together.

TABLE 2.5

Specifications for Individual European-made Retarders

Manufacturer (Country)	Model	Type	Applications	Power @2000 RPM	Weight (lb.)	Notes
ADE (Germany)		Exhaust		N/A	N/A	
Asanco (England)		Exhaust		N/A	N/A	i,t,u
ATE (Germany)		Hydraulic		N/A	N/A	
Bosh (Germany)		Electric		N/A	N/A	c,e,i
Clayton Dewandre (England)		Exhaust		N/A	N/A	h,y
Cobbco (Australia)		Exhaust		N/A	N/A	
Daimler Benz (Germany)		Hydraulic		N/A	N/A	
Ferrodo (England)	S	Hydraulic	Busses	N/A	N/A	z
	M					c,z
	G					d,z
	A					f,z
Ilasa (Spain)	axle 995	Electric	Trailers, Semi-trailers	880	N/A	f,i
	all other axles			605	N/A	f,i
Perkins (England)		Exhaust	Perkins engines	N/A	N/A	b
Pye (England)		Electric		N/A	N/A	
Richard Hailer (Germany)		Exhaust		N/A	N/A	
Saurer (Switzerland)		Exhaust		N/A	N/A	
Smith (Australia)	SGV	Exhaust	4-stroke engines	N/A	16	g,h,t,u,x
Telma (France)	CA65	Electric	Commercial Vehicles	179	290	c,f,g,i,u,v
	CA100			275	326	
	CA135			399	453	
	CA160			440	711	
	CA200			549	711	
	CC65			179	317	
	CC80			220	317	
	CC135			399	506	
	CC160			440	506	
	CC170			467	660	
	CC200			549	660	
	CC220			605	726	
	CC250			687	726	
	Focal 115		Compact Commercial Vehicles--Busses	316	275	
	Focal 130			357	286	
	Focal 155			426	363	
	Focal 170			467	376	
	Focal 205			564	506	
	Focal 250			687	583	
	Telmatic	Hydraulic	Lighter Commercial Vehicles	80	N/A	b,o,g
Voith (Germany)	DIWA 0851 transmissn	Hydraulic	Busses	N/A	N/A	a,l,u
	Type 180	Hydraulic	Commercial Vehicles	N/A	N/A	a,c,f,h,k,m,r
ZF (Germany		Exhaust		N/A	N/A	

where

P = horsepower

η = rotational speed in revolutions/minute

τ = torque in foot pounds

When descending a grade, potential energy is being converted to kinetic energy at the rate:

$$P = 2.67 \times 10^{-5} \cdot W \cdot \alpha \cdot V \tag{10}$$

where

W = vehicle weight (lb)

α = grade of descent (%)

V = speed (mph)

A steady-state descent that does not require use of the foundation brakes occurs when the power in (potential energy being converted to kinetic energy--Equation (10)) equals the power out (kinetic energy or work being converted to heat--Equation (9) plus all other sources of energy dissipation such as rolling resistance, driveline and engine friction, and air resistance).

2.2.1 Engine Brake. The engine brake operates by converting the engine from a power-producing motor to a power-expending air compressor. During normal operation of a four-stroke diesel engine, the cycle of a particular cylinder consists of (1) sucking air into the cylinder through the open intake valve as the piston moves down while fuel is being injected, (2) compressing the fuel-air mixture as the piston moves up with the valves closed—an action that requires work and has the result of raising the temperature of the mixture until it ignites, (3) the piston being driven down by the pressurized gas—pressurized mainly because of combustion, but also because of the compression in the previous stroke, and (4) pushing the gases out of the open exhaust valve as the piston moves up. The engine is converted to an air compressor by changing the timing of the exhaust valve. In the retarding mode, the exhaust is opened near the end of the second stroke and kept open during part of the third stroke. As a result, the work spent compressing the air-fuel mixture is lost when the gases are vented through the open valve, rather than pushing the piston back down. The same principal applies to retarders installed on two-stroke diesels that employ exhaust valves (e.g., Detroit Diesel), in which case the exhaust valve is opened at the top of every stroke to vent the compressed air.

Because the valve timing is changed, engine-brake retarders must be integrated into the engine design. At this time, only two engine brakes are marketed in the U.S. One of these is offered by Mack Truck as an option on some of their engines, while the other, manufacturered by Jacobs Engineering, is sold as an after-market item. The Mack "Dynatard" uses a special cam shaft that causes the engine to act as a retarder when the valves are adjusted to have zero backlash, and to act as a motor when a certain amount of backlash is present. Switching between the two modes is accomplished by hydraulically adjusting valve backlash, using the pressurized engine oil as the operating fluid. The "Jake brake," made by Jacobs, provides an independent hydraulic mechanism for lifting the exhaust valves. This also uses the pressurized engine oil as the operating fluid. In the retarding mode, the hydraulic lifter associated with a cylinder is actuated by the injector pushrods of other cylinders, or in some cases, the valve pushrods of other cylinders. Response times for both kinds of engine brakes are short—being on the order of several tenths of a second. The engine-brake retarder provides a more-or-less constant torque resisting the rotation of the fly-wheel, although it does decrease slightly with engine speed. Hence, the limit in performance for this type of retarder is achieved at the maximum rated engine speed when its power-absorption rate is greatest. This occurs when the gearing is the lowest that can be selected at a given vehicle speed.

Although performance of an engine-brake retarder depends on the design of the retarder components, the torque limitations are ultimately imposed by engine size and compression ratio. The absorbed-power limitation in turn depends on both the torque and the maximum rated engine speed. Absorbed power capability ranges from 60-100 percent of the power-producing engine specification, with the higher figure applicable to turbo-charged engines with high rpm ratings. Since many other forces act to retard a commercial vehicle besides the engine, the overall performance of an engine-brake retarder acting together with other frictional forces is generally comparable to the engine acting as a power plant against the other frictional forces. From the point of view of the truck driver, this means a given grade can be safely descended without use of the foundation brakes at the same speed and gearing that it can be ascended. While an under-powered vehicle will need to descend at slower speeds, due to a limited retarding capability of its smaller engine, the same vehicle is already limited to comparably slow climbing speeds.

An engine that is not absorbing significant power when descending long downgrades will cool, resulting in thermal stress cycles and subsequently less efficient running when the cold engine is again used to generate power. In contrast, with an engine retarder, the engine is being heated during descent and its temperature can be maintained at or near a normal operating level. (While retarding, about half of the resultant heat is dissipated by the cooling system; the other half goes out the exhaust.) Increased engine life due to constant temperature is a benefit sometimes claimed for engine-brake retarders.

When either brand of engine brake is working, the fuel supply is either completely cut off, or reduced to the idle-delivery level, depending on the engine design, until the engine speed drops to idle. At this time, fuel is re-introduced and an electric switch is tripped which deactivates the retarder, turning the engine from an air compressor back into a motor. If the fuel supply is at the idle-delivery position, a small amount of fuel savings is a potential advantage, as a faster descent speed will mean that less time is spent consuming fuel during descents.

The engine-brake type of retarder offers a great deal of flexibility, since the retarding level is greatly dependent on the driver's choice of gears. Potential problems exist, however, as an inappropriate choice of gears can result in overly high engine speed and resulting engine damage unless the driver resorts to the vehicle foundation brakes. Should the engine speed increase beyond the rated maximum, shifting to a lower gear to obtain more retarding torque is not possible and an attempt to do so will leave the driver with the transmission in neutral (or a high gear with less retarding torque) and completely dependent on the foundation brakes of the vehicle.

Exterior noise levels during the retarder mode are comparable to those during the motoring mode for equivalent engine speeds. But the noise is always described as being noticeably different, consisting of a "popping" noise while retarding as opposed to a "roaring" during normal operation. On one hand, the popping noise is claimed to be beneficial because it helps prevent build-up of deposits in the components of the exhaust system. On the other hand, the popping is sometimes perceived as a more objectionable noise.

2.2.2 Exhaust Brake. Exhaust brakes also exploit the inherent braking of the engine, although usually not as efficiently as the engine brake. An exhaust brake operates simply by constricting the flow of exhaust gas through the manifold, raising the back pressure. This is accomplished with either a butterfly or sliding-type valve. As the back pressure rises, work spent by a piston compressing the air in the exhaust manifold during the exhaust stroke is not recovered when the exhaust valve of the cylinder is closed on the following down stroke. The back pressure increases until it over-powers the valve-return springs, which then no longer keep the exhaust valves closed. When this happens, the pressurized gas in the exhaust manifold re-enters cylinders on the down stroke, and also enters the intake manifold through the open intake valve. Some exhaust brakes feature adjustable retarding levels by means of an adjustable orifice that vents the pressurized gas in the exhaust manifold to the atmosphere. These adjustable orifices are also used to keep back pressure within limits specified by the engine manufacturer—limits that are usually imposed to prevent the compression of the exhaust valve return springs at full back pressure. To prevent stalling at low rpm levels, it is often necessary to limit the back pressure and lower the idle speed.

The exhaust brake usually results in a retarding horsepower that is 30-70 percent of the rated horsepower of an engine (although higher efficiencies are sometimes possible) and, like the engine brake, the greatest horsepower is achieved when the gearing is selected to keep engine speed near the maximum rated limit. Unlike the engine brake, the exhaust brake is applicable only to four-cycle engines and is less efficient with turbo-charged engines. The rule-of-thumb for drivers using exhaust brakes is that descent of a given grade should be made one gear lower (and thus at a lower speed) than the gear needed for climbing.

Exhaust brakes do not have to be specially designed to fit particular engine models, although provisions need to be made for cutting off the fuel supply for carbureted gasoline engines. In some cases, the fuel supply is not cut off and some combustion still takes place. Note that because the exhaust brake causes air to flow from the exhaust manifold to the intake manifold, reducing the vacuum, vacuum-assisted brakes or other vacuum-assisted devices are disabled when the retarder is operating unless provisions are made to provide a vacuum.

When activated, the exhaust brake is similar to the engine brake in that it maintains a "hot" engine temperature. Noise levels are not considered to be excessive relative to the levels present when the engine is producing power; however, naturally aspirated engines will make a low-frequency noise at the air inlet that is sometimes considered objectionable and requires an additional intake silencer or throttling of the intake air when the exhaust brake operates.

Actuation of the exhaust-restricting valve is usually quick—approximately 1/10 second—although a little more time is needed for the back pressure to build in the exhaust system. The build-up time depends on the volume of the exhaust system upstream of the exhaust-brake valve and on the size of the vent orifice, with a quicker response resulting when the valve is installed close to the manifold and when the orifice is small.

All in all, the exhaust brake can be viewed as performing qualitatively as a less efficient, but usually quieter, engine brake in terms of its usage, effects on (allegedly reduced) engine wear, and limitations. The primary difference in performance is that current exhaust brakes provide less retarding torque, with the result that vehicles equipped with exhaust brakes should usually descend grades slower than they can climb them.

2.2.3 Electric Retarder. An electric retarder slows a vehicle by converting mechanical energy into heat through the use of an eddy current brake. This type of retarder does not in any way depend on the engine and is not even coupled directly to it. Rather, it provides a retarding torque to another rotating component; usually, the propellor driveshaft, but in some cases, the drive axle differential, or a trailer axle.

The rotating component is attached to a steel disc that turns in the flux field of a set of fixed electro-magnets. When the magnets are energized, eddy currents are developed in the disc. These currents create another magnetic field whose orientation relative to the field of the fixed magnets is such as to resist the rotation. The resulting torque depends mainly on (1) the strength of the magnetic field produced by the electro-magnets, (2) the electrical and magnetic properties of the disc material, (3) the rotation speed, and (4) the design geometry.

The speed dependency of the electric retarder is decidedly nonlinear. Torque is, of course, zero at zero speed. Over a low range of rpm, torque increases rather linearly with rotational speed. At a low-to-moderate rpm level, however, this function saturates and, thereafter, torque is more-or-less independent of speed. Electric retarders are generally designed such that normal usage will occur in this speed-independent range.

The retarding torque is nearly proportional to the strength of the magnetic field produced by the electro-magnets, and manufacturers typically allow the driver to select from a range of retarding levels by powering more electro-magnets when more torque is wanted. Response times of electric retarders are usually several tenths of a second. Safe descent speeds are dictated by the retarder size relative to the vehicle weight. Depending on the retarder size, the descent speed of a grade could be more or less than the climbing speed.

Electric retarders can be made to absorb very high horsepower. However, in practice, maximum torque capability of the retarder is dictated by the design of the driveline which is usually sized to match the engine. Hence, the retarder can generally be only a little more powerful than the engine unless a higher-strength driveline is used.

Because electric retarders produce a torque proportional to speed at low rpm, an electric retarder alone cannot bring the vehicle to rest. Furthermore, if the foundation brake is applied together with the retarder such that the retarded axle approaches lockup, the contribution from the retarder will diminish to the point that lockup (hopefully) will not occur. (Unless, of course, the torque produced by the foundation brakes alone is sufficient to cause lockup.)

The power dissipated in an electric retarder heats the disc, which is cooled by convection and, if the temperature rises enough, radiation. During prolonged usage, the disc heats up enough that its electrical and magnetic material properties and its geometry are altered, with the result of lowering the retarding torque. At maximum capacity, the retarding torque is typically reduced by nearly half after 20 minutes of continuous operation.

Due to its location in the drivetrain, operation of an electric retarder is completely independent of gear selection or engine performance. The retarder should have no effect on fuel consumption or engine temperature, which will have the same levels that would occur if only the natural retarding capability of the engine were being used. By itself, the electric retarder is noiseless. Although the retarder does not produce much torque at low rpm levels, its demands on the electrical system to energize the electro-magnets still persist. Accordingly, electric retarders commonly have a low-speed detector, which cuts off the current to the retarder when the rpm drops below some limit.

2.2.4 Hydraulic Retarders. This category covers a wide range of retarder designs and configurations whose similarities are limited to a common means of converting kinetic energy to heat by shearing a liquid. This is accomplished by fixing a plate with vanes to a rotating component (the rotor) inside a chamber that has stationary vanes (the stator). The device is actuated by filling the chamber with fluid, which resists the rotor movement. As the fluid is churned, heat is generated and removed by a cooling system. Depending on the specific retarder design, the fluid may be taken from a supply reserved exclusively for the retarder, or from fluid contained in the engine (i.e., engine oil or water in the cooling system), or from oil in an automatic transmission. Likewise, the engine cooling system is employed to remove heat from the chamber in some cases, while in others, a separate cooling system is provided for the retarder.

Hydraulic retarders are more dependent on speed than the other types, as the resisting torque is more-or-less proportional to the square of the rotational speed and thus the expended power is proportional to the speed raised to the third power. Thus, the hydraulic retarder, like the electric retarder, is incapable of causing axle lockup because it produces no torque at the zero rpm condition. The retarding torque can be adjusted in most versions by controlling the amount of fluid that is allowed in the chamber. The response time of a hydraulic retarder is mainly determined by the amount of time taken to fill the chamber. Lags of only .5 second are possible, but lags on the order of two seconds are more common. During operation, the retarder should never produce any noticeable noise.

Further generalizations about hydraulic retarders are inappropriate since they come in so many forms. Clearly, a hydraulic retarder coupled to the engine will perform according to engine speed and thus gearing, and will behave similarly to an engine brake or exhaust brake. On the other hand, a retarder coupled to the transmission or trailer axle will behave like an electric retarder. Retarding capability is determined by the stator/rotor geometry, properties of the fluid, and the spin rate of the rotor; thus, the hydraulic retarder is similar to the electric retarder in that its capabilities are not explicitly dependent on the engine size.

2.3 Analysis of Retarder Market

2.3.1 Current Market. The first step in analyzing the market for supplementary braking devices was an extensive series of interviews with manufacturers of retarder systems. Extensive contacts were then made with users, and prospective users, of the supplementary braking devices. Finally, appropriate personnel within state agencies were interviewed (by telephone) for information concerning laws, regulations, administrative edicts, etc., that affect supplementary brake installations. Assessments were also made relative to future governmental action that could potentially impact the future use of supplementary braking systems.

It is estimated that the current annual sales of supplementary braking devices in the United States is 33,000-46,000 units, as shown in Table 2.6. The majority of the devices (about 50 percent) were engine brake retarders installed on class-eight heavy-duty trucks. The next largest generic class of installations were the exhaust-brake retarders, which are standard equipment on many class six- and class-seven trucks imported into the United States from Europe. These vehicles, which are being sold primarily in the eastern and mid-western part of the United States, account for 4,000-6,000 of new retarder-equipped units in 1979.

Hydraulic retarders accounted for a market share of 7,000-12,000 units, with their application about evenly spread between construction machinery and class-eight heavy-duty trucks.

The total sales of electric retarders in the United States in 1979 was less than 500 units, with their heaviest demand being in retrofit into transit applications.

Table 2.7 shows an estimate of where retarding devices were placed into service. As would be expected, the western United States is, by far, the area of greatest market penetration. It is estimated that about 80 percent of installations into class-eight trucks are found in this

TABLE 2.6

ESTIMATED 1979 U. S. SALES OF SUPPLEMENTARY BRAKE DEVICES, BY TYPE

		APPLICATION			
		Heavy-Duty Truck			
Type	Total	Class 8	Class 6 & 7	Construction Machinery	Transit
Engine Brake	21 - 27,000	20 - 25,000	500 - 1,000	< 500	< 500
Electric Brake	500	100	100	< 100	< 200
Hydraulic Brake	6 - 10,000	3 - 5,000	--	3- 5,000	---
Exhaust Brake	6 - 9,000	2 - 3,000	4 - 6,000	< 500	< 100
Total	33 - 46,000	25 - 33,000	4 - 7,000	3- 6,000	< 1,000

area. The mountainous terrain makes supplementary braking devices a necessary safety protection on large trucks that are heavily loaded and operating over the steep grades. The heavy-duty trucks are also equipped with retarders in the mountainous areas of the eastern United States for much the same reason.

Because of the sales of European-made class-six and class-seven trucks in the eastern half of the United States, retarders on these classes of vehicles are most heavily concentrated in this area.

Transit vehicles use retarders because of the perceived benefits from increasing brake life; this benefit occurs regardless of terrain. Therefore, the retarder installations on this class of vehicle are most directly related to the transit vehicle population exclusively. This explains the greater number of retarder installations in the eastern United States.

The total dollar value for the retarder market described in Table 2.7 is in the $45-75 million range, at retail. Even though this volume is significant, there is ample room for further growth, as seen in Table 2.8. Except for the class-eight trucks in the western United States, all other applications are less than 15 percent retarder equipped.

The estimated 1980 population of trucks (greater than 19,000 GVW) and transit vehicles is shown in Table 2.8. The population is segmented by major geographic area according to terrain. There are about 1.1 million trucks, class eight and larger (over 33,000 lb GVW), in the United States. About 15 percent of these vehicles are in the eleven western states; however, the greatest penetration of retarders are found in this area. About 40-70 percent are retarder equipped; the heavier the vehicle the greater the retarder share.

The mountainous regions of the East have a significantly lower percentage of trucks equipped with retarders. Only 5-15 percent of 33,000 GVW and larger (class eight plus) have the supplementary braking devices. Less than 10 percent of the 19,000-33,000 GVW (class six and seven) trucks are equipped with retarders; and less than five percent of transit vehicles are so equipped.

TABLE 2.7

ESTIMATED 1979 U.S. SALES OF SUPPLEMENTARY BRAKE RETARDERS, BY LOCATION

		APPLICATION			
		Heavy Duty Truck			
	Total	Class 8	Class 6 & 7	Construction Machinery	Transit
Western U.S.	23-30,000	20-25,000	1- 2,000	1 - 3,000	< 250
Midwest U.S.	3- 5,000	1- 2,000	1- 1,500	1 - 1,500	< 250
Eastern U.S.	7-12,000	4- 6,000	2- 4,000	1 - 1,500	< 500
Total	33-46,000	25-33,000	4- 7,000	3 - 6,000	<1000

TABLE 2.8

ESTIMATED 1980 POPULATION OF HEAVY DUTY TRUCKS AND BUSES AND PERCENT WITH RETARDERS, BY REGION

	MOTOR TRUCK/BUS APPLICATION					
	Heavy Duty Truck					
	Class 8+		Class 6 & 7		Transit	
	Number(3) (000)	Percent (5) With Retarder	Number(3) (000)	Percent(5) With Retarder	Number(4) (000)	Percent (5) With Retarder
Western (1)	180	40-70%	190	< 10 %	18	< 5 %
East (2)	240	5-15	230	< 10	36	< 5
Other	700	< 5	730	< 1	46	< 5
Total U.S.	1100	10-20 %	1150	< 5 %	100	< 5 %

1) CA., OR., WA., MN., UT., ID., AZ., NM., WY., CO., NV.

2) VT., NH., NY., PA., NJ., WV., NC., TN., OH.

3) Estimated from 1977 Census of Transportation Truck Inventory and Use Survey

4) Estimated from 1978 MVMA Motor Vehicle Facts and Figure.

5) Estimated from Field Interviews.

2.3.2 Future Markets. The future market for retarders is a function of the buying public's perceptions of the benefits resulting from purchasing the devices. (Indeed, this perception has been the driving force in past retarder purchases.) The generally recognized areas where benefits are potentially available are:

-improved vehicle safety

-improved brake life

-better fuel economy

-increased tire life

-increased utilization.

The major reason heavy-duty trucks are equipped with retarders is to provide an additional safety margin to the driver. Field interviews with retarder users continually reflect this point.* Likewise, those operators without retarders made their rejection decision largely on the basis of not needing the additional safety, either because foundation brakes were considered adequate or because incidents of brake overload were thought to be rare.

Subsequent sections of this report examine the questions of safety performance in great detail. Suffice it to say at this point, however, that safety concerns have thus far dominated the buyer's selection criteria. It accounts for the strong segmentation of the market into mountain terrain, and to very heavy trucks where brake performance is so critical.

The future role of safety as a motivating factor in retarder purchase is expected to remain high. The continuing decline in vehicle rolling resistance (discussed in other sections of this study) will place even greater demands on braking systems. It is expected that this increase in braking requirements will result in the growing opportunities

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*As an example, a senior engineer with a U.S. retarder manufacturer spent several months in 1978-79 interviewing Western U.S. users of retarder-equipped trucks. The respondents were asked to rank the following retarder features in order of importance: price, performance (i.e., safety), availability, service, product name, reliability. In every instance, the respondents ranked performance (safety) as one of the two most important features.

for retarders in lighter-weight vehicles and in less mountainous terrain than has occurred in the past because the foundation brakes won't be meeting the perceived safety minimum.

An area of growing importance in a buyer's decision is the potential for increased brake life. There is strong evidence to suggest that foundation brake life will increase when retarders are utilized. As a rough first-order estimate, the wear rate of the vehicle's foundation brakes may be expressed by the formula:

$$W_R = W_{Ro} \left[\frac{W}{AR_p} \left(\frac{\ddot{x}}{g}\right) \frac{\overline{V}_{ave}}{550} - \frac{hpr}{AR_p} \right] \tag{1}$$

in which

W_R = brake wear rate, actual

W_{Ro} = brake wear rate, nominal

A = total foundation brake lining area (in^2)

R_p = brake lining power rating (hp/in^2)

W = vehicle weight (lbs)

$(\frac{\ddot{x}}{g})$ = average rate of deceleration (ft/sec^2)

$\overline{V}$ = average velocity during the stop (ft/sec)

hpr = retarder horsepower used during an average stop.

As the equation indicates, the brake wear is affected by the amount of horsepower (hrp) the retarder absorbs. The increase in brake life resulting from installation of a retarder is commonly referred to as the "retarder brake-life-extension factor."

$$\text{Retarder brake-life-extension factor} = \frac{W_{R(\text{retarder})}}{W_{R(\text{w/o retarder})}} = B_{Lef}$$

The B_{Lef} range varies from slightly over 1.0 to a reported high of 8.0-9.0, and tends to cluster as functions of type of retarder, vehicle size, vehicle application, and geographic region of operation. Probably the single factor that has the greatest relationship to the potential upper limit for B_{Lef} is the life expectancy of the truck's brakes when operating without retarder. Simply, vehicles that are operating in applications causing frequent brake lining replacement have greater opportunity for a large B_{LEF}. Table 2.9 presents some typically reported operating life profiles for 15 different applications. Also shown are estimates of typical life expectancies for the vehicles. Those applications with short brake life, typically less than six months, can expect to have B_{Lef} in the range of 2-4 (or better if a higher-horsepower retarder is installed). In rare instances, such as transit operations, the B_{Lef} might even approach 8.0 or better, with use of electric retarders.

In most situations, it is estimated that B_{Lef} would be less than 2.0, especially when normal brake wear rates require brake relining at intervals beyond 1-1/2 to 2 years.

To determine the economic attractiveness of retarder installation on the basis of brake life extension, a series of return-on-investment analyses were performed. Factors considered in the analyses are given in Table 2.10. The first six parameters were varied through the analyses, the remainder were held constant at the values shown. In all, a total of 720 evaluations were made. They are included in Appendix B.

Figures 2.12 through 2.15 display a series of the data for a selection of retarder installation profiles described in Appendix B. (The illustrations are a portion of a larger set contained in Appendix C.) The figures indicate, among other things, the significant effect of "time-to-first-brake-overhaul" on the return-on-investment. Likewise, it is easy to see the importance of the brake-life-extension factor. Even in the most unlikely of circumstances (a two-axle truck, with only a four-year life), a retarder costing \$3500 will produce an internal rate of return in excess of 10 percent if the time-to-brake-overhaul is six months and the brake-life-extension factor is 2.0, or better. Conversely, even the most optimistic scenario (five axles, 10-year vehicle life, \$450 retarder cost, and one-half-year-to-brake-overhaul) will develop a negative return-on-investment as the brake-life-extension factor approaches one.

TABLE 2.9

Typical Truck Operating Life, Size, and Brake User Characteristics for Selected Applications

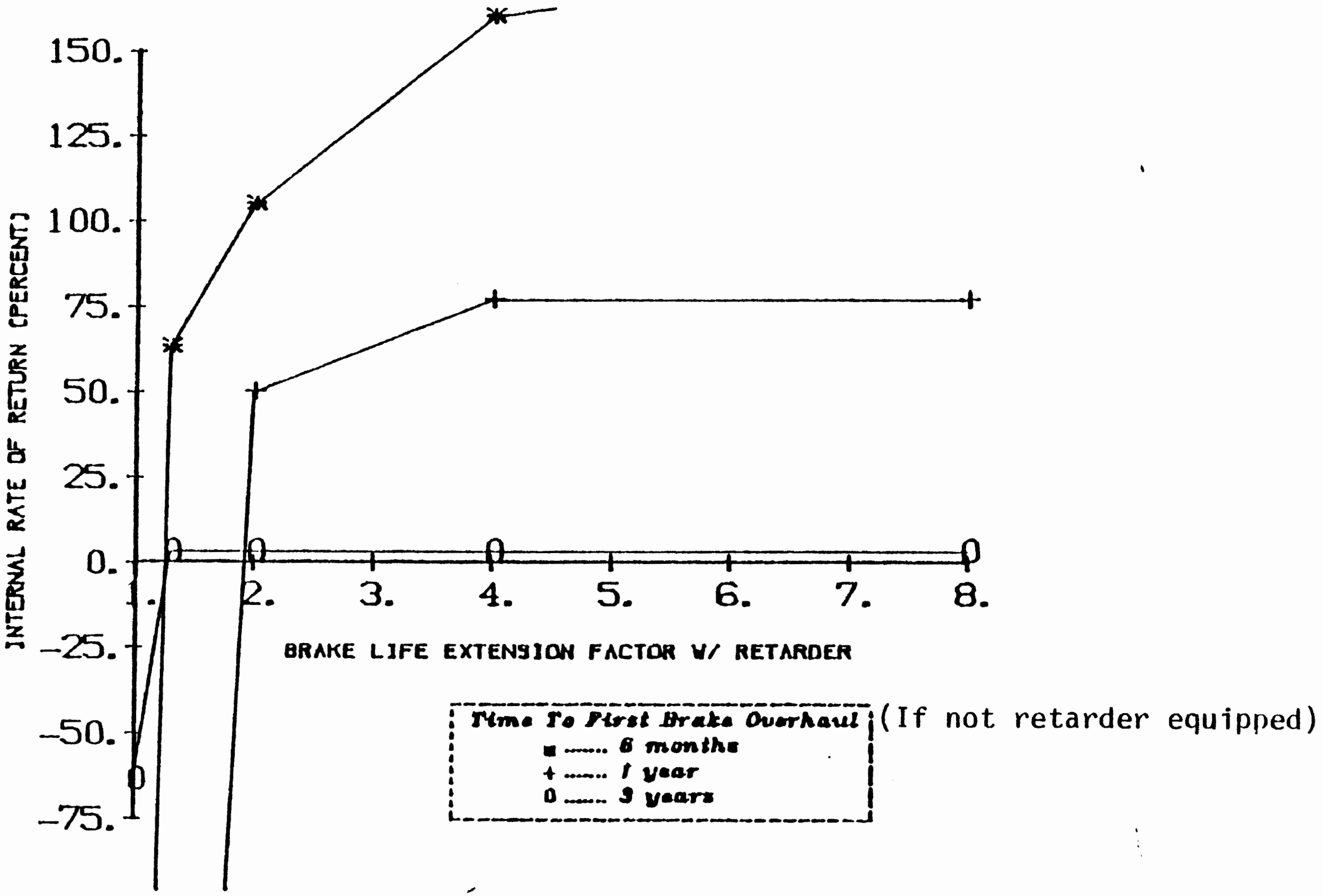
	Class 6&7 (19,33,000 lbs)				Class 8 (above 33,000 lbs)							
					Medium Load				Heavy-Very Heavy Load			
	GVW (000#)	Axles	Veh. Life Expec. (Yrs)	Brake Life (Yrs)	GVW/ GCW (000#)	Axles	Veh. Life Expec. (Yrs)	Brake Life (Yrs)	GCW (000#)	Axles	Veh. Life Expec. (Yrs)	Brake Life (Yrs)
Van Delivery	27.5	2	6-10	1-3	45	2	6-10	1-3	60	3	6-10	1-3
City, Short-Haul					50	3	7-12	1-3	80	4	7-12	1-3
Beverage	33	2	2-12	1-3	50	3	7-12	1-3	--			
Utility	33	2	10-12	.5-2	50	3	10-12	1-3	--			
Refuse	33	2	5-7	1-3	56	3	5-7	.5-2	--			
Farm	33	2	10-12	1-3	60	3	10-12	1-3	80	5	10-12	1-3
Dump	33	2	5-8	.5-3	56	3	5-8	.5-2	80	5-8	5-8	.5-2
Transit Mixer				1-3	56	3	5-7	1-3	80	5	5-7	1-3
Liquid/Bulk	33	2	5-8	1-3	56	3	6-8	.5-1.5	80+	8	6-8	.5-1.5
Line Haul	--				73	5	6-8	.5-1.5	80+	5	6-8	.5-1.5
Equipment	--				--				80+	5	5-8	1-3
Logging	--				--				80+	8	5-8	.5-1.0
School Bus	24	2	8-10	1-4	--				--			
Fire Truck	33	2	10-15	1.5-4	56	3	10-15	1.5-4	--			
Transit	28	2	8-10	.5-1	33	2	8-10	.5-1	--			

SOURCE: Interviews with truck owners.

TABLE 2.10

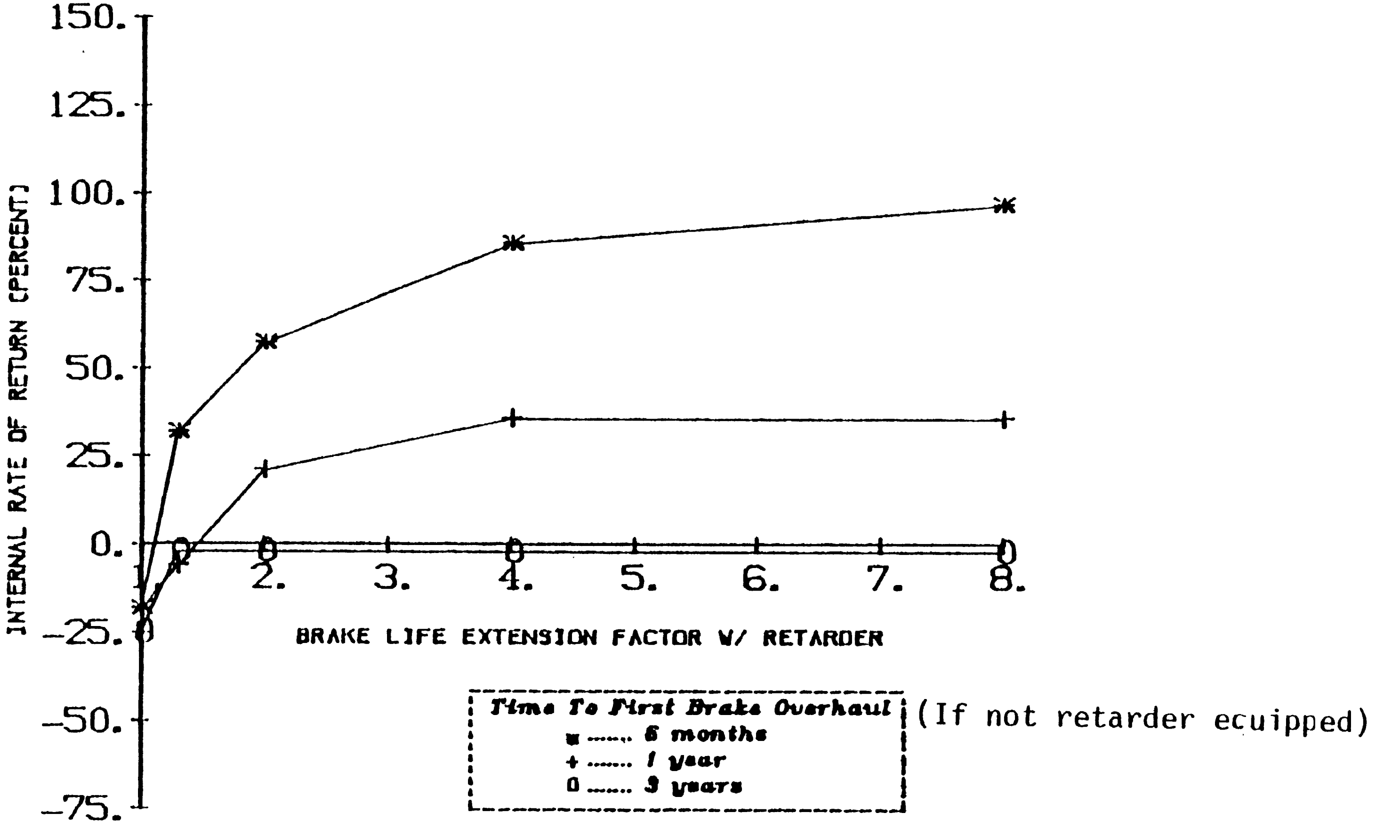
Factors Considered in Return-on-Investment Analysis of Retarder Installations

Factor	Description	Assigned Values
Axles on Truck and Trailers	The number of axles on the tractor and pulled trailer	Truck: 2, 3 Trailer: 2
Years in Service	The expected operating life of the tractor (and trailer unit)	4, 6, 10
Years to Brake Overhaul	The expected miles to brake overhaul divided by expected miles per year of operation	.5, 1.0, 3.0
Retarder Cost	The installed cost to the vehicle owner of a retarder system	\$450, \$900, \$1800, \$3500
Resale Value	The trade-in value of the retarder at the end of the operating life	Depreciate at 15%/year of undepreciated balance. Exception: \$450 retarder assumed no resale value.
Brake Life Exten. Factor (B_{Lef})	The expected life of the braking system with retarder relative to life without retarder	1.00, 1.30, 2.00, 4.00, and 8.00
Internal Labor Rate	The rate in 1980 dollars for labor hours on brake overhauls. Include overhead allocations	\$20
Minor Service	The cost in materials and labor for tractor brake overhaul. Includes replacing brake lining and minor parts. Cost is per axle. Assumed is that 2 out of 3 overhauls is a minor overhaul.	Tractor labor hours:5 Trac.Parts:\$175 Trailer labor hours:4 Trlr.Parts:\$160
Major Service	The cost in materials and labor for tractor brake overhaul. Includes replacing brake lining, and turning drums. Cost is per axle. Every 3rd overhaul is a major overhaul.	Tractor labor hours:6 Parts: \$290 Trailer labor hours:5 Parts: \$275
Discount Rate	Rate for discounting future benefits and costs to a present value	10%/year
Tax Factor	Tax factor applied to taxable income	46%
Investment Tax Credit	U.S. Capital investment credit allowed for new investment	7%
Inflation Rate	Rate of growth in amount of money required to purchase a constant amount of goods	10%



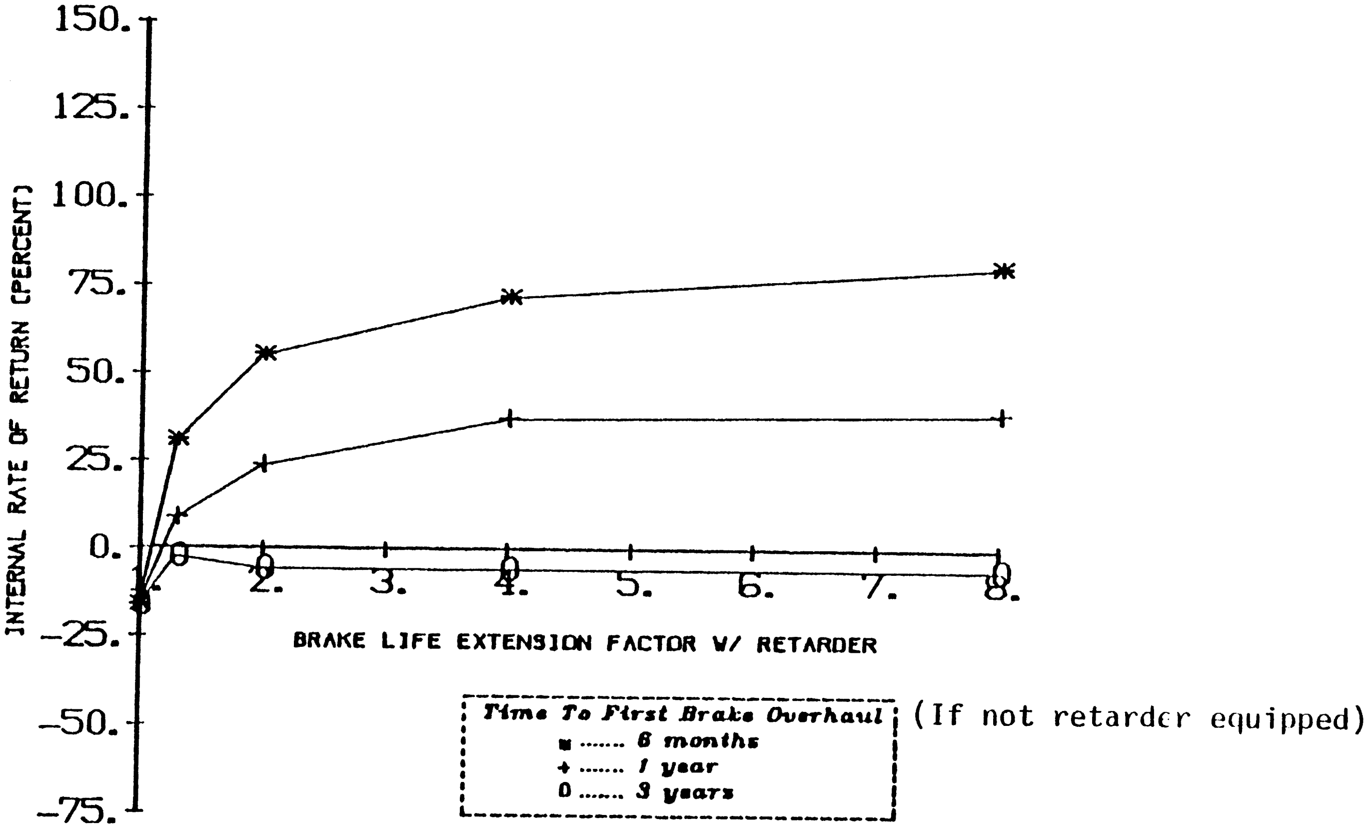
Installed Retarder Cost, dollars	*450*
Expected Vehicle Life, years	*4*
Total Truck Trailer Axles, number	*2*

FIGURE 2.12



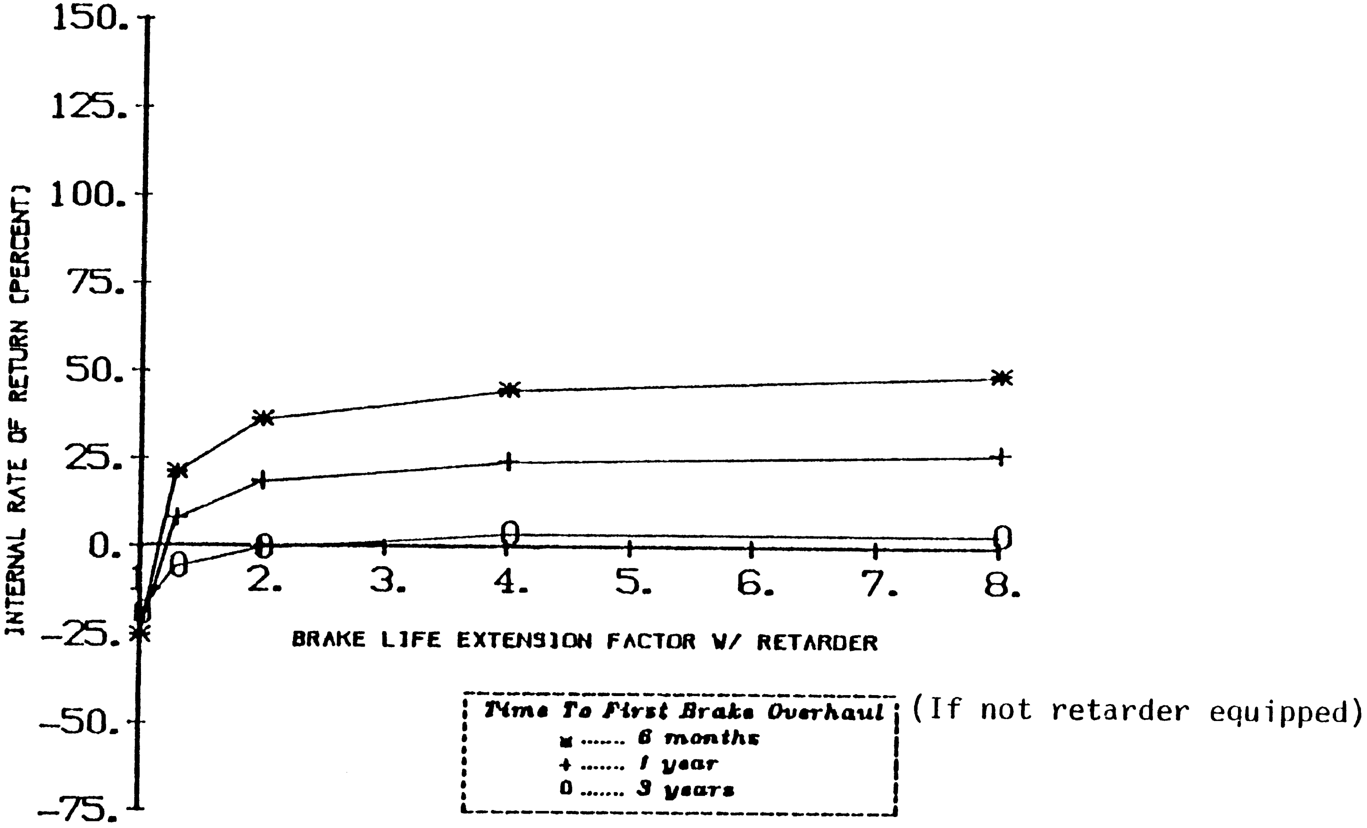
Installed Retarder Cost, dollars	*900*
Expected Vehicle Life, years	*4*
Total Truck Trailer Axles, number	*2*

FIGURE 2,13



Installed Retarder Cost, dollars	*1800*
Expected Vehicle Life, years	*6*
Total Truck Trailer Axles, number	*3*

FIGURE 2.14



Installed Retarder Cost, dollars	*3500*
Expected Vehicle Life, years	*10*
Total Truck Trailer Axles, number	*3*

FIGURE 2.15

Tables 2.11 through 2.22 are analyses of the retarder penetration potential for major truck and transit bus application categories. Included on each table are estimates of the truck population segmented by weight/axle and by geographic region. Purely on the basis of brake savings, the strongest markets of the future probably will be the applications of bus transit, logging, line haul, and liquid bulk. In these applications opportunities exist in specific circumstances even for the most expensive retarders.

As the price of the retarders is reduced, additional applications can have an attractive benefit from use of retarders. At $900 retarder cost, the devices are economically attractive on large farm trucks, utility vehicles, dump trucks, and refuse trucks. And at $450 retarder cost, almost every heavy-duty (33,000-lb GVW and above) application has attractive potential; even the class 6 and 7 trucks can show a satisfactory return on investment in many applications.

2.4 Legal, Social, and Subjective Factors Affecting Retarder Use

To determine the affect of legal, social, and subjective factors upon retarder use, a series of interviews and field contacts were made, both with state government and with industry (as truck operators).

In the state government contacts, the interviews covered the questions of (1) brake regulations, (2) vehicle inspection systems that might cause users to look more favorably on retarder use, (3) methods of reporting accidents, and (4) other systems (such as run-off ramps) that would lessen the safety benefit of retarders. Appendix D summarizes the results of the state government contacts.

As far as could be determined, there are no regulations in any of the states specifically relating to brake retarders. Most states have additional regulations to complement the Federal Motor Carrier Regulation (S393.40-393.52). Probably the most common expansion is to stipulate that there shall be two separate means of applying brakes, and that a vehicle traveling at 20 mph shall be capable of being stopped within 40 feet. Appendix D describes the regulations associated with each state. In addition, the enforcement agency in each

TABLE 2.11
Retarder Application Summary - Van or Delivery Trucks

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33k GVW	33+GVW	19-33k GVW	33+GVW	19-33k GVW	33+GVW	19-33k GVW	33+GVW
Western Mountain*	4,100	100	1,500	2,200	--	500	5,600	2,800
Eastern Mountain**	5,200	300	1,200	4,100	100	800	6,500	5,200
Other	13,700	300	3,100	14,600	300	4,600	17,100	19,500
Total	23,000	700	5,800	20,900	400	5,900	29,200	27,500

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

Not considered a strong market except possibly for low cost retarders. Long brake life (1-3 years), and relatively low axle configuration in mountainous regions are indicative of operations where foundation brakes are generally considered adequate. With retarders costing less than $1000 some penetration would occur in vehicles having three or more axles. If retarder costs were $500 or less, 2-axle market would be available, especially in mountain regions where safety is also a factor.

Summary of Market Potential

Retarder Cost	Number of Axles		
	2	3-4	5+
$450	some	moderate	good
$900	little	moderate	moderate
$1800	--	some	moderate
$3500	--	--	little

TABLE 2.12

Retarder Application Summary - City and Short-delivery Trucks

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33k GVW	33+GVW	19-33k GVW	33+GVW	19-33k GVW	33+GVW	19-33k GVW	33+GVW
Western Mountain*	3,600	200	1,300	1,400	--	400	4,900	2,000
Eastern Mountain**	5,100	200	700	900	--	300	5,800	1,400
Other	13,700	1,400	5,100	5,700	200	1,200	19,000	8,300
Total	22,400	1,800	7,100	8,000	200	1,900	29,700	11,700

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

Not considered a strong market except possibly for low cost retarders. Long brake life and relatively light weight are indicative of operations where foundation brakes are generally considered adequate. With retarders costing less than $1000 some penetration would occur in vehicles having 3 or more axles, especially mountainous regions. If retarders cost less than $500, 2-axle market value would be available, especially in mountain regions.

Summary of Market Potential

Retarder Cost	Number of Axles		
	2	3-4	5+
$450	some	moderate	good
$900	little	moderate	moderate
$1800	--	some	some
$3500	--	--	little

TABLE 2.13
Retarder Application Summary - Beverage Delivery Trucks

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW
Western Mountain*	6,500	100	200	600	--	100	6,700	800
Eastern Mountain**	12,000	300	200	600	--	300	12,200	1,200
Other	26,400	800	1,100	3,500	200	1,200	27,700	5,500
Total	44,900	1,200	1,500	4,700	200	1,600	46,600	7,500

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

Not considered a strong market except possibly for low-cost retarders. Long brake life (1-3 years) and relatively low-axle configuration in mountainous region are indicative of operations where foundations are generally considered adequate. With retarders costing less than $1000 some penetration would occur in vehicles having three or more axles. If retarder costs were $500, or less, 2-axle market would be available, especially in mountain regions where safety becomes a more significant factor.

Summary of Market Potential

Retarder Cost	Number of Axles		
	2	3-4	5+
$ 450	some	moderate	good
$ 900	little	moderate	moderate
$1800	--	some	moderate
$3500	--	--	little

TABLE 2.14
Retarder Application Summary - Utility Vehicles

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33k GVW	33+GVW	19-33k GVW	33+GVW	19-33k GVW	33+GVW	19-33k GVW	33+GVW
Western Mountain*	4,200	300	200	700	--	--	4,400	1,000
Eastern Mountain**	9,300	1,800	--	100	--	--	9,300	1,900
Other	17,500	800	900	1,200	100	2,000	18,500	4,000
Total	31,000	2,900	1,100	2,000	100	2,000	32,200	6,900

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

Is considered to have modest market potential, especially in low-cost retarders, because the vehicles are long-lived (10-12 years retention). But the long brake life and relatively light weight of the vehicles preclude a significant share.

Summary of Market Potential

	Number of Axles		
Retarder Cost	2	3-4	5+
$ 450	some	good	good
$ 900	little	some	moderate
$ 1800	--	little	some
$ 3500	--	--	some

TABLE 2.15
Retarder Application Summary - Refuse Packers

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW
Western Mountain*	4,500	500	1,900	3,200	--	100	6,400	3,800
Eastern Mountain**	5,000	1,600	300	3,700	100	600	5,400	5,900
Other	8,900	1,500	1,400	6,500	100	700	10,400	8,700
Total	18,400	3,600	3,600	13,400	200	1,400	22,200	18,400

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

The relatively short period between brake overhauls indicate operational profile favorable to retarder installation. A favorable return-on-investment is estimated for all retarder installations less than $1000. Selectivity increases with increase in cost above that amount; but even $3500 installations can be justified in mountainous or hilly areas and/or when more than four axles are involved.

Summary of Market Potential

Retarder Cost	Number of Axles		
	2	3-4	5+
$450	good	good	good
$900	some	some	good
$1800	some	some	some
$3500	--	some	some

TABLE 2.16
Retarder Application Summary - Farm Trucks

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW
Western Mountain*	58,400	1,600	7,600	10,500	600	18,600	66,600	30,700
Eastern Mountain**	39,700	2,000	3,900	8,600	600	17,600	44,200	28,200
Other	255,600	9,700	26,400	55,300	1,200	61,400	283,200	126,400
Total	353,700	13,300	37,900	74,400	2,400	97,600	394,000	185,300

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

The long vehicle life is favorabLe, even though large segments of the population have brake lives that would be unfavorable. Sheer numbers of vehicles indicate a good market opportunity, especially for trucks with three or more axles. Some of the 5-axle rigs are favorable even for $3500 retarder units.

Summary of Market Potential

	Number of Axles		
Retarder Cost	2	3-4	5+
$450	some	good	good
$900	some	some	good
$1800	--	some	some
$3500	--	--	some

TABLE 2.17
Retarder Application Summary - Dump Trucks

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW
Western Mountain*	16,700	2,200	3,000	15,900	400	9,600	20,100	27,700
Eastern Mountain**	36,300	5,900	2,600	18,000	100	6,000	39,000	29,900
Other	72,200	12,000	9,600	61,600	600	20,000	82,400	93,600
Total	125,200	20,100	15,200	95,500	1,100	35,600	141,500	151,200

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

A large segment of the dump trucks have short brake life, life, which would be favorable for installation of retarders. This is partially offset by the short vehicle life of 5-7 years. The market, on balance, is attractive especially for trucks with 3 axles or more.

Summary of Market Potential

	Number of Axles		
Retarder Cost	2	3-4	5+
$450	some	good	good
$900	some	some	good
$1800	some	some	some
$3500	--	some	some

TABLE 2.18
Retarder Application Summary - Cement Mixers

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33k GVW	33+GVW	19-33k GVW	33+GVW	19-33k GVW	33+GVW	19-33k GVW	33+GVW
Western Mountain*	400	200	700	8,000	---	---	1,100	8,200
Eastern Mountain**	300	400	400	6,000	---	400	700	6,800
Other	600	3,100	2,200	26,400	---	700	2,800	30,200
Total	1,300	3,700	3,300	40,400	---	1,100	4,600	45,200

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

The vehicles are nearly all 3-axle, or larger, and are very heavy. The result is significant market opportunity especially in mountain regions, opportunity exists even for $3500 retarder systems.

Summary of Market Potential

Retarder Cost	Number of Axles		
	2	3-4	5+
$450	moderate	moderate	good
$900	some	some	moderate
$1800	--	some	some
$3500	--	some	some

TABLE 2.19
Retarder Application Summary - Liquid/Bulk Trucks

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW
Western Mountain*	10,600	500	1,400	6,400	400	10,200	12,400	17,100
Eastern Mountain**	16,600	4,600	1,200	7,700	100	14,800	17,900	27,100
Other	66,700	4,400	4,000	17,300	700	41,800	71,400	63,500
Total	93,900	9,500	6,600	31,400	1,200	66,800	101,700	107,700

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

A significant market for the heavy duty trucks with five axles, especially in the mountain regions. The potential is strong for retarders of $1800, or less, moderate even for more expensive systems.

Summary of Market Potential

Retarder Cost	Number of Axles		
	2	3-4	5+
$450	some	moderate	good
$900	little	some	good
$1800	little	some	good
$3500	--	little	some

TABLE 2.20
Retarder Application Summary - Equipment Hauler

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW
Western Mountain*	300	200	700	1,700	500	4,500	1,500	6,400
Eastern Mountain**	600	200	1,000	3,600	500	4,300	2,100	8,100
Other	1,700	500	3,000	10,800	700	15,300	4,400	26,600
Total	1,600	900	4,700	16,100	1,700	24,100	8,000	41,100

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

The application is concentrated in vehicles over 33,000 GVW, and large numbers of axles. Vehicle age is relatively short (5-8 years), brake life is 1-3 years. Major potential results from large number of axles, and heavy loads. Potential fades as retarder cost increases.

Summary of Market Potential

	Number of Axles		
Retarder Cost	2	3-4	5+
$450	--	moderate	good
$900	--	--	some
$1800	--	--	some
$3500	--	--	little

TABLE 2.21
Retarder Application Summary - Line Haul Trucks

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW
Western Mountain*	3,800	1,000	8,700	16,700	1,500	37,200	14,000	54,900
Eastern Mountain**	58,600	5,100	8,700	47,400	1,100	50,800	68,400	103,300
Other	145,200	10,400	23,700	102,600	2,000	131,000	170,900	244,000
Total	207,600	16,500	41,100	166,700	4,600	219,000	253,300	402,200

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

This is a key market. The vehicles generally experience brake overhauls for .5 to 1.5 years; there are large numbers of vehicles (over 200,000) with 5 axles, and carrying heavy loads. While the relatively short vehicle life (6-8 years) has some impact, it doesn't overshadow the positive market features.

Summary of Market Potential

Retarder Cost	Number of Axles		
	2	3-4	5+
$450	--	good	good
$900	--	good	good
$1800	--	moderate	good
$3500	--	some	some

TABLE 2.22
Retarder Application Summary - Logging Trucks

1977 Vehicle Population:

	2-axle		3-4 axle		5+-axle		TOTAL	
	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW	19-33K GVW	33+GVW
Western Mountain*	200	100	400	1,700	200	8,000	800	9,800
Eastern Mountain**	2,000	300	700	2,600	700	1,900	3,400	4,800
Other	400	200	300	500	200	700	900	1,400
Total	2,600	600	1,400	4,800	1,100	10,600	5,100	16,000

*Includes California, Oregon, Washington, Nevada, Arizona, Utah, Idaho, Montana, Wyoming, Colorado, New Mexico.

**Includes New Hampshire, Vermont, New York, Pennsylvania, New Jersey, West Virginia, North Carolina, Tennessee, Ohio.

Application Comments:

Probably every vehicle in this application that is located in mountain regions is equipped with retarder. The brakes have short lift; the equipment is generally heavily loaded. Return on investment is attractive even with most expensive retarders.

Summary of Market Potential

Retarder Cost	Number of Axles		
	2	3-4	5+
$450	moderate	good	good
$900	moderate	good	good
$1800	some	moderate	good
$3500	--	little	some

state is indicated. Because of the rarity of retarder-related regulations, it is believed that the adoption of any new standard would have a marketing impact. But it was not possible to detect any movement by any state to consider such a regulation.

Industry does not look positively upon the implementation of retarder braking standards. In every case, the industry representative indicated the feeling that retarder installation should be voluntary.

Probably the major negative factor concerning government regulation was in the area of noise control. It was learned that isolated communities, particularly in the Pacific Northwest, rigidly enforce local noise ordinances concerning retarder use. Operators indicated that in some of these communities the use of a retarder is interpreted by the local police officer as being a de facto violation of the ordinance. These ordinances have had some local impact on retarder use, but it was not possible to determine if they have impacted retarder purchase.

In several other nations, especially France, specific incentives exist to encourage retarder installation. Examples are (1) quoting special insurance rates for retarder-equipped fleets and (2) permitting vehicles to disregard the weight of the retarder as part of the maximum legal weight. None of these incentives exist in the United States Several insurance companies were contacted; none indicated even being approached for consideration of retarders as a credit factor. In the case of permitting the deduction of retarder weight from the legal weight limit, it was learned that the International Brotherhood of Teamsters had considered the matter for lobbying into state legislation. The matter was not given high priority, however.

There has been extensive consideration given to the development and emplacement of run-off ramps. Appendix D contains a listing of these ramp locations. An important aspect of ramp usage (besides saving the vehicle and, perhaps, the driver's life) is that they provide an excellent data source for analysis of brake failures. (Indeed, this type of data has been studied in other sections of this report.) As these data are analyzed by groups within state governments, it is possible that the information will be used to catalyze pro-retarder action within the state.

3.0 SAFETY PERFORMANCE ANALYSIS

A loaded tractor-trailer on a steep hill without brakes is likely to become a newsworthy event. But such accidents are uncommon enough that they have not been regularly tabulated by state agencies, and no state seems to provide a unique code for these on their accident reports. As a result, establishing a count of the number of such events nationally is not a straightforward matter.

Three approaches have been attempted. The first of these is to take information from a clipping service provided by the Pennsylvania Department of Transportation. This generally allows a review of experience at individual sites, but does not help with a national estimate directly. The second approach is to devise a surrogate measure of truck runaways in an existing national file--in our case the FARS--and to tabulate these. The third is to acquire data from a few sources which have tabulated runaways in special studies--notably California, Pennsylvania, and Colorado, supplementing these with data from the literature.

Each method provides information which is useful to the present study in a different way. The clipping service yields individual accident details which describe the consequences of runaways, and indicates the public concern for the problem. The FARS data permit a rough estimate of the number of fatal runaway accidents, and their national distribution. The runaway and ramp usage tabulations allow some inference to be made regarding the principal causes of runaways, and furnish data for a model to evaluate prospective countermeasures.

This section of the report is organized in the following parts: (1) the introduction; (2) a discussion of sources of data used, (3) a tabulation of runaway accidents and incidents, (4) an estimate of the costs associated with such incidents, and (5) a model to estimate the safety benefits of using retarders.

3.1 Data Sources

Factors which should be considered in predicting a runaway truck include:

- steepness of slope
- length of the hill
- degree of curvature or frequency of curves
- condition of the truck brakes
- the presence or absence of retarders
- the gross vehicle weight of the truck (or alternatively, the percentage of the maximum rated weight)
- the experience of the driver in mountain driving.

It would clearly be desirable to have a single set of data both in an exposure and runaway population for which all of the above factors were known. Unfortunately, no such single set of data has been available, and we have been forced to use information from many sources to identify these factors.

In a study centered on runaway trucks, the reviewer comes to the belief that all truck accidents seem to be runaways. Yet this is really not the case. Runaway truck accident frequency might well be compared with that of fire accidents. When they happen they tend to be spectacular, and prompt extensive news coverage. Yet at a particular site—say Interstate 80 on the hill from the Nevada/California border to Gold Run—there have been about nine "runaway" accidents per year for the past three years. It would take a long time to collect enough data to define the interactions among the seven factors mentioned in the opening paragraph if the data collection were to be done at only one site. While there are a number of locations which have maintained records of runaway accidents or ramp usage in the past, there is no nationally consistent practice. Thus the data used in this study have come from many sources, in many forms, and are interpreted more by judgment than by statistics.

Specific data we have used in this study include:

1. Ramp usage and runaway accident reports furnished by the Colorado State Patrol.

Since 1977, the Colorado State Patrol has completed a special form—originally for instances of runaway ramp usage, and more recently for some runaway accidents. A copy of this report form is shown as Figure 3.1.

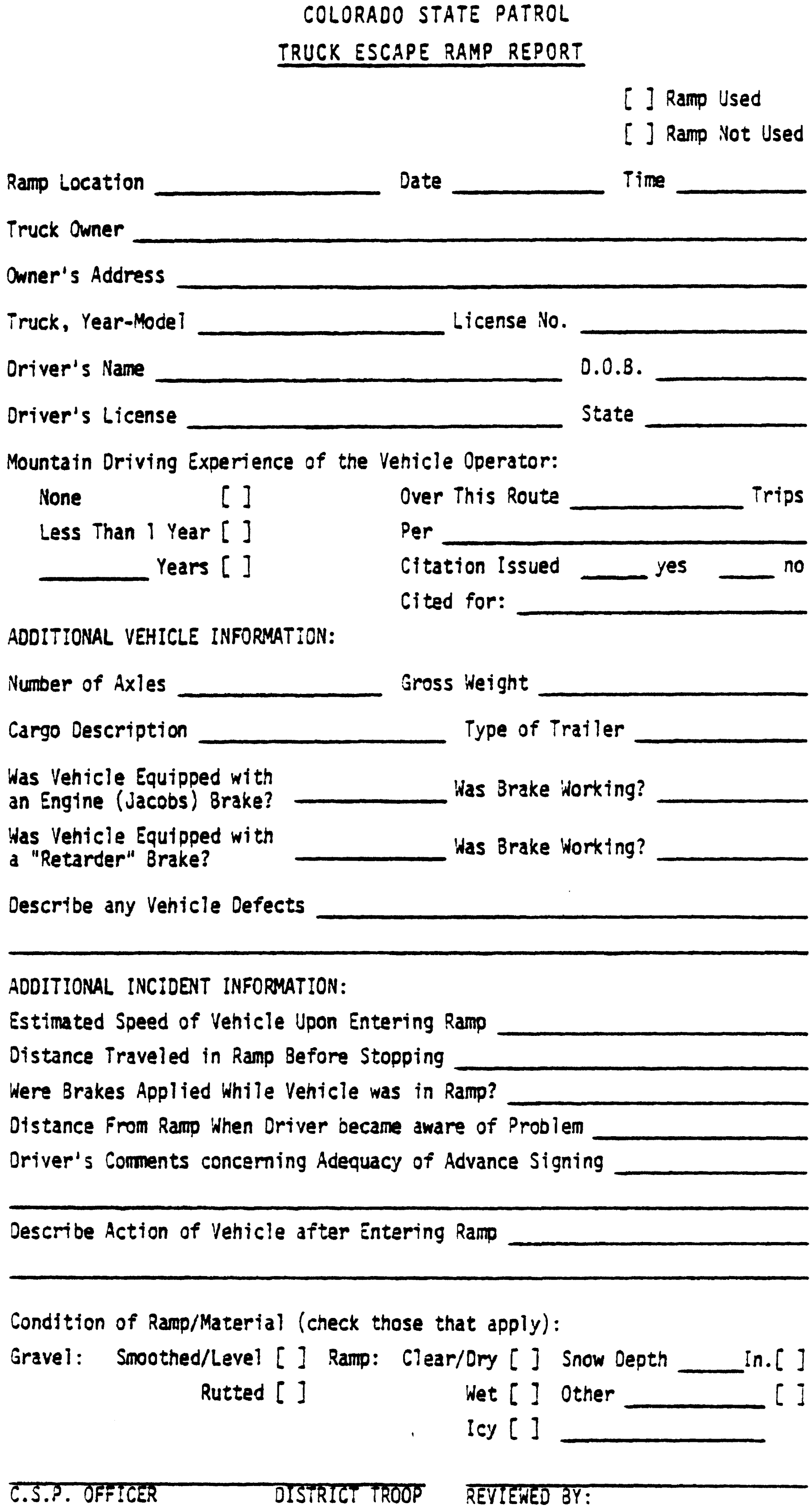
Included in the report are the vehicle identification and description, a notation of the driver's experience in mountain driving, a record of the presence of a retarder, maximum speed during the episode, occasional reports on the vehicle "defects," and other factors.

The completeness of the form has improved with time, so that the last year's data are regarded as the most representative. These data have been keypunched into a form permitting a variety of analyses, and have been used to determine runaway frequencies, the presence of retarders in runaway events, etc.

2. Accident records from Interstate 80 in California, provided by the California Highway Patrol.

The California Highway Patrol post at Gold Run has maintained a special file on runaway accidents for the past four years, and the post commander provided us with copies of these reports. In addition to the conventional California Highway Patrol (CHP) accident report, most of these cases included an inspection report written by a commercial vehicle officer/inspector. These have been of particular value in establishing the distribution of "defects" which led to the loss of braking power. In addition, when these data are compared with truck inspection information from the same highway (for non-accident vehicles), they provide an indication of the importance of brake condition in preventing runaways. The existence of retarders on the truck is reported in some instances, but is too sporadic to permit an accurate evaluation of their importance.

Appendix E is a copy of a commercial officer's report for a fatal collision. The detail is typical of non-fatal reports as well.



COLORADO STATE PATROL

TRUCK ESCAPE RAMP REPORT

☐ Ramp Used
☐ Ramp Not Used

Ramp Location ______ Date ______ Time ______

Truck Owner ______

Owner's Address ______

Truck, Year-Model ______ License No. ______

Driver's Name ______ D.O.B. ______

Driver's License ______ State ______

Mountain Driving Experience of the Vehicle Operator:

None ☐ Over This Route ______ Trips
Less Than 1 Year ☐ Per ______
______ Years ☐ Citation Issued ______ yes ______ no
Cited for: ______

ADDITIONAL VEHICLE INFORMATION:

Number of Axles ______ Gross Weight ______

Cargo Description ______ Type of Trailer ______

Was Vehicle Equipped with an Engine (Jacobs) Brake? ______ Was Brake Working? ______

Was Vehicle Equipped with a "Retarder" Brake? ______ Was Brake Working? ______

Describe any Vehicle Defects ______

______

ADDITIONAL INCIDENT INFORMATION:

Estimated Speed of Vehicle Upon Entering Ramp ______
Distance Traveled in Ramp Before Stopping ______
Were Brakes Applied While Vehicle was in Ramp? ______
Distance From Ramp When Driver became aware of Problem ______
Driver's Comments concerning Adequacy of Advance Signing ______

______

Describe Action of Vehicle after Entering Ramp ______

______

Condition of Ramp/Material (check those that apply):

Gravel: Smoothed/Level ☐ Ramp: Clear/Dry ☐ Snow Depth ______ In. ☐
Rutted ☐ Wet ☐ Other ______ ☐
Icy ☐ ______

C.S.P. OFFICER DISTRICT TROOP REVIEWED BY:

Figure 3.1. Ramp Usage Report Form

3. The Fatal Accident Reporting System (FARS) data for several recent years.

Runaway accidents, as such, are not identified within the FARS data. There are possible surrogate variables which seem likely to be associated with runaways, and we have used the FARS computer files to list such cases. This procedure is intended to provide some sort of national estimate of fatal runaway crashes, and has been supplemented by identifying particular fatal cases by reading the original accident reports or finding them in the California or Colorada data above.

4. The Bureau of Motor Carrier Safety accident data for 1976-78.

As in FARS, runaway accidents are not specifically identified. There is less detail about crash circumstances than in FARS (for example, no record of whether or not the crash occurred on a grade), but for some purposes it has been useful to define a surrogate measure of runaways in this data set. While not of value in establishing a national frequency, we have used these data in estimating damage costs associated with such accidents.

5. Ramp usage and runaway accident data from Pennsylvania.

The Pennsylvania Department of Transportation (PennDot) maintains some records of runaway events, and these are relatively complete for several locations. In addition, PennDot furnished us with numerous newspaper clippings which give good accounts of the runaway problem as observed by reporters in cities surrounded by hilly terrain. These have been useful in establishing runaway rates in an eastern environment. The reporting of the presence of retarders is sporadic, but detail on cargo and weight is often available.

Some traffic count data were available from Pennsylvania, and these permit an estimate of the relative frequency of runaways in that state.

6. Occasional ramp usage and accident data from other states.

As a part of the general survey of states, we have received replies to our queries about runoff ramp installations, usage, and some accident data. Where sufficient detail was available, these events (accidents and ramp usages) were coded into the same form as the Colorado or California data, and for some purposes were included in analyses.

7. Rural Mileage and Travel and Vertical Alignment Adequacy rating for selected states provided by the FHWA.

Data reporting the percentage of various road classes (and vehicle miles traveled on those road classes) for which the vertical was considered inadequate for one reason or another. These data are used to indicate which parts of the U.S. may be most appropriately considered for enhanced truck braking and retarding cabability. These data were available for only 39 states.

8. Other sources.

Some data were obtained from the literature, particularly descriptions of existing steep slopes and runaway ramps, and of vehicle brake condition.

3.2 The Frequency of Runaway Events

As with accidents in general, it is difficult to speak of the number of such events without carefully defining the item in question. One might construct a scale of "runaway severity" for which the minimum was "smoking brakes" and the maximum a high speed fatal collision as shown in Figure 3.2.

In general the cost of damage etc. associated with these events will be inversely proportional to the number. Retarders may be considered of potential value in reducing the frequency of all of these.

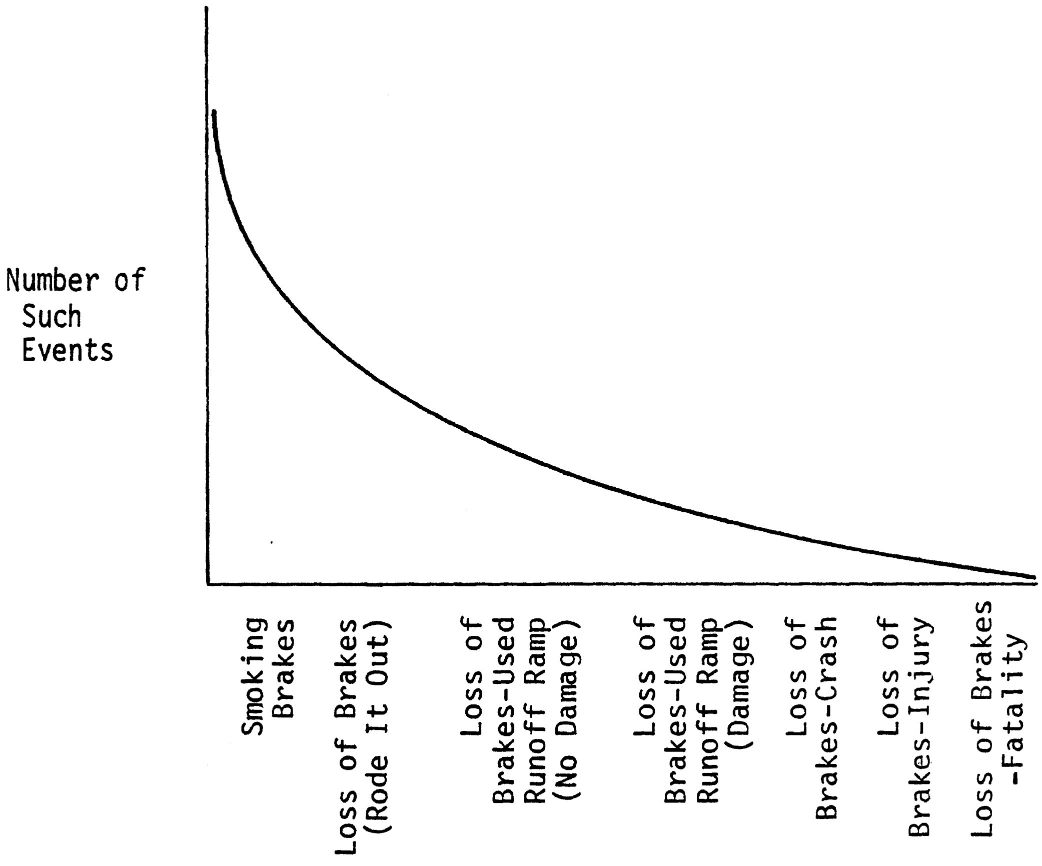


Figure 3.2. Hypothetical distribution of runaway events by severity

Hard data on the frequency of smoking brakes (without any attendant untoward event) is not available. A newspaper article in Uniontown, Pennsylvania noted that the residents of Hopwood (a suburb at the bottom of a long, steep descent on U.S.-40 were "sick and tired of the smell of smoking brakes" coming from trucks passing through town. A Salt Lake City resident told us that he smelled smoking brakes "every morning" while traveling down the Parley's Canyon road on Interstate-80 near that city. As evidenced by witness's statements in accident reports, it is not uncommon for one truck driver to call another on the CB radio to tell him that his brakes are smoking. About the only conclusion to be drawn from this is that it is evidently not an unusual event, and that it occurs much more frequently than do the other kinds of problems in Figure 3.2.

Runaways which survive without an accident or a ramp usage are also hard to count. Eck [1] reported that in an interview series with drivers who had had mountain driving experience, one out of four had "lost his brakes" one or more times during his driving experience. Again, this would seem to be a not-uncommon circumstance, but there are no precise statistics.

3.2.1 Ramp Usage and Runaway Accidents. For each of several escape ramps in the United States, traffic data have been available permitting the computation of a "runaway rate." There are, of course, many environmental factors which will affect such a rate--the slope and length of the hill being the primary ones. The western hills, at least those for which data have been available in this study, are generally long (more than a few miles), and of moderately severe slope. In Colorado, downslopes at Rabbit Ears westbound, Vail Pass westbound, Straight Creek westbound, Slick Rock eastbound, and Wolf Creek westbound--all of which are equipped with runaway ramps--are all about seven miles long with relatively continuous slopes of six to seven percent. California's Donner Summit downslope to Sacremento has nearly 20 miles of intermittent grades of up to five percent. By contrast, slopes in eastern United States are likely to be shorter but steeper. Typical heavily traveled hills east of Pittsburgh have grades of more than eight percent, but lengths of one to four miles. States which have constructed one or more escape ramps are identified in Figure 3.3.

Ramp usage rates are computed, where possible, in the last column of Table 3.1 for selected locations. They range from one runaway in 1,000 transits at Rabbit Ears Pass in Colorado to an estimated one in 400,000 for a one-mile grade at Indiana, Pennsylvania.

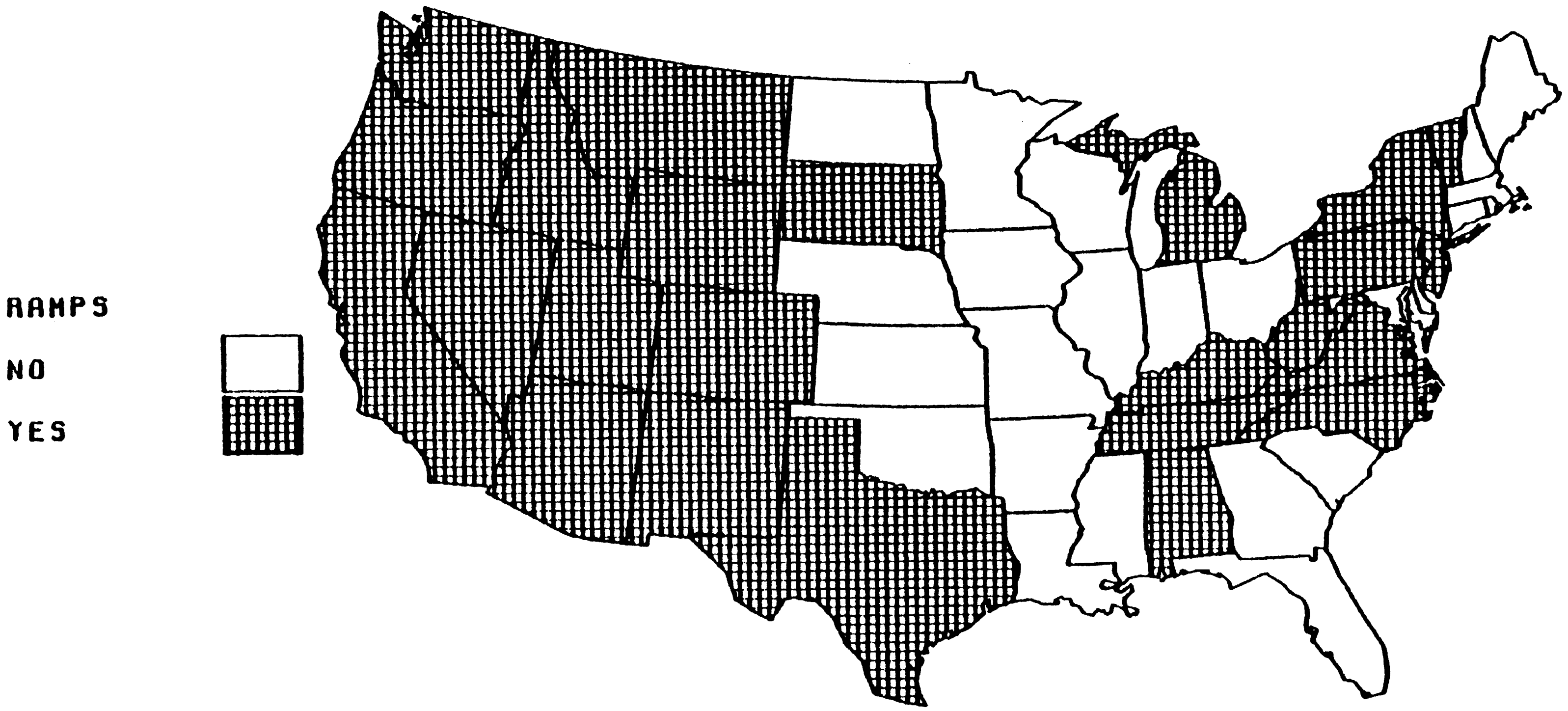


Figure 3.3. Presence of one or more truck escape ramps in the United States

NOTE: States which have one or more escape ramps are shaded; those without ramps are white. Michigan seems to be an anomaly; has one ramp in the northern part of the lower pennisula which has never been used.

TABLE 3.1

Characteristics of Selected Downgrade Sites

Site	Length of Downgrade	Approx. Slope	Truck Downhill ADT	Ramp Usage /Time	Accidents /Time	Ramp Usage or Accident Rate
Interstate-80 Donner Summit, Calif.	15 mi.	3-5%	(800)		27/3 yrs.	(1/32,000)*
U.S.-99, Calif.	3.5 mi.	5-6%	(500)	36/1 year		1/5,000
Williamette, Oregon	3.5 mi.	5-6%	256	12/10 mos.		1/6,500
Siskiyou, Oregon	7 mi.	5-6.5%	1150	32/3 mos.	12/year	1/35,000* 1,3300
Vail Pass, Colorado	7 mi.	6%	235	18/year		1/5,000
Rabbit Ears Pass, Colorado	7 mi.	6%	65	12/year		1/2,000
Parley's Canyon, Utah	10 mi.	4.5-6%	(750)	(26/year)		(1/10,000)
Cheat Mountain U.S.-50, W. Virginia	3 mi.	8%	112		5/year	1/8,000*
Patrick County, Vir. Virginia	3 mi.	8%			3/4 years after ramp was built	-
I-77, Virginia	3.7 mi.	4%	?	Not used in 3 yrs.	?	?
Indiana, Pennsylvania	1 mi.	8%	1100	17/21 mo.	?	1/40,000
Montego Mountain, Tenn.	?	?	?	18/6 weeks	22/17 mo.	-
Old Fort, N. Carolina	5 mi.	6-8%	750	78/22 mo.	10 fatals/12 mos. before ramp instal.	1/6400

*Accident rate. NOTE: Numbers in parenthesis not supported by hard data.

It is hard to compare these directly, since the data recording method varies from one site to another. However, for purposes of further model development we will assume runaway rates (as evidenced by ramp usage) to be on the order of 1 in 5000 transits.

A similar computation may be made for runaway accidents. Most states do not keep a specific record of a runaway event in an accident report. The data available for the Donner Summit area are believed to be complete. Twenty-seven accidents were reported in a period of three years, for an accident rate on this long slope of about 1 in 32,000 transits. Most of the other data come from areas with escape ramps, and it is hard to determine which runaways would lead to accidents and which would not. Long-term records in Pennsylvania, maintained mostly by newspaper reporters, suggest that the accident rate would be lower than the ramp usage rate, i.e., at least some of the ramp users would not have crashed. On the other hand, many of these sites still report trucks which have lost brakes beyond the ramp areas. The occurrence of a crash, of course, depends much on the curvature of the road and the amount of traffic. Indeed, on the Donner Summit hill in California there are trucks which lose their braking power but still make down the hill without incident. For purposes of the analysis here, we will simply assume that the accident rate is somewhat lower than the runaway rate.

An idea of the frequency of unreported events might be gained from the following sequence observed in Colorado.

> A tractor-trailer had entered an escape ramp, and a police officer had parked at the entrance to interview the driver.
>
> While the officer was talking to the driver a second truck passed the ramp entrance at high speed, was unable to enter, and rolled over about a half mile below the site.
>
> As the officer went to investigate that accident, a third truck passed the ramp with smoking brakes.

A second sequence very similar to this was also reported in Colorado in the following year. In North Carolina a second ramp was opened near an existing one because of the expectations that the first would be in use when it was needed [1].

3.2.2 Fatal Accidents. One category of accident for which a national frequency might be established is the fatal crash. The Fatal Accident Reporting System (FARS) does not identify runaway accidents as such, but does report speed, grade, and brake failure or defects. None of these items seems to be reported consistently--some states not reporting speed at all, and grade and brake defects being subject to some local interpretation. Nevertheless, we have identified tractor-trailer accidents in FARS for 1976-1978 which reported either "grade, and brake defect" or "grade and speed greater than 65 mph. In each year FARS reported about 100 such accidents. Copies of the original accident reports were reviewed for a sample of these, with the conclusion that about one-quarter were obviously runaways, one-quarter obviously not, and the remainder uncertain (but likely half-and-half). Based partly on these observations, and partly on the actual number of runaway fatal accidents noted in Pennsylvania, Colorado, and California records, we estimate that there are 25 to 50 such accidents annually in the United States.

Figure 3.4 displays the states with various numbers of fatal accidents identified with the FARS surrogate measure. There are some obvious anomalies--one wonders about the definition of "grade" in Florida, for example--but the pattern generally identifies the mountainous states.

3.2.3 The Environment. Another illustration of the geographic distribution of the runaway problem is derived from the FHWA records of vertical sufficiency ratings by state. For various road classes within a state, two grade adequacy categories are of interest.

Road segments coded as grade "3" are defined as "infrequent grades and vertical curves that impair sight distance and/or

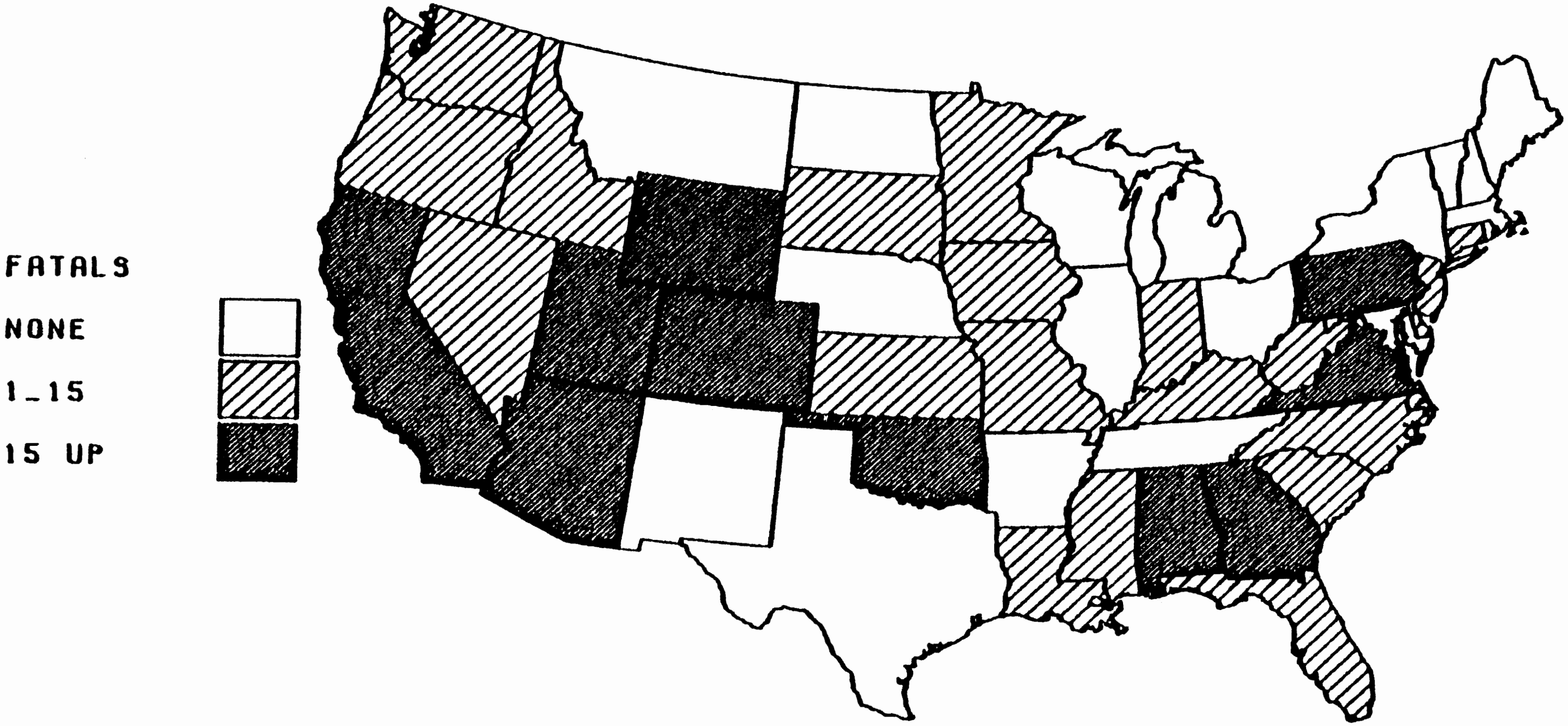


Figure 3.4. Numbers of fatal accidents by state which may be runaways

NOTE: Data from FARS were filtered for tractor-trailer crashes with "grade and speed greater than 65 mph" or "grade and brake failure (defect)." Numbers shown were the sum of the years 1976-1978. Darker states exhibit the highest counts for this surrogate measure of runaways.

affect the speed of trucks if truck climbing lanes are not provided." Segments coded "4" contain "frequent grades and vertical curves that impair sight distance and/or severely affect the speed of trucks and truck climbing lanes are not provided." Figures 3.5, 3.6, and 3.7 display states in the United States which exhibit these characteristics. Again, the mountainous states are obvious. At the time of writing, data were not available for California, Pennsylvania, and New York and several others; these are shown as unshaded on the maps.

3.3 Costs of Runaway Events

Given the range of events shown in Figure 3.2, the least costly is no doubt the "smoking brakes." There would seem to be no immediate cost associated with this, although there may be a need for more frequent relining or adjustment. Such expenses are considered elsewhere in this report, and will not be dealt with further in the safety section.

Ramp usage is another matter. Many of the ramps in use involve a gravel-bed arrestor which, though quite effective in retarding the vehicle, also makes it impossible for the driver to get out without assistance. Even if there is no damage to the truck, it is likely to involve several hours of waiting plus a bill for $150 for towing. In addition, many highway departments will bill the trucker (or his insurance carrier) for repairs or regrading of the gravel. Added to a time delay of several hours, we might expect the average ramp entry to cost $300 or so.

Although ramps have been designed to minimize the probability of damage to the truck, about one in ten ramp usages does lead to substantial damage. In one case in Colorado a heavy truck continued over the end of 1300 foot ramp and was totalled. In a Pennsylvania case, a tractor-trailer jackknifed in rolling backwards at the ramp. We estimate that one in ten ramp entries, then, would result in a larger cost on the order of $2000.

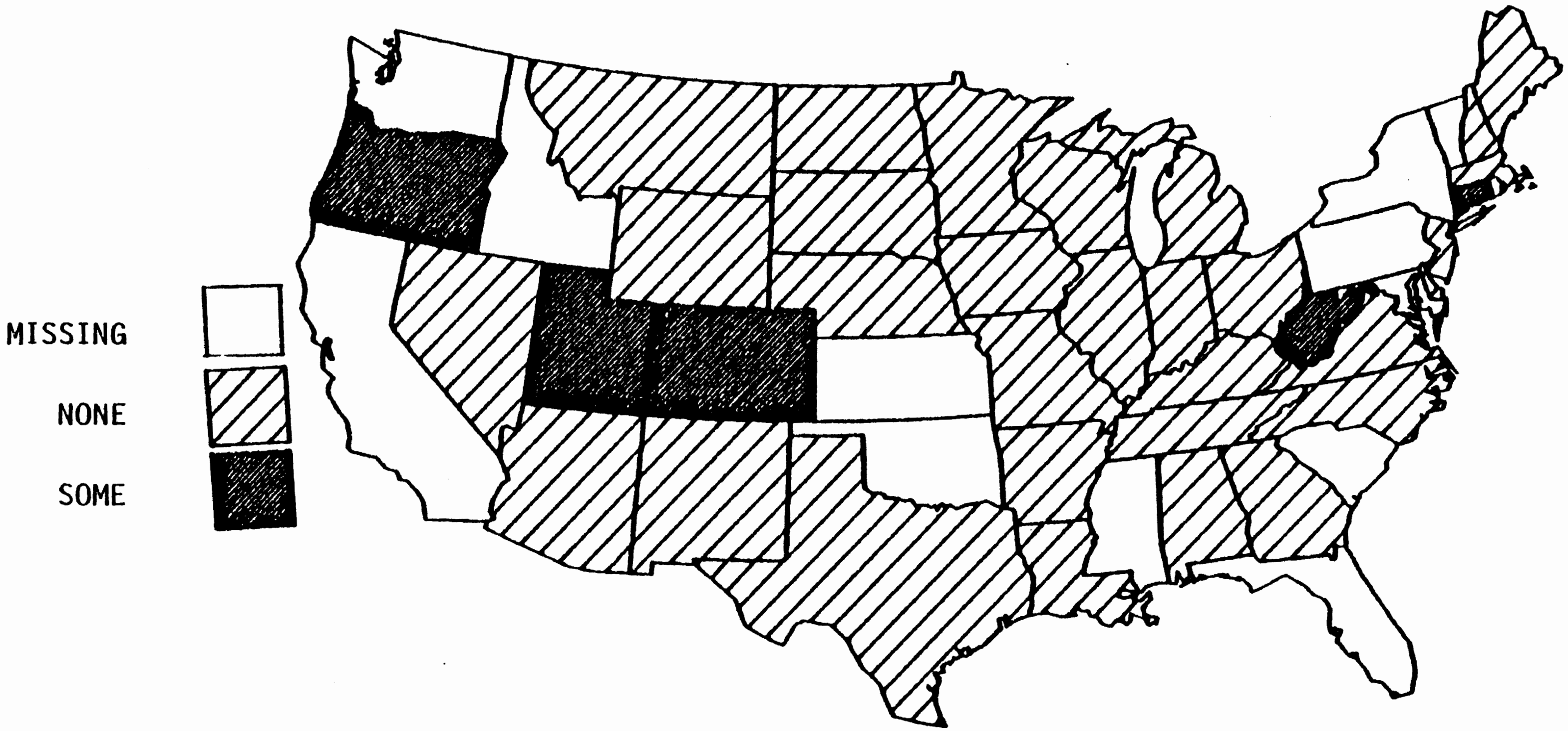


Figure 3.5. Vertical adequacy at code 3 or 4, Interstates

NOTE: The shading indicates those states with a measurable fraction of their Interstate roads which have a vertical adequacy rating at code 3 or 4.

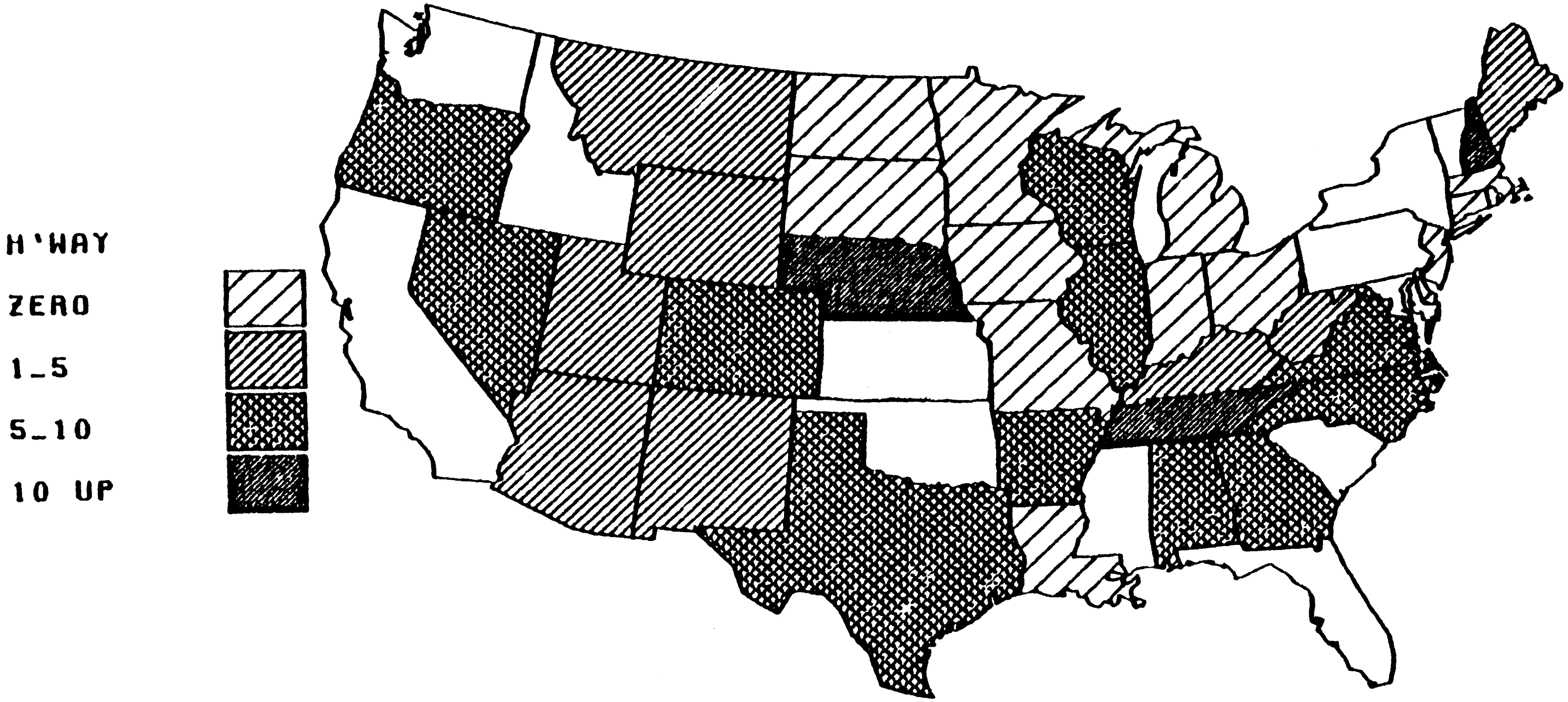


Figure 3.6. Vertical adequacy at Code 3, other primary arterials.

NOTE: The shading indicates the percent of non-interstate principal arterial vehicle miles traveled under vertical adequacy code 3: Infrequent grades and vertical curves that impair sight distance and/or affect the speed of trucks if truck climbing lanes are not provided. The darkest shaded areas indicate states with more than 10 percent of their VMT under such conditions. The lighter shades are as shown in the legend. No data were available for the states shown as blank.

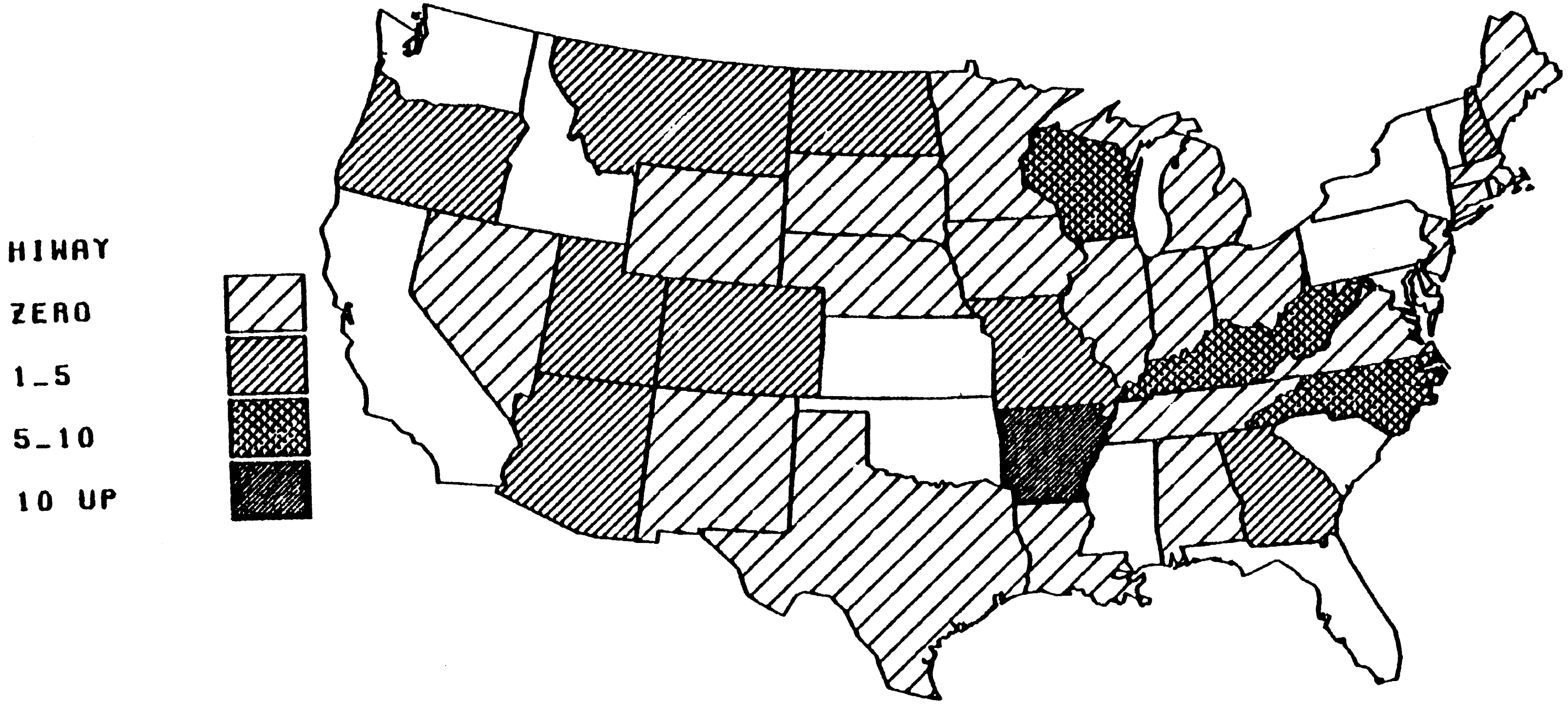


Figure 3.7. Vertical adequacy at code 4, other primary arterials

NOTE: The shading indicates the percent of non-interstate principal arterial vehicle miles traveled under vertical adequacy code 4: Frequent grades and vertical curves that impair sight distance and/or severely affect the speed of trucks and truck climbing lanes are not provided.

Runaway accidents, too, must come in various degrees of damage. Those for which the best data are available tend to be the more serious ones. Even when these do not involve injury or fatality, total loss of the vehicle and cargo is not unusual. Estimates of the property damage costs in police and newspaper reports are suspect, but those reported by the carriers to BMCS would seem to have some validity. We have taken the mean costs for non-fatal rollovers reported there in 1978, and this is about $15,000 per incident. Fatal rollovers of tractor-trailers, by contrast, average about $34,000. Fatal collisions with other vehicles average $45,000 in property damage. We have used $40,000 in our estimates here.

Fatal accidents, of course, should also be charged with the societal costs of the fatalities. The mean number of fatalities sustained in the runaway surrogate accidents from FARS (in 1977) was 1.13, so that each runaway fatal accident might be costed at the estimate of the property damage plus 1.13 times the societal cost of a fatality. Various estimates of this have been produced, but for purposes of this study we will choose $455,000* in 1980 dollars. Severe injuries might also be estimated. The NCSS distributions indicate that survivable AIS-4 and -5 injuries are roughly equal in number to fatalities (although these are taken only from passenger car towaway crashes). Marsh, et al. [4] estimated the direct costs associated with AIS-5 injuries as a mean value of $73,000 and $47,000 for AIS-4. Assuming these to be about equal in number, approximately $60,000 in 1980 dollars per serious injury may be added, with a number of cases equal to the number of fatalities. Less severe injuries will be neglected in these computations.

In summary, we have used the following estimates in assessing the costs of runaway events (see Table 3.2):

- average ramp entry - $300
- damage in 1 in 10 ramp entries - $2000
- average property damage in a fatal accident - $40,000
- societal cost incurred by a loss of life - $455,000
- direct costs associated with a serious injury - $60,000
- other accidents - $15,000

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*"The Value of Saving a Life: Evidence from the Labor Market," by Richard Thaler and Sherwin Rosen, University of Rochester. In Household Production and Consumption, ed. N.E. Terlekyi, National Bureau

TABLE 3.2

Estimates of the Numbers of Runaway Events and Their Annual Costs in the United States

Event	Annual Frequency in U.S.	Unit Cost	Total Cost
Ramp Usage (no damage)	1935	$300	$580,000
Ramp Usage (damage)	215	$3000	$645,000
Fatal Runaway Accidents	25-50*	$40,000 Property Damage + $455,000/Fatality x 1.13 Fatals/Accident	$13,853,750- $27,707,500
Non-Fatal Accidents (Serious Injuries)	25-50*	$40,000 Property Damage + $60,000 x 1.13 Injuries/Accident	$ 2,695,000- $ 5,390,000
Other Non-Fatal Accidents	100-200*	$15,000	$1,500,000- $3,000,000
Totals	2300- 2450		$19,273,000- $37,322,500

*The lower and higher values are based on interpretations of the FARS data as discussed above.

3.3.1 Frequency of Runaway Events. We would like to establish a national estimate for the various kinds of runaway events, but we have only the scattered data presented above as a basis. An analysis of FARS leads to the conclusion that there are about 25 to 50 fatal accidents attributable to runaway trucks.

Ramp usages might be estimated by tallying the average usage rate for ramps for which we have data, and multiplying by the total number of ramps in the United States. The simple average of those for which we have records is about 25, ranging from 0 usages per year to 124. The total number of run-off ramps currently in use in the United States is 86, and a first estimate of ramp usage event frequency is thus 2150 per year. As shown in Table 3.2, 10 percent of these might be expected to produce substantial damage, the remainder only recovery costs.

The estimated annual number of fatal runaways has been taken from the FARS analysis presented above, and a range of 25 to 50 such accidents is shown in the table. Costs associated with each fatal accident include an estimate of $40,000 property damage (taken from the BMCS-reported costs for rural tractor-trailer fatal crashes), and $455,000 as the societal costs incurred from the loss of a life, taken from Thaler and Rosen's paper [5] as adjusted for the increase in the Cost Production Index.

Non-fatal accidents resulting in serious injuries are estimated to be equal to the number of fatal accidents, and are similarly multiplied by 1.13 to account for the estimated number of such injuries per crash. Costs for this are taken from Marsh, Kaplan, and Kornfield, as noted above.

Other non-fatal accidents are probably the most difficult to estimate. Various records from states suggest that these are as low as 2.5 times the number of fatalities to as large as ten times the number of fatalities. Property damage costs have been estimated from BMCS-reported costs for the average rural rollover crash involving a tractor-trailer.

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of Economic Research, 1976. Thaler and Rosen estimate the societal costs incurred by a loss of life at $200,000 plus or minus $60,000 at the 1967 wage rate. For 1980, with a CPI of 227.6 in November 1979, estimate $455,000.

With the values assumed, the total is dominated by the number of fatal crashes. There have been other estimates of the societal costs associated with a loss of life—for example, that of Faigin [6] at NHTSA—which are somewhat lower than the one chosen here. But even if the fatality costs were half that shown in the table, this would still be the major factor.

3.4 A Model Interrelating the Major Vehicle-Related Factors in Runaways

While the general purpose of this study is to determine the importance of retarders in reducing the probability of runaway trucks, there are other truck-related factors which should be considered. Nearly all "runaways" ultimately involve a total brake failure, and the initial condition of the brakes prior to the runaway event has been cited as relevant. Further, the weight of the vehicle (or perhaps its actual weight relative to a recommended maximum gross vehicle weight) might be expected to affect the probability of a runaway. In this section, a model will be presented (within the limits of the available data) to look at the relative contributions of weight, brake condition, and presence of retarders to the runaway process.

It would have been nice to have had a large population of vehicles operating in hilly areas within which we could identify each of these factors in both a runaway and a control population. Such data do not seem to be available, and we have been forced to look at different factors in different populations, and to take exposure information from relatively indirect sources. A major limitation of this process is that we cannot discern any interactions among the factors or their joint contributory effects on the runaway incidents directly.

We proceeded, therefore, to develop estimates of the effect on runaway probability of each of these factors independently.

3.4.1 Brake Condition and Runaway Trucks. The California Highway Patrol Gold Run Post has kept records of runaway truck accidents which occurred on Interstate-80 during the period 1977-1980. For nearly all of these accidents the truck involved was inspected subsequent to the accident by a commercial vehicle officer/inspector, and his findings are generally included in the traffic accident report.

Since all of the cases we have reviewed were originally filed under the heading "runaway truck," it should not be surprising to find that nearly all had some kind of "brake failure." The purpose of this section is to show the distribution of the kinds of failure observed. For those cases in which the truck was still available, the commercial vehicle officer usually checked the air pressure and measured the push rod travel at each braked wheel upon application of the brake pedal. Notation was also made of air fitting failures or leaks, and on frequent occasions the driver was cited for a violation of a California ordinance requiring proper brake adjustment to be maintained. For purposes of this study we will divide such "defects" into two classes--(1) brake fade occasioned largely by imporper adjustment supplemented by the increase in temperature on the downhill run, and (2) sudden or catastrophic failures, such as a broken air fitting, or other component. Table 3.3 shows the number of cases in each category observed in the set of runaway accidents occurring on Interstate 80 in California in a three-year period and on the downhill segment from the agricultural inspection station to Gold Run. Also shown in the table, in the second column, is the estimated proportion of improperly adjusted brakes in the exposed population derived from a roadside inspection carried out at the agricultural station at an earlier time (which indicated about 40 percent of the trucks to have improperly adjusted brakes).

TABLE 3.3

Estimates of the Frequencies of Improper/Proper Brake Adjustment in Accident and Exposure Populations

Brake Status	Accident Involvement	No Accident Involvement
Improper Adjustment	18(72%)	40%
Proper Adjustment	7(28%)	60%
TOTAL	25(100%)	100%

Two probabilities are recorded from this table: (1) the probability of improper adjustment given a runaway crash, which is 0.72; and the probability of improper adjustment in the exposed population 0.40. These will be used in the later development of the model.

3.4.2 Runaways Versus Weight of Vehicle. Others things being equal, one might expect the probability of overheated brakes to be directly related to the gross vehicle weight in a downhill run. Data are presented which seek to explain this relationship. Using only the Colorado ramp usage data, and eliminating pickups, buses, etc. from consideration, the proportion of runaway vehicles above 60,000 pounds was 73 percent vs. 27 percent below that weight.

To get a comparable population for comparison we have taken Colorado accidents for trucks in non-local service from the BMCS files for the year 1978. Using the same break point, 47.2 percent of the vehicles had a reported gross vehicle weight greater than 60,000 pounds, and 52.8 percent less than that. Table 3.4 shows these figures in a manner parallel to the tabulation for brake condition.

TABLE 3.4
Proportion of Vehicles in Two Weight Classes,
Runaways vs. General Population

Weight Characteristic	Runaway Vehicles	Exposed Population (No Runaway)
Greater than 60,000 lbs.	73%	47.2%
60,000 lbs. or Less	27%	52.8%
Total	100%	100.0%

Two probabilities are recorded from this table: (1) the probability of a load greater than 60,000 pounds in the runaway population (0.73), and (2) the probability of a load greater than 60,000 pounds in the exposed population (0.472). These will also be used in the model.

3.4.3 Runaways vs. Presence of Retarders. Colorado runaways over the period 1977-1980 are reported with a variety of data--including (for a portion of the cases) whether or not a retarder was present on the runaway vehicle.

On the Colorado report, the principal "failure" or "defect" associated with the runaway incident is assigned a level like: brake fade, broken air fitting, runaway engine, etc. We have grouped these failures into three general classes: (1) Brake fade or overheating, (2) Other brake problems, and (3) Other component failures not directly involving brakes (such as "transmission shift lever broken off," clutch failure, etc.). Table 3.5 shows the distribution of this recoded variable with retarder presence.

While the strength of the differences in Table 3.5 is small (e.g., the chi-square for the 3 x 2 data is significant at about the 12 percent level), there is at least a suggestion that retarder equipped vehicles are relatively less likely to have brake

TABLE 3.5

Presence of Retarders on Runaways in Colorado for Trucks Greater Than 60,000 lbs., vs. Type of Failure Reported

Type of Failure	Retarder Present	No Retarder Present	Total
Brake Fade	6	10	16
Other Brake	1	4	5
Other Failure	7	3	10
Total Runaways	14	17	31

failures, and more likely to experience some other kind of failure. Of more interest, perhaps, is the comparison of the proportion of retarder-equipped vehicles in this runaway population with the general population. For vehicles in the 60-80,000 pound class in Colorado, it is estimated that about 70 percent are retarder-equipped vs. 30 percent not so equipped. Table 3.6 illustrates the relationship between the runaway population and a (30-70) general population. With a total of 31 runaways, then, and the distribution shown in Table 3.5, Table 3.6 shows the estimated runaway rates for retarder-equipped and non-retarder-equipped trucks.

TABLE 3.6

Presence of Retarders in Runaway and Exposed Populations

Retarder?	Runaway Population	Exposed General Population
Yes	14 (45%)	70%
No	17 (55%)	30%
Total	31 (100%)	100%

There has been no sorting of these data for the type of retarder used. In the Colorado data the majority of retarder-equipped trucks evidently have the "Jake" brake, but there are some equipped otherwise.

The usable probabilities which come from this table are (1) the probability of a retarder in the runaway accident population (0.45) and (2) the probability of a retarder in the exposed population (0.7). These two probabilities will be used in the following model development.

The foregoing cursory examinations of the influences of brake condition, loads, and retarders on the runaway incidents based on the limited data that are available indicate all three factors as having some effect on the runaway incidents. Their joint contribution to the runaway incidents or the interrelationship that may exist among the three factors can not be determined. Without the assessment of the joint effect, the three separated pieces or arguments are not quite meaningful. To model the joint effect of these three factors necessitates certain assumptions be made. These assumptions will undoubtedly influence the outcome of the analysis. The reasonableness of the assumptions and the influence on the outcome will be discussed within the next section.

3.4.4 The Probability Model. Given that brake condition, load, and retarders have some influence on the occurrence of the runaway incident, our problem can be stated mathematically as follows:

Let X_1 be a dichotomous variable representing either good brakes or bad brakes.

X_2 be a dichotomous variable representing loading under or over 60,000 lbs.

X_3 be a dichotomous variable representing the presence or the absence of a retarder.

Y be the occurrence of the runaway incident.

Thus the probability of a runaway incident in a particular combination of X_1, X_2, and X_3 is

$$P(Y|X_1X_2X_3) = \frac{P(X_1X_2X_3|Y)\ P(Y)}{P(X_1,X_2,X_3)}$$

where P(Y) is the observed average probability of a runaway.

If X_1, X_2, X_3 are assumed to be independent of one another, then

$$P(Y|X_1X_2X_3) = \frac{P(X_1|Y)}{P(X_1)}\ \frac{PX_2|Y)}{P(X_2)}\ \frac{P(X_3|Y)}{P(X_3)}\ P(Y)$$

Under the independence assumption, the probabilities of the runaway incidence given the three factors can be expressed in terms of the probability of each X_1, X_2, and X_3 in the accident population and the exposure population.

For any number of factors, say N, the model can be described as

$$P(Y|X_1, \ldots, X_N) = \frac{P(X_1|Y)}{P(X_1)} \ \cdots \ \frac{P(X_N|Y)}{P(X_N)} \cdots P(Y) \qquad (12)$$

Based on equation (12), the probability of an occurrence of a runaway incident in terms of different brake conditions, load, and retarders can be estimated as shown in Table 3.7.

TABLE 3.7

Probability of Runaway by Brake Condition, Load, and Retarder

Brake Condition	Loading	Retarder	Probability of Runaway
Bad	over 60,000	No	5.104 P(Y)
Bad	over 60,000	Yes	1.79 P(Y)
Good	over 60,000	No	1.323 P(Y)
Good	over 60,000	Yes	0.464 P(Y)

Table 3.7 is based on the data set wherein the proportion of retarders is 0.7 in the exposure population and 0.45 in the accident population.

The model has been developed to this point without regard to interactions among the three factors. Possible interactions include:

1. Retarder-equipped trucks might also have better maintained brakes; in this case, the estimated effect of the retarder might in fact be the result of the better brakes. This intervention would overestimate the benefit to be derived from retarder usage. The opposite case might also be argued, that is, that the presence of the retarder caused the brakes to be in better condition.
2. If trucks over 60,000 pounds were more likely to have poorly maintained brakes, the model would overestimate the effect of load. If larger trucks have better maintained brakes, load may be even more important than shown.
3. Retarders may be highly correlated with load—trucks carrying the heaviest loads being more likely to have retarders.

Although there seems to be little data to confirm the presence of interactions 1 and 2 above, we suspect that they are minimal. Truck brakes, as measured by the California Highway Patrol, are not very good in the entire population, and there is no indication that retarder-equipped vehicles are different from the general population in this regard. The same sort of argument might be made for interaction 2—load and brake condition. Interaction 3, however, is likely to be real. Purchasers of retarders buy them because they carry heavy loads. The effect of this interaction on the model would be to make retarders somewhat more effective than they appear to be under the independence assumption.

3.4.5 The Effect of Retarders and Brakes on Runaways. Other factors being ignored, the effect of the retarder alone may be computed as follows:

- We have estimated that there are as many as 2450 runaway events occurring annually in the United States, as shown in Table 3.2.

- In addition, we have estimated that the probability of a runaway in a downhill trip is 1/5000.
- Multiplying these provides an estimate of the annual frequency of such trips—12,250,000.
- With 45 percent of the runaway vehicles being retarder-equipped, versus 70 percent of the exposed population, the runaway rate for retarder-equipped vehicles is (.45 x 2540)/(.7 x 12,250,000) or .0001286. (This translates to one in 7776 trips.)
- The runaway rate for non-retarder-equipped vehicles is (.55 x 2540)/(.3 x 12,250,000) or .0003666—2.85 times as great.

If the assumed 70 percent retarders were increased to 100 percent, the number of runaway incidents would be reduced from 2450 to 1575. If retarders were not present at all, the number of runaway incidents would be 4491—nearly double the present value. This straight-line relationship is plotted on Figure 3.8.

A parallel argument may be developed regarding brake condition. Figure 3.9 shows the relationship between the expected number of runaway events and the proportion of trucks with properly adjusted brakes—in this case a ratio of probabilities of 3.86.

3.4.6 Costs and Potential Benefits. It has been estimated elsewhere in this report that the proportion of heavy trucks with retarders installed in the western United States is between 50 and 80 percent. We have used 70 percent for computations in this study as a reasonable estimate for such vehicles in Colorado.

Estimates of retarder sales in the eastern United States are much lower. Yet in a series of Pennsylvania runaways for which we were able to determine the presence of retarders, about 40 percent of the runaway vehicles there also were so equipped. The average eastern sales data probably do not apply to the mountainous regions, and a truck dealer in a mining region in Pennsylvania told us that "three out of four trucks he sold" were equipped with either an engine or exhaust retarder. It would seem, then, that a majority of the trucks which travel primarily in mountainous terrain are presently equipped. Accident and runaway involved drivers evidently

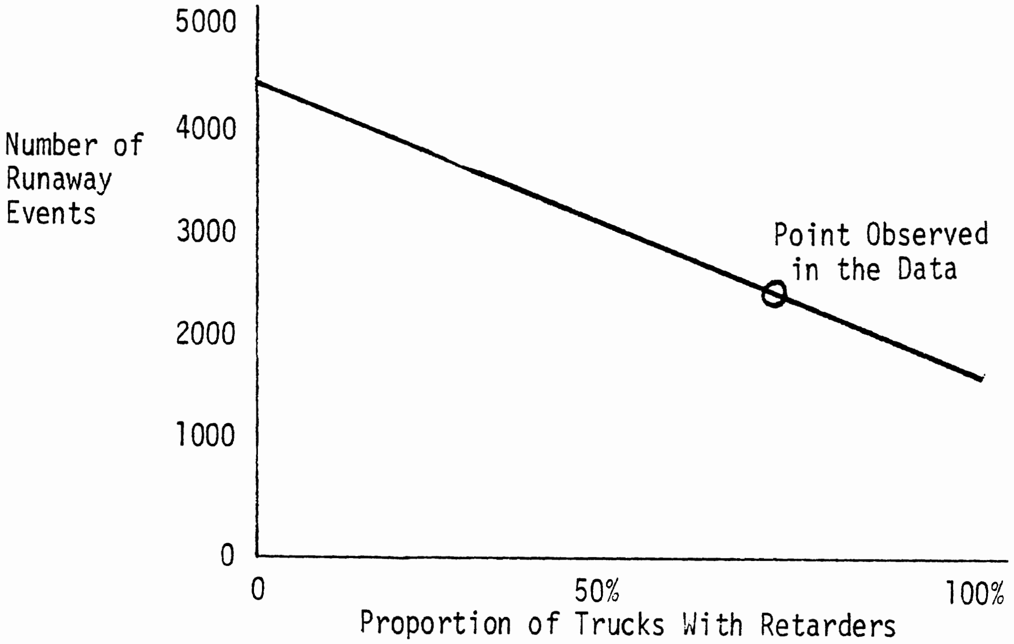

Figure 3.8. Runaway Frequencies vs. Retarder Presence

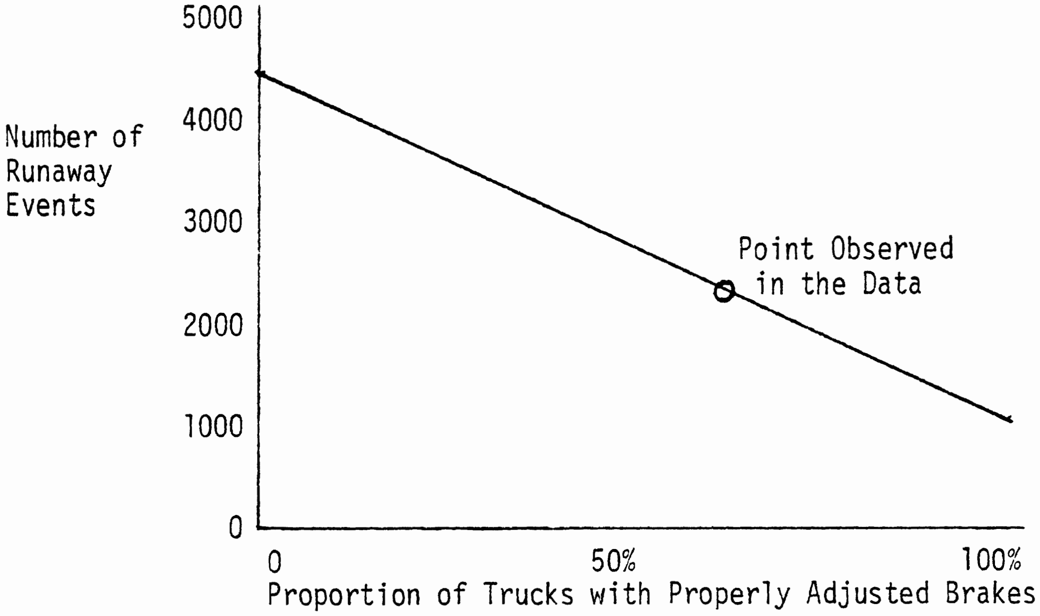

Figure 3.9. Runaway Frequencies vs. Brake Adjustment

believe in the safety potential of retarders, and it is not unusual to find the statement on a police report that the driver "wished he had had a Jake Brake."

As a first estimate of potential cost savings, we take the total costs computed in Table 3.2 ($35,322,500) and find that, if the 30 percent of the trucks which did not have them had been equipped, the number of runaways (from Figure 3.8) would have been reduced from 2450 to 1575. This 35.7 percent reduction translates to a potential annual cost saving of $12.6 million dollars.

The average cost of a runaway event, computed from Table 3.2, is $14,300. With a runaway probability of 1/5000 per downhill transit, a truck which went down 100 hills per year could justify nearly $200 per year toward the purchase of a retarder.* No doubt many of these already have them. But for a truck which travels down such hills only 10 times per year, the value would be only $20 annually.

3.5 Safety Summary

The data analysed in this section indicate that both brake condition and the presence of retarders are important contributors in minimizing the probability of a runaway truck. Under the assumption that these two factors are independent, brake condition is the more important one, but the present data estimate that full use of retarders in mountainous areas could reduce the number of runaway events by about 35 percent. Load also appears to be an important factor, but is judged to be beyond the control of the vehicle designer. The reader should view these findings with some caution, since the data available were sparse and sometimes incomplete.

In considering the effect of retarders here we have grouped all retarder-equipped trucks together for analysis. It is clear that there are many different kinds of retarders, each with a

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*Assuming that the retarder would prevent two out of three runaways.

particular capability. The data available would not support any more detailed breakdown.

Perhaps of more importance is the observation that retarders as such do not absolutely prevent runaways. Nearly half of the runaway vehicles in the pertinent data from Pennsylvania and Colorado noted the presence of retarders. There were a few occasions when the retarder itself failed or was inoperative. But for the most part, retarder-equipped vehicles which run away do so just like their unequipped counterparts. This suggests a strong interaction between the equipment and the driver's actions—such that the driver is going as fast as he thinks is safe without a retarder, and the same with a retarder (but this is faster). In a spectacular example a driver in Pennsylvania ran away twice on the same hill within two weeks in a retarder-equipped truck—the second time at 65 mph on what seemed to be a 10-mph hill.

If a truck could be equipped with a retarder without the driver's knowledge, so that the driver would descend slopes at the speed he would have chosen without the device, there is little question that the retarder would provide a great improvement. It is unreasonable to expect this, because, in addition to safety per se, a major reason for installation of a retarder is the increased downhill speed capability that can be attained without excessive wearing of the foundation brakes. A really clever retarder design, however, should somehow encourage the driver to operate a little more toward the safe side.

One potential effect of retarders which we have not been able to observe is the interaction with brake condition. In the discussion above we noted that there was no evidence that retarder-equipped trucks had better or worse brakes, but we might speculate that, since retarders have the potential for increasing brake life (and the time between relinings and/or adjustments), a given amount of time devoted to maintenance should result in better brakes on these vehicles. We attempted to find data relating brake inspections to retarder presence, but no one seems to record the latter. Such a correlation would indicate a secondary benefit of retarders, but weaken their observed direct effect.

4.0 OPERATIONAL, COST, AND SAFETY BENEFITS TO BE DERIVED FROM EXPANDED USE OF RETARDERS

In this section, the information presented in Sections 2 and 3 will be applied, to the extent possible, in assessing the benefits to be derived from using retarders. Three types of benefits will be emphasized: (1) operational benefits resulting from increased productivity due to shorter trip times, (2) maintenance cost savings obtained through reduced brake lining wear, and (3) safety benefits due to decreasing the probability of a runaway accident. In order to allow the future possibility of combining these benefits into an overall measure of merit, each of them is eventually quantified in units of dollars (even though expressing safety in terms of dollars may be highly judgmental).

4.1 The Potential for Reduced Trip Time

The potential for reducing the time spent traversing downgrades depends upon the specific characteristics of the route to be followed and the vehicle involved. The highway factors of importance are the magnitudes of the grades, the length of each grade, the miles between grades, and the practical velocity of travel between grades. (The latter two items are to be used for determining brake temperature.) For example, a trip could be described by a sequence of non-downgrade and downgrade sections as follows:

Trip Sequence: $m_1, \ell_1; \ldots; m_i, \ell_k; \ldots; m_N, \ell_N; m_{N+1}$

where m_i are the lengths of the non-downgrade sections

ℓ_k are the lengths of the downgrade sections

(The length of the trip = $\sum_{i=1}^{N+1} m_i + \sum_{k=1}^{N} \ell_k$)

Associated with each m_i there is a speed of travel V_i. (The m_i, V_i pairs will be used for estimating initial brake temperatures at the start of each downgrade.

Associated with each ℓ_k there is a grade, θ_k. (Each θ_k, ℓ_k combination will be used, along with initial brake temperature, to calculate control velocities for a particular vehicle operating without a retarder or with a retarder of specified capability.)

Vehicle factors of importance in determining the control velocities are the weight (GCW), natural retardation, retarder capability, and brake temperature parameters (cooling rate and effective time constant). The physical interaction of these vehicle properties with highway characteristics during downgrade descents was examined, analyzed, and explained in Section 2.1. The results presented in Section 2.1 can be employed in making preliminary estimates of time savings for trips of interest.

For example, consider a hypothetical trip described by the following sequence (Table 4.1) of non-downgrade and downgrade sections.

Table 4.1. An Example Trip.

Sequence Indices i and k	m_i miles	V_c	ℓ_k miles	θ_k %	*V_{Bk} mph	**(Q_{oi}) °F	***V_{BRk} mph
1	40	50	6	5	26	(150°)	55
2	40	50	5	6	16	(150°)	38
3	10	30	6	4	24	(300°)	55
4	100	50	3	7	12	(150°)	38
5	60						

$\Sigma m_i = 250$ $\Sigma \ell_k = 20$ miles at grade

total length 270 miles

*V_{Bk} = Control speed, brakes alone; **(Q_{oi}) = Initial temperature;

***V_{BRk} = Control speed, brakes plus retarder.

Let the vehicle be the 80,000-lb combination used in constructing Figures 2.7, 2.10, and 2.11. Solutions for this vehicle's control velocities are shown in the right two columns of Table 4.1. The velocity, V_{Bk}, is the control speed determined from Figure 2.10 for the case in which the foundation brakes are used without a retarder. Note that an initial temperature of 300°F was estimated for the segment of the trip corresponding to the third row of Table 4.1. As shown in the table, the brake control speeds, V_{Bk}, are considerably less than the velocities, V_{BRk}, for the case in which both the retarder and the foundation brakes are applied.

The velocities, V_{BRk}, are taken from Figure 2.11. In this example, the retarder can absorb 200 hp over the natural retardation from the engine. The velocities, V_{BRk}, may be slightly conservative because they are based on an initial brake temperature of 300°F. In this respect, a safety factor has been included in these results. (That is, the foundation brakes are allowed to absorb a limited amount of power.) Nevertheless, the results for V_{BRk} are (1) representative of what might be achieved and (2) useful for estimating savings in trip time.

Given the applicable velocities for each downgrade segment of the trip, the savings in trip time can be determined by straightforward calculations using the following equations:

$$t_{Bk} = \ell_k / V_{Bk}$$

where t_{Bk} is the time using the foundation brakes alone

and

$$t_{BRk} = \ell_k / V_{BRk}$$

where t_{BRk} is the time using both the brakes and a retarder. Table 4.2 summarizes the results of analyzing the situation presented in Table 4.1. As indicated in Table 4.2, approximately 0.6 hours (36 minutes) can be saved on the 20 miles of downgrade.

Table 4.2. Time Savings for an Example Trip.

Indices	ℓ_k	V_{Bk}	V_{BRk}	t_{Bk} hours	t_{BRk} hours
1	6	26	55	.23	.11
2	5	16	38	.31	.13
3	6	24	55	.25	.11
4	3	12	38	.25	.08
5					

Σt_{Bk} = 1.04 hrs., $\Sigma t_{BRk} = 0.43$

The time savings, $\Delta t = \Sigma t_{Bk} - \Sigma t_{BRk} = 0.61$ hrs.

To estimate the benefit of this time savings, it is necessary to select a dollar value for a unit of vehicle-operation time. Suppose (for purposes of this example) that time is worth $20/hr. Then, the cost savings per trip, C_{BT}, is given by

$$C_{BT} = \Delta t \, D_t$$

where $D_t = \$20/\text{hr}$

i.e., $C_{BT} \simeq \$12$

Whether this amount of saving can actually be achieved depends upon the circumstances of the trucking operation involved; however, presuming that it can be achieved, the number of trips per year will determine the annual benefit. This benefit could be large if a number of trips are required. For example, 200 trips per year could mean a benefit of $2400, which is substantial compared to the cost of a retarder.

The example presented above corresponds to a route consisting of four severe downgrades. Clearly, different routes will produce significant changes in the time savings possible. Greater time savings will occur for routes through regions containing many, closely spaced downgrades. Nevertheless, the example does illustrate that a non-negligible savings may accrue even if only a limited percentage (less than 7.5%) of a trip is on significant downgrades.

Further generalizations concerning time savings should be based on more extensive work to be performed in the future. Three of the items to be considered are (1) the relationship between retarder horsepower capabilities and the severity of the grades to be traveled in a particular service, (2) the compromises amongst (a) minimizing trip time, (b) reducing the work done by the foundation brakes during mountain descents, and (c) providing a margin of safety through limited use of the foundation brakes on severe grades, and (3) the influences of brake imbalances, varying maintenance practices, etc., on the temperature rises occurring in actual operation. The preliminary work performed in Phase I provides a foundation for a practical examination of the potential benefits available from saving time due to the use of retarders in downgrade descents.

4.2 The Potential for Reduced Brake Lining Wear

On a per-axle basis, the potential benefits from reduced brake lining wear are directly related to the brake life extension factor, and to the nominal brake wear encountered before use of the retarder. Table 4.3 shows the approximate range of annual savings one might expect (including materials and labor) on a per-axle basis. The benefits would range from a high of over $3000 per axle to zero. The data clearly show why operations experiencing rapid brake wear should consider retarders solely on the basis of brake wear savings.

Table 4.3

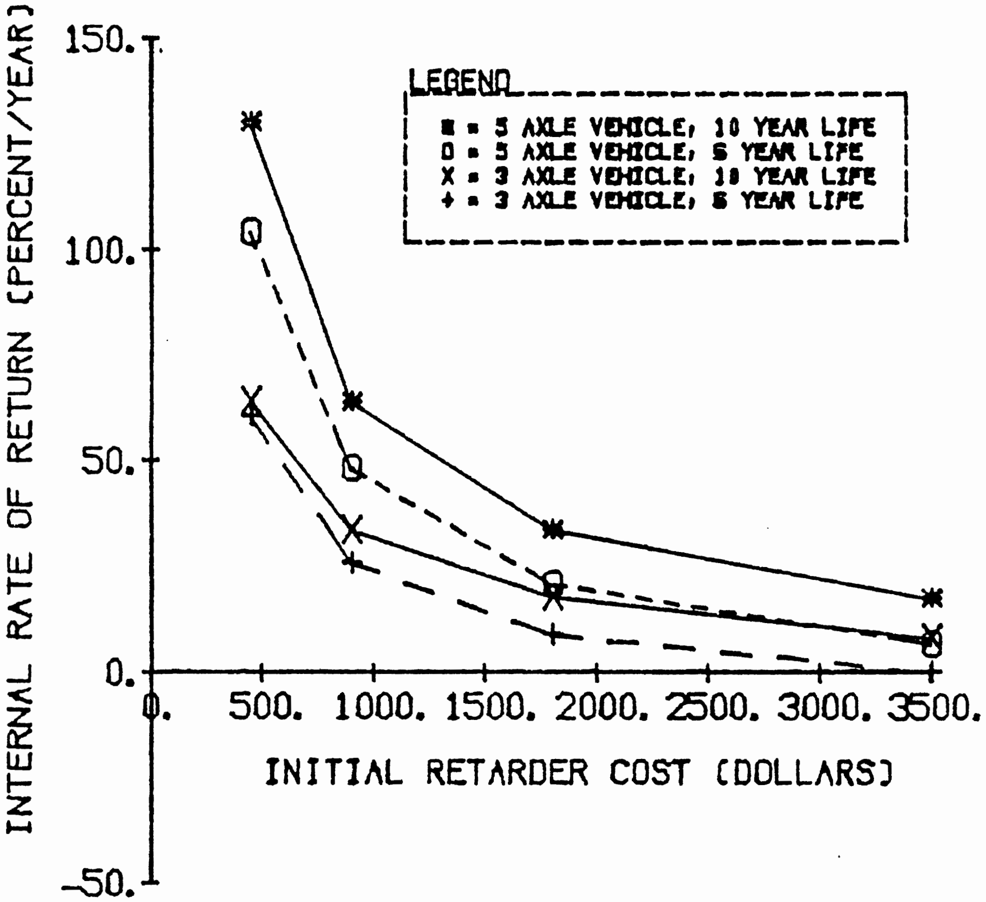
Approximate Savings Per Axle Per Year (1980 $)
As Functions of Brake Life Extension Factor

Brake Life Extension Factor	Nominal Time to First Brake Overhaul (Assuming No Retarder)		
	6 Months	1 Year	3 Years
1.0	0	0	0
1.3	$ 300-475	$ 155-240	$ 50-80
2.0	$1000-1570	$ 515-785	$172-265
4.0	$2000-3140	$1080-1570	$345-530

Source: Calculated per the methods of Section 2.3.2

The above savings are not discounted to a present value nor do they reflect the costs associated with installing and maintaining the retarder. But it appears that when these factors are taken into account, there is still an attractive return-on-investment potential for a large portion of the nation's truck fleet.

Figure 4.1 presents some retarder return-on-investment curves for a "typical" truck operation experiencing moderately heavy brake wear of one year to overhaul. (Table 2.9, shown earlier, indicated that there are trucks in every application evaluated that could expect brake lives of this duration.) The figure shows how original cost affects return on investment. It is clearly indicated that attractive return on investment could be obtained for any three-axle or larger vehicle operating in a one-year-to-brake-overhaul environment if a



RETARDER INVESTMENT RATE OF RETURN
AS A FUNCTION OF VEHICLE AXLES AND LIFE
[BRAKE EXTENSION = 30 PERCENT
AND TIME TO OVERHAUL = 1 YEAR]

FIGURE 4.1

retarder can improve brake life by 30 percent (B_{LEF} of 1.30). Also, the effects of lowering first cost are seen. As the market expands and the manufacturer is able to increase volume (and decrease costs), there should be new markets appearing simply because of more favorable economics that result from the increased volume.

There are approximately 1.1 million three-axle trucks, and larger, in the United States, as seen in Table 4.4. These trucks have a total of about 4.7 million axles. If only 25 percent of these axles were on retarder-equipped trucks, there would be an approximate annual gross savings of $185-275 million in brake life, assuming the retarder-equipped vehicles experience a 30-percent brake life improvement and were experiencing one brake overhaul each year. (From this gross savings would be deducted the depreciated capital cost of the retarder.) The number is of sufficient magnitude to indicate that serious attention should be directed to increased retarder utilization, perhaps even as a matter of public policy.

TABLE 4.4

Estimated Population of Trucks Over 19,000 GVW (3) By Number of Axles (Including Trailer) By Region (Thousands of Units)

	Number of Axles (Truck & Tractor)									
	Two		Three		Four		Five		Six Plus	
	6&7 (3)	8+ (3)	6&7 (3)	8+ (3)	6&7 (3)	8+ (3)	6&7 (3)	8+ (3)	6&7 (3)	8+ (3)
Western 1)	150	10	25	55	4	20	3	80	1	10
East 2)	200	25	15	50	8	55	3	95	1	6
Other	640	50	65	190	20	130	7	280	1	20
Total	990	85	105	295	32	205	13	455	2	26

1) California, Oregon, Washington, Montana, Utah, Idaho, Arizona, New Mexico, Wyoming, Nevada, Colorado

2) New Hampshire, New York, New Jersey, West Virginia, North Carolina, Tennessee, Ohio, Vermont

3) Class 6 = 19,000 - 26,000 GVW; Class 7 = 26,000 - 33,000 GVW; Class 8+ = Greater than 33,000 GVW

Source: Estimated from the 1977 Census of Transportation, Trucks in Use Survey.

4.3 The Potential for Reduced Accident Costs

Eck [1] reported a tendency for truck runaway accident rates to decrease with length of grade, although the data to support this finding were limited. He attributes this to the idea that when drivers approach a long grade they are more likely to downshift to minimize braking problems. The statistic we have used (runaways per descent, rather than per mile traveled) would take account of this concept. Yet there is obviously considerable variation in the "per descent" runaway rate. One hill in Colorado (Rabbit Ears Pass) had one runaway in 2000 descents, while Vail Pass, with similar length and grade, had less than half that rate.

With the data available, we have not attempted to develop the relationship between runaway rate and roadway characteristics, although the effects of truck weight and brake condition have been considered. Eck developed a rather detailed model using West Virginia data which considered length of grade, number of horizontal curves per mile, percent grade, and other factors—both singly and in combination.

Generally, the direction of change in the runaway rate as a function of the major factors can be assumed. Trucks operating at lower-than-maximum load should be less likely to run away. Grades with many curves will probably have a higher ratio of accident to non-accident runaways, etc. To develop an estimate of the safety value of a particular retarder on a particular trip there are many factors which should be better quantified. If effort can be devoted to further development of a predictive model, the detail necessary to support it should be sought. To some extent, this may derive from the experimental program to be conducted in Phase II of this project, wherein the capabilities of various kinds of retarders will be evaluated. The methods presented by Eck to relate runaway rate to road characteristics could be extended by incorporating data from other states. Other vehicle factors, particularly brake condition, should be included.

Table 2.2 (and Figure 2.10) presented information on the relationship between temperature rise of the brake drums, traveling speed, and the slope and length of descending grades. It was noted in Section 2 of this report that brake overheating (above 425°F) at a given speed was very sensitive to the length of the hill. An 80,000 lb truck with well-adjusted brakes may travel at 55 mph for 6.6 miles down a 4 percent grade without exceeding the critical temperature, but if the hill is 7 miles long, it must descend at 37 miles per hour.

The above example is based on an initial brake temperature of 150°F, a value that might be obtained from light usage of the brakes prior to descending the hill. An alternative value shown in Table 2.2 is an initial brake temperature of 300°F, which might be obtained if the truck had been making frequent use of brakes over a period of a half hour or so before arriving at the hilltop. In this case, the same truck would be limited to 3.3 miles on the 4 percent grade. Other combinations for 6 percent, 8 percent, and 10 percent grades are also shown. These computations are made for a tractor-trailer of 80,000 lbs gross weight, well-maintained brakes, and an engine/tire/shape drag representative of a fuel-efficient vehicle.

For purposes of modeling the safety effect of various retarders, we suggest that slope/length combinations less than those plotted at 55 mph in Figure 2.10 are relatively unlikely to produce runaways, and combinations greater than that fall in the range for which runaway data have been presented. In a simple model, the probability of a runaway for a fully loaded, well-maintained truck with minimal braking history prior to the grade might be considered near zero for lengths shorter than 6.6 miles, but average (i.e., once in 5000 descents) for lengths greater than that. For trucks with moderate brake usage prior to the slope, the length limit would be 3.3 miles.

To estimate the probability of a runaway on a particular hill, then, one would start with the initial brake temperature (150°F for minimal usage, 300°F if the truck had been traveling in hilly terrain prior to the slope in question), determine the length and slope of the hill, and assign a probability of 1/5000 if the slope/length combination limit from Table 2.2 was exceeded, zero if not. In dollar terms, based upon an average prorated cost of a runaway event, a retarder-equipped truck would avoid (save) an average cost of approximately $2.00 per descent of a severe hill (i.e., a hill with 1/5000 chance of a runaway).

For trucks without a full complement of drag reduction equipment, it would be appropriate to compute new limits defining a severe hill. Probably new limits should be set for trucks without well-maintained brakes.

In any case, most trucks are going to get down even the steepest and longest hills safely because the driver has recognized the hazard and adjusted his speed to account for it. The chance (1/5000) nature of the runaway comes about because of occasional and, to a large extent, unpredictable improper operation.

5.0 GUIDANCE FOR PROSPECTIVE BUYERS OF RETARDERS

Truck owners who do not already own retarders are most likely to buy them on the basis of anticipated cost savings. Three different areas of potential cost savings have been discussed—increased brake life (and the consequent reduction in brake maintenance costs), increased productivity (essentially the capability to go down hills safely at higher speeds), and increased safety (a lowered probability of a runaway event of any kind). These benefits are, of course, interlinked. If the operator chooses to use the retarder only to maximize speed down hills, still depending on foundation brakes for a substantial portion of the braking, neither the brake life nor the safety factor will increase as much as it could. At the other end of the spectrum, if the operator chooses to maximize safety by depending on the retarder (and the appropriate gears) to go down hills, brake life and safety will increase more. How the retarder is used (and this depends on the specific capabilities of the retarder chosen) will be important.

Given the means for evaluating the benefits of brake life extension, productivity, and safety, it is conceptually reasonable to search for an optimum mode of retarder utilization for any particular trucking operation. As an initial step in developing this ultimate capability, the following discussion outlines how the preliminary results and techniques developed in Phase I may be applied to aid in deciding whether to buy a retarder. In so doing, the discussion presents a summary of the items a prospective buyer "needs to know" in order to estimate the cost benefits to be obtained from various levels of retarder power.

Probably the most important physical parameter is the loaded weight, W, of the vehicle or vehicles under consideration. The weight of the vehicle is fundamental in determining either the amount of kinetic energy to be dissipated during speed reductions or the amount of potential energy to be dissipated during mountain descents. Also, the weight will be a factor in selecting an engine with sufficient horsepower, thereby having an influence on the amount of natural retardation available.

Of the types of cost benefits being considered, savings on brake maintenance are applicable to all types of terrain, making them the most universal benefit (that is, the least dependent upon the existence of hills). A key quantity in assessing brake savings is the brake life extension factor, B_{LEF}. If B_{LEF} is large enough, the return on investment analyses previously presented indicate that the purchase of a retarder can be readily justified on the basis of brake savings alone for typical heavy vehicle applications.

In addition to B_{LEF}, the calculation of the benefits of brake savings requires information on (1) brake maintenance costs and schedules and (2) financial cash-flow projections. Table 5.1 lists the items included in a return on investment analysis of the benefits from brake savings [7]. The financial considerations included in this analysis could be extended in the future to the other benefits of retarders.

The level of retarder capability (horsepower) enters the brake savings analysis through the brake life extension factor and the initial cost and resale value of the retarder. The determination of the initial cost and resale value is relatively straightforward compared to estimating B_{LEF}. The major hurdle to predicting cost savings accurately lies in estimating the influence of retarder power on brake wear.

One approach for estimating B_{LEF} is to compute the ratio of (a) the energy absorbed by the foundation brakes and the retarder, divided by (b) the energy absorbed by the foundation brakes during a typical period of service (a vehicle mission) [8]. Limited experience making this type of calculation indicates that predictions of B_{LEF} in the neighborhood of 3 to 7 are quite likely to occur using this approach.

The approach referenced above assumes that brake wear is proportional to the work done by the brakes. Although significantly large values of B_{LEF} are obtained assuming that wear is proportional to work, empirical evidence indicates that wear may proceed more rapidly than this assumption implies [9]. Hence, there is evidence that estimates of B_{LEF} proportional to the brake-work ratio might even be conservative.

Table 5.1. Information Used in Analyzing Brake Savings.

1. Parts and Labor Costs for Brake Maintenance.
2. Sequence of Brake Overhauls (e.g., minor/major or minor/minor/major).
3. Operational Data
    - Years of service
    - Vehicle miles per year
    - Number of axles
    - Miles to first brake overhaul
4. Financial Data
    - Retarder price
    - Retarder resale value
    - Inflation rate
    - Tax factors
    - Discount rate
5. Brake Life Extension Factor

Nevertheless, information from actual service experience is desirable for increasing confidence in predictions of B_{LEF}. Without this experience, a proposed scheme for estimating B_{LEF} is illustrated in Table 5.2. The scheme consists of (1) dividing the total kinetic and potential energy to be absorbed in a particular vehicle application into three categories (stopping, slowing, and retarding) that may have different potentials for retarder effectiveness; (2) estimating the percentage of the work that will be done by a retarder in absorbing the energy demands in each of the three categories of speed control (this will depend upon the retarder power capability and the nature of the vehicle route and mission); (3) calculating the percentage of the total work done by the brakes in absorbing the energy requirements of the vehicle mission; and (4) computing B_{LEF} as the ratio of the total work to the work performed by the brakes.

For rough estimates, the entries in Columns (a) and (b) of Table 5.2 may be obtained using practical judgment. However, as evidenced in [8], and to a limited extent, in the development of Table 4.2,* a typical vehicle trip can be analyzed to provide representative values for predicting B_{LEF}.

It should be noted that, in addition to physical considerations, the driver's utilization of the retarder in each of the three categories of speed control will have a strong influence on the results. Of course, greater actual utilization of retarder power is necessary to achieve increased brake life.

The discussion at the end of Section 4.1 mentions compromises amongst minimizing trip time, saving the foundation brakes, and providing a margin of safety. For a first trial at estimating the benefits from purchasing a retarder, the prospective buyer might select a retarder based on brake savings alone and simply add the cost benefits of reduced trip time and safety to those accrued through brake savings. This approach seems reasonable unless the particular vehicle in question is going to be used in a

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*Although Table 4.2 presents vehicle velocities based on Figures 2.10 and 2.11, the analysis employed to construct these figures could be used to solve for the power absorbed which, when combined with the time periods involved, will yield the work or energy dissipated.

Table 5.2.. B_{LEF} Estimation Scheme

Example Calculation

	(a) % of Total Work for Speed Control	(b) % of (a) Done by a Retarder	(c) % of (a) Done by the Brakes	(d) = (a) × (c) = % Brake Work
Complete Stops (Stopping)	30	30	70	21
Slowing for Traffic (Slowing)	40	80	20	8
Downhill Speed Control (Retarding)	30	90	10	3
Totals	100%			32%

$$B_{LEF} = \frac{\text{(a) Total}}{\text{(d) Total}} = \frac{100}{32} = 3.1$$

region with many severe grades. In that case, the safety justification for a retarder seems obvious and the productivity benefits would appear to be so large that the only question is how much retarder power is available without an excessive weight penalty or an enormous initial cost. In this context, tentative guidance for identifying severe grades is provided by Table 2.2.

For operation on a route with a small, but not negligible, percentage of moderate-to-severe grade, an initial choice of retarder power that would achieve reasonable levels of brake, time, and safety savings could be determined by selecting a suitable control speed for the steepest grade to be traveled without using the foundation brakes. Given this choice of retarder power, the brake savings can be computed as before and the time savings could be computed using a control speed versus grade curve based upon evaluating the following relationship at various speeds:

$$\theta_{V_c} = \left(\frac{HP_R + HP_N(V_c)}{W\ V_c}\right)375 \qquad (13)$$

where

V_c is the control speed in mph

HP_R is the selected retarder horsepower

$HP_N(V_c)$ is the natural retardation horsepower evaluated at V_c

W is the weight of the vehicle

and θ_{V_c} is the grade corresponding to V_c

(Equation (13) is derived from equating the power of the hill to the retarder power plus the natural retardation.) The form of the resulting curve is illustrated in Figure 5.1. For each grade, θ_{V_c} along the route, an appropriate control speed, V_c, can be found, as shown in Figure 5.1. Knowing the length of each grade and the control speed, the time on the grade can be computed for use in estimating time savings versus the case in which the foundation brakes are used exclusively.

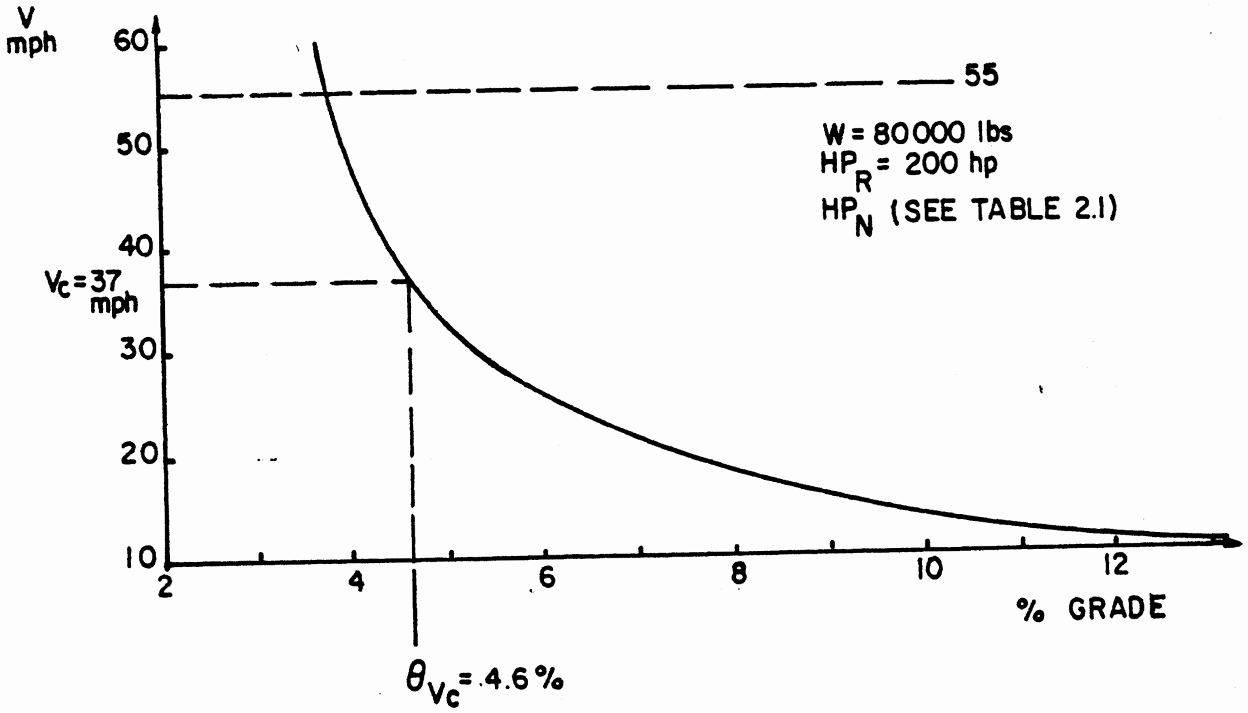

Figure 5.1. Control speed versus grade.

Table 5.3 summarizes the items needed as input information for making a detailed analysis of the time savings and the contribution of downgrade speed control to the brake life extension factor. Using this information, a computational procedure similar to that presented in Section 4.1 can be employed in calculating time savings using Equation (13) (Figure 5.1) instead of Figure 2.11.

As discussed in Section 4.3, the safety benefits obtained from retarder usage can only be estimated crudely from the accident information available. A simple procedure for estimating safety benefits is to assume a savings of $2.00 in avoided accidents for each truck equipped with a retarder for each trip down any severe grade where a severe grade is defined by Table 2.2 (or, possibly, by available accident information for downgrade sites with bad accident records). To employ this procedure, the needed input information consists of counts of (1) the number of severe grades based on accident experience or grade length and slope information and (2) the number of passes over these severe grades per year.

Table 5.3. Input Information for Analysis of Downgrade Speed Control.

1. Highway Factors on the Route
    - Magnitude of grades
    - Lengths of grades
    - Miles between grades
    - Velocity of travel between grades
2. Natural Retardation
    - Engine drag (horsepower, fuel efficient or not)
    - Rolling resistance (tire type, bias or radial)
    - Aerodynamic drag (frontal area, wind screens)
3. Vehicle Factors
    - Weight
    - Brake temperature parameters (cooling rate, effective time constant)
4. Retarder Horsepower Capability
5. Value of an Hour of Vehicle Operation
6. Number of Trips Over the Route Per Year

Further insight into the relationship between economic considerations and safety can be gained by examining Figure 5.2. This figure presents predictions in dollar amounts for safety benefits to be obtained by using retarders of various levels of effectiveness in preventing runaways. In this figure, safety benefits are expressed in terms of the initial cost of the retarder that would represent a "break-even" situation, that is, when the costs associated with expected runaway events equal the initial cost of the retarder. For example, if each vehicle in a large fleet of vehicles made 300 trips per year down severe hills and the use of a retarder would reduce the probability of a runaway event by 50 percent, then in five years the savings resulting from reduced (avoided) runaway events alone would be equivalent to investing \$2400 per vehicle for retarders. As illustrated by this example, a prospective buyer of a retarder can use Figure 5.2 to estimate a dollar amount corresponding to the safety benefit of using retarders in a particular type of service.

In summary, this section supports the following point of view. The return on investment from brake wear reduction can be substantial if the brake life extension factor is only moderately greater than 1.0, even if severe grades are not involved. If severe grades are involved in a particular trucking operation, then the use of a retarder will provide appreciable time savings and safety benefits in addition to almost certainly ensuring a high enough B_{LEF} to provide a good return on investment through brake savings.

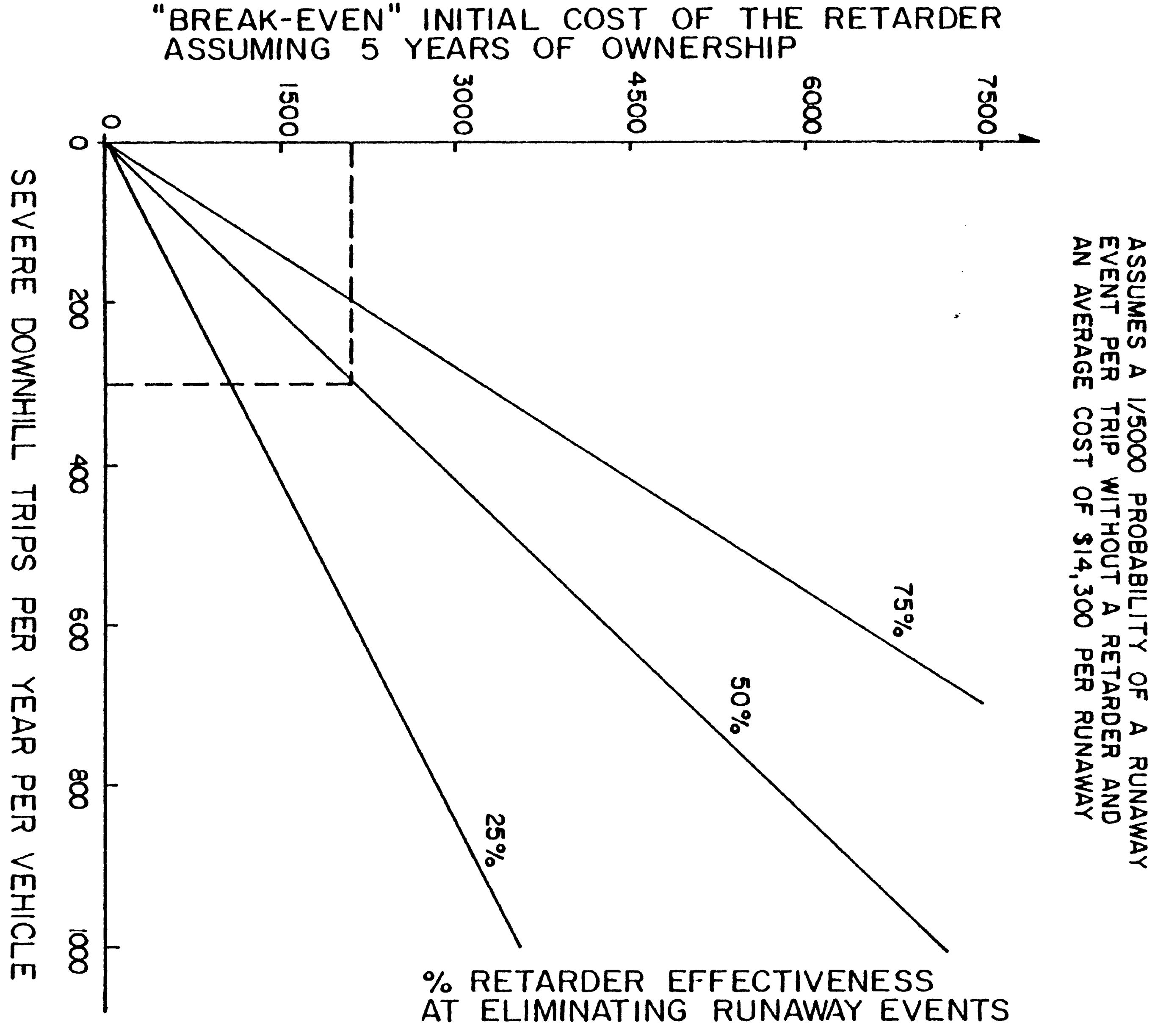

Figure 5.2. Safety benefit based on the number of runaway events avoided.

6.0 CONCLUDING STATEMENTS

The use of retarders has the potential for producing savings on (1) brake maintenance, (2) trip time, and (3) accident costs. In particular applications, each of these three types of savings can individually exceed the cost of a retarder suitable for the application. In the case of savings on brake maintenance, the return on investment can be substantial.

To aid prospective buyers in decisions related to purchasing or selecting a retarder, an outline of a procedure for estimating the dollar value of purchasing a retarder has been developed (see Section 5). Even at this interim point in this project, it appears reasonable to speculate that the final version of this estimation procedure will show that, from a cost benefit standpoint, retarders should be included in a vehicle's set of braking equipment for almost all trucking applications.

Field experiments, first in testing and then in use, are needed to assess the reasonableness of these glowing predictions. The assessment procedures outlined herein do not contain negative features (other than initial cost) that would tend to reduce the attractiveness of retarders. Two examples of negative features that may have some importance are (1) the cost of maintaining the retarder and (2) the additional weight of the retarder (and the loss of payload implied thereby). Furthermore, the addition of a retarder clearly increases the braking torque capability available at the wheels on the axle or axles associated with the retarder. Although the retarder torque applied to the wheels may be no more than 10 percent of the torque capability of the foundation brakes, the retarder torque could be a significant fraction (even the major part) of the total torque desired on a slippery surface. Hence, the wheels on the retarder axle(s) may operate at a higher longitudinal slip than they would have if the retarder were not used. Under certain conditions of loading, road friction, and brake proportioning the additional torque from the retarder could contribute to directional control difficulties during braking. In any event, field tests could aid in identifying the extent of these and other negative aspects of using retarders.

In support of retarder use, there is at least one aspect of increasing safety that has not been considered in the analysis presented here. This benefit has to do with accidents that may occur after a vehicle has recently finished a downhill descent. The vehicle may not have encountered difficulty in negotiating the hill, but, if it does not have a retarder, the brake temperature may have risen to the point where the stopping capability available for resolving traffic conflicts is significantly reduced. No data are available for quantifying the number or frequency of accident occurrences of this type, but they are not unheard of.

Finally, the potential benefits of retarders appear to be large enough to consider the possibility of including them in the overall design of braking systems for particular heavy trucks. One study along these lines [10] suggests that a retarder could be used for downhill speed control, thereby allowing lighter foundation brakes. From an overall braking system standpoint, a vehicle designer might consider using a retarder for normal deceleration and downhill speed control with the foundation brakes designed for, and proportioned for, rapid stops in short distances. However, this type of design would require careful evaluation to ensure safe, desirable braking performance over the ranges of vehicle loading and road surface conditions encountered in heavy truck applications. Furthermore, recent difficulties in developing suitable antilock braking systems may have served to emphasize the many factors influenced by changing the braking systems of heavy trucks. If retarders receive widespread acceptance, the idea of incorporating them in the overall design of a vehicle's braking capability may then become attractive.

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