UM-HSRI-82-23

RETARDERS FOR HEAVY VEHICLES: PHASE II FIELD EVALUATIONS

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Contract No. DOT-HS-9-02239
Contract Amount: $106,336

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June 1982

Prepared for the Department of Transportation, National Highway Traffic Safety Administration under Contract No.: DOT-HS-9-02239.

Technical Report Documentation Page

1. Report No.	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle RETARDERS FOR HEAVY VEHICLES: PHASE II FIELD EVALUATIONS		**5. Report Date** June 1982 **6. Performing Organization Code** 017691
7. Author(s) P.S. Fancher, J. O'Day, C.B. Winkler		**8. Performing Organization Report No.** UM-HSRI-82-23
9. Performing Organization Name and Address Highway Safety Research Institute The University of Michigan Huron Parkway & Baxter Road Ann Arbor, Michigan 48109		**10. Work Unit No.** **11. Contract or Grant No.** DOT-HS-9-02239
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration U.S. Department of Transportation Washington, D.C. 20590		**13. Type of Report and Period Covered** Final (Phase II) 10/80 - 5/82 **14. Sponsoring Agency Code**

15. Supplementary Notes

16. Abstract

A field survey of 117 heavy trucks operating on severe grades near Cumberland, Maryland has produced findings indicating that the average temperature of brakes on vehicles equipped with retarders is approximately 60°C less than that found on vehicles without retarders. No evidence was found to suggest that commercial vehicles equipped with retarders have foundation brakes which are better maintained than those installed on non-retarder-equipped vehicles. In fact, truck brake maintenance appears, in general, to be rather poor, given that many of the inspected vehicles had one or more brakes out of proper adjustment. It can be concluded that the lower temperatures observed on vehicles equipped with retarders should lead to benefits in both safety and brake wear.

The retardation forces deriving from engine "drag," aerodynamic drag, rolling resistance, and retarder systems were measured in a test program utilizing a trailer to serve as a "Mobile Retardation Dynamometer" (MRD). The characteristics of the MRD are described. Retardation measurements performed on two tractors and three retarders are presented.

A detailed description is given of the calculation procedure developed to predict the retardation performance of trucks. Example calculations employing data obtained with the MRD are presented. The procedure, as presented, assists the user in selecting a retarder for a particular application.

17. Key Words Retarders, Downgrade Speed Control, Brake Temperature, Brake Life, Brake Adjustment	**18. Distribution Statement** UNLIMITED

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
NONE	NONE	109	

ACKNOWLEDGEMENTS

Considerable assistance was provided by individual staff members of the Maryland State Police, the Bureau of Motor Carrier Safety, and the National Highway Traffic Safety Administration during the in-service survey performed near Cumberland, Maryland. Their names are contained in Appendix C of this report.

Mr. J. Borione of Compagnie Francaise Telma donated two electrical retarders for use in the Mobile Retardation Dynamometer developed in this study.

Mr. G. Bloom of Jacobs Manufacturing Company and Mr. W. Fuetterer of the Cummins Engine Company arranged the loans of tractors equipped with retarders for the purposes of our field tests.

Mr. R. Radlinski of NHTSA's Vehicle Research and Test Center furnished an instrumented tractor-semitrailer for making temperature measurements with and without a retarder in operation.

Mr. Robert Clarke of NHTSA provided helpful guidance as the Contract Technical Manager.

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APPENDICES

1. INTRODUCTION

This report describes the research conducted in Phase II of a two-phase study originally entitled "A Study of the Safety and Cost Benefits Derived from Using Retarders in Heavy-Duty Commercial Vehicles." The study has been conducted by the Highway Safety Research Institute (HSRI) of The University of Michigan for the Office of Heavy-Duty Vehicle Research within the National Highway Traffic Safety Administration (NHTSA), U.S. Department of Transportation.

Phase I consisted of five discrete research tasks which, on completion, were documented in a technical report [1], entitled "Retarders for Heavy Vehicles: Evaluation of Performance Characteristics and In-Service Costs." This report described the potential for safety enhancements, cost savings, and productivity gains in trucking that could derive from the increased use of retarders in heavy truck operation. This document included:

a) an analysis of the physical factors affecting downhill speed control,

b) a discussion of the characteristics of currently available retarders,

c) an assessment of the retarder market and its future potential (with savings on brake wear being identified as an important factor), and

d) a safety performance analysis based on available accident information.

The findings and conclusions presented in the Phase I report were necessarily based on the information and data available to the research team at that point in time.

Phase I called for the development and submission of two plans, viz., "Supplemental Data Development Plan" and a "Retarder Performance Evaluation Plan." Their approval by NHTSA led to HSRI being authorized to conduct the Phase II study reported herein. The objectives were to:

a) gather information from the field to provide additional characterization, use, and safety data relative to retarders, and

b) conduct evaluations of the performance of retarder-equipped vehicles by means of field tests and analytical procedures.

Section 2 of this report addresses the first objective by presenting the findings obtained during an in-service survey of heavy trucks operating on downgrades in the vicinity of Cumberland, Maryland. Section 3 addresses the second objective by presenting

a) a description of the device developed to test tractors equipped with retarders,

b) the results of field tests in which this device was used, and

c) a truck retardation prediction procedure based on field test findings and the information obtainable from retarder manufacturers.

Conclusions and recommendations, as derived from this Phase II study, are presented in Section 4 of the report.

With this two-phase study having been completed, it is found that several questions remain. These questions can be posed as follows:

1) What directional control problems can occur, if and when retarders are used on road surfaces with a low coefficient of friction?

2) How large are the savings in brake wear which accrue from the use of retarders?

3) What types of instructions and training activities are needed to enhance the abilities of the drivers of heavy vehicles to employ retarders in a manner that maximizes their safety and economic benefits?

In order to answer these questions, further work will be required. Nevertheless, it can be stated that the findings of Phase II do support the earlier Phase I findings, namely, that heavy vehicles equipped with retarders constitute opportunities for achieving increased safety levels and reduced brake wear.

2. IN-SERVICE SURVEY OF HEAVY TRUCKS ON DOWNGRADES

The principal goal of this survey was to observe and record the characteristics of trucks which had descended a long, steep grade. The work was carried out over a period of four days at three sites east and west of Cumberland, Maryland, on U.S. Routes 40 and 48. During this period, 117 large trucks were weighed and inspected, with particular concentration on brake condition and temperature. A major purpose of the experiment was to compare observed brake characteristics with the presence or absence of retarders. Certain ancilliary or related data were also collected at the site.

In this section of the report, the experimental design and operation will be described, and the pertinent results regarding brakes and retarders will be detailed. Additional statistics describing the observed truck population are presented in Appendix E.

2.1 Background

As noted in the Introduction, this report is a sequel to an earlier report [1] concerning the physical performance characteristics and the economic and safety benefits of retarders as used on various commercial vehicles. In Reference [1], analyses of available accident data identified three factors as being strongly associated with the chance of a downhill runaway—improper brake adjustment, high gross vehicle weight, and the absence of a retarder. Tables 1-3 are taken from the referenced report and indicate the relationships found there.

Table 1 is based on data obtained by the California Highway Patrol at Gold Run (near Donner Pass), and indicates that 72 percent of the 25 trucks involved in runaway accidents at that site had poorly adjusted brakes—i.e., the slack adjusters were set, usually for more than one wheel, well beyond the manufacturer's recommended limits. By contrast, in roadside observations conducted periodically near the same site, about 40 percent of the tractor-trailers checked had one or more brakes improperly adjusted.

Table 1

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

Brake Status	Accident Involvement	Exposed Population
Improper Adjustment	18 (72%)	40%
Proper Adjustment	7 (28%)	60%
Total	25 (100%)	100%

Table 2

Proportion of Vehicles in Two Weight Classes Runaways versus General Population

Weight Class	Runaway Vehicles	Exposed Population
Greater than 60,000 lbs.	73%	47.2%
60,000 lbs. or less	27%	52.8%
Total	100%	100%

Table 3

Presence of Retarders in Runaway and Exposed Populations

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

Table 2 shows a similar distribution based on Colorado runaway data which indicate that 73 percent of the runaway vehicles (mostly vehicles which used runaway ramps on Colorado mountain descents) weighed more than 60,000 lbs versus only 47.2 percent of the exposed population. This indicates a strong relationship between weight and the probability of a runaway. Table 3 is also based on the Colorado data, and indicates that 45 percent of the runaways had retarders, as compared with an estimated 70 percent of the exposed population of trucks, indicating that the presence of retarders is thus associated with a lower chance of runaway.

While it was concluded that each of these factors—poorly adjusted brakes, lack of a retarder on the vehicle, and heavy gross vehicle weights—associated with an increased chance of a runaway, it was generally not possible to observe correlations among these factors. For the runaways with and without retarders observed in escape ramp records from the State of Colorado, there was little detailed brake condition information. It is possible, then, that the observed reduction in runaway frequency for retarder-equipped trucks was (at least in part) due to the fact that owners or operators of those trucks also gave more attention to brake condition, keeping brakes of retarder-equipped trucks in better adjustment. It is also possible that the presence of a retarder contributes to the probability that brakes will be in adjustment since its use decreases brake wear.

While there are other applications of retarders, the major safety application was taken to be the prevention of the downhill runaway. A runaway truck is rather simply defined as a truck on which the brakes have failed. Brake failures observed in the previous study (using data provided by the California Highway Patrol) could be placed in one of two categories—a failure resulting from overheating of the brake system (expansion of the drums, fade), or a catastrophic failure (a broken air line, blown engine, faulty air pump, etc.). The retarder can serve primarily toward reducing the probability of the first type of failure.

Without a retarder, a truck driver who desires to descend a steep hill at a constant speed must balance the forces of gravity which tend to accelerate his vehicle by choosing a gear such that the engine retarding horsepower will counterbalance, and/or by applying brakes so that the absorbed energy heats the components in the brake system. The retarding force available from the brake system is, in part, a function of the stroke required for the brake actuation, a typical relationship for which is shown in Figure 1. The abscissa shows the number of inches of pushrod travel, and the ordinate shows the effective brake chamber area for specific levels of air pressure (psi).

One effect of a temperature rise at the brake drum is to expand the diameter of the drum, lengthening the pushrod travel, and thus reducing the brake force available from that particular brake. A temperature rise of 200°C leads to an increase in pushrod travel of approximately 0.3 inch. Thus a brake pushrod which had a cold setting of two inches (capable of developing 90 percent of the maximum force at 100 psi in the example shown) would (at 200°C) have a stroke of 2.3 inches and only 79 percent of the maximum force.

Although there are a number of different kinds of retarders, all of them serve the function of dissipating energy by using devices other than the foundation brakes. In the observations made in this study, the most common type of retarder was the engine brake. Three retarders based on hydraulic principles were seen in this study. Neither electric retarders nor exhaust brakes were observed here.

Under the same descent conditions, the expected effect of the retarder is to lower the temperature rise occurring in the brake drums. However, the driver has considerable choice in the relationship among gear ratio, retarder usage, brake application, and speed of travel. For example, with a retarder, he might use a higher gear, a higher travel speed, but the same braking as he would use without the retarder—thus developing the same temperature in the brakes but traveling at higher speed. Alternatively, he could choose to operate at the same speed, essentially substituting the retarder for the brakes. In the latter case, the brake temperature would be lower, thus saving wear, and reducing the chance of fade or failure.

2.2 The Experiment

Two issues, that were not resolved in the previous study (Phase I), are to be addressed here. The first is represented by the question, "How do drivers actually make use of the retarder in a hill descent—i.e., do they increase speed and develop the same brake temperature as without a retarder, proceed

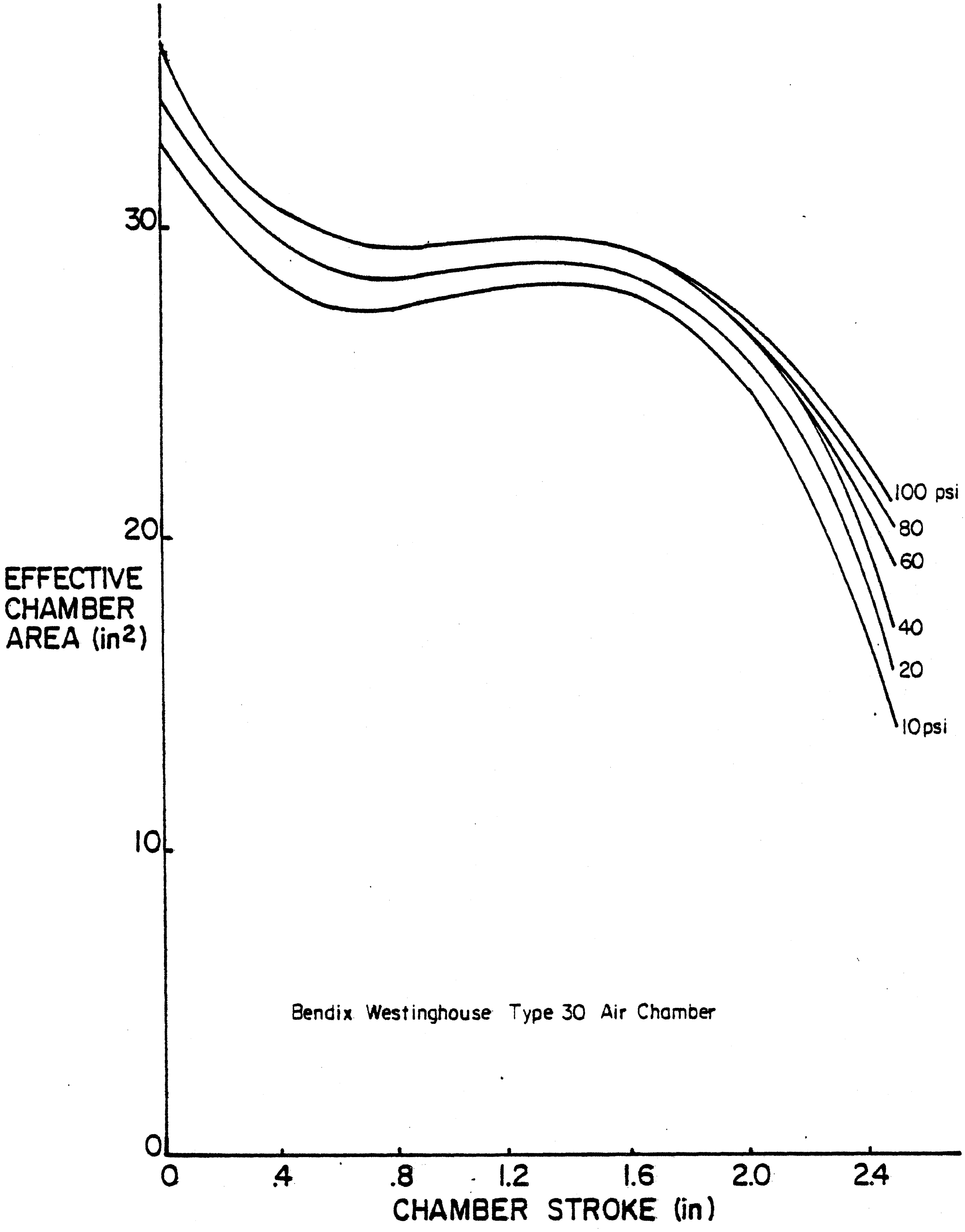


Figure 1. Measured characteristics of a Type 30 air chamber.

at the same speed with reduced brake temperature, or something in between?" The second is, "Do operators using retarders on trucks also have better-adjusted brakes—either because of lower wear rates or more attention to maintenance, or both?" It had also been observed in the earlier report that retarders were more likely to be installed on vehicles of higher gross weight, and a confirmation of this was sought.

The first of these questions will be addressed by examining brake temperatures (with consideration of vehicle weight, brake adjustment, etc.) for descent of a particular hill for vehicles with and without retarders. The possible variation of speed on the hills used in this test is small, but if brake temperatures for retarder-equipped trucks are substantially lower, we may conclude that drivers are using the retarders in a manner consistent with greater safety.

The second of these questions will be addressed by examining brake condition (primarily in terms of pushrod travel) for trucks with and without retarders. If retarder-equipped trucks have better adjusted brakes, then we may infer that the (previously observed) probability of runaway for retarder-equipped trucks is, at least in part, the result of better-adjusted brakes. Alternatively, if brake systems on retarder-equipped trucks are in essentially the same (adjustment) condition as other trucks, we may conclude that the retarder and brake effects previously observed are independent.

2.3 The Design and Experimental Layout

The plan for this experiment was based on the memorandum attached as Appendix A. Briefly, it was desirable to obtain enough observations to determine (1) whether retarder-equipped trucks had significantly better brake adjustment and (2) the magnitude and significance of temperature differences between retarder-equipped and non-retarder-equipped trucks.

Arrangements were made with the Maryland Department of State Police to make the desired observations (of truck brake and other characteristics) in connection with a typical portable weighing team operation. A survey of possible sites in mountainous regions of western Maryland identified two major hills and three locations for inspection sites at the bottom of (or part way down) the hill. For the first two days of data collection, the inspection site was at an exit ramp just past the bottom of a 3.6-mile descent on U.S. Route 48 (eastbound) near Frostburg, Maryland (called hereafter Frostburg or Site 1). Most of the trucks traversing this route had descended the 3.6 miles after having climbed a long hill (at Big Savage Mountain), and the brake drums can be assumed to be at ambient temperature at the top of the grade. This grade has an average slope of 4.5 percent.

On the third day of observation, the inspection site was on westbound U.S. 40 east of Cumberland at the bottom of Martin's Mountain. This was a 3.0-mile descent with an average grade of 6 percent. It will be referred to hereafter as Martin's Mountain or Site 2.

On the fourth day of observation, the inspection site was further down the grade of the hill of Site 1 (called hereafter Site 3), on the eastbound side of Route 48 near Vocke Road—a distance of 9.2 miles, with an average slope of 3.7 percent.

The posted speed limit for eastbound trucks on this section of U.S. 48 was 45 mph, and observations of the speed of travel confirmed that the actual travel speed for the trucks observed was somewhat higher than this, but usually less than 55 mph. Figure 2 is a map of the portion of Allegany County, Maryland, near the City of Cumberland. The three sites are indicated on the map.

Weather during the week of observation was generally clear or cloudy and cool. Temperature varied, but was generally in the range of 40° to 50°F (4° to 10°C), and there was essentially no precipitation up until the end of data-taking on the fourth day.

At each of the first two sites (Frostburg and Martin's Mountain), the inspection arrangement was similar. The setup for Frostburg is shown in Figure 3. A Maryland State Police cadet was stationed several hundred yards ahead of the weighing station on the exit ramp, and he directed trucks into this area. At the weighing station, Maryland State Police officers guided the vehicle over the scales, recorded the weight and length violations, if any, and instructed the driver to proceed to the next station. At this station the vehicle wheels were checked, and two measurement processes began—one, the difference in pushrod position

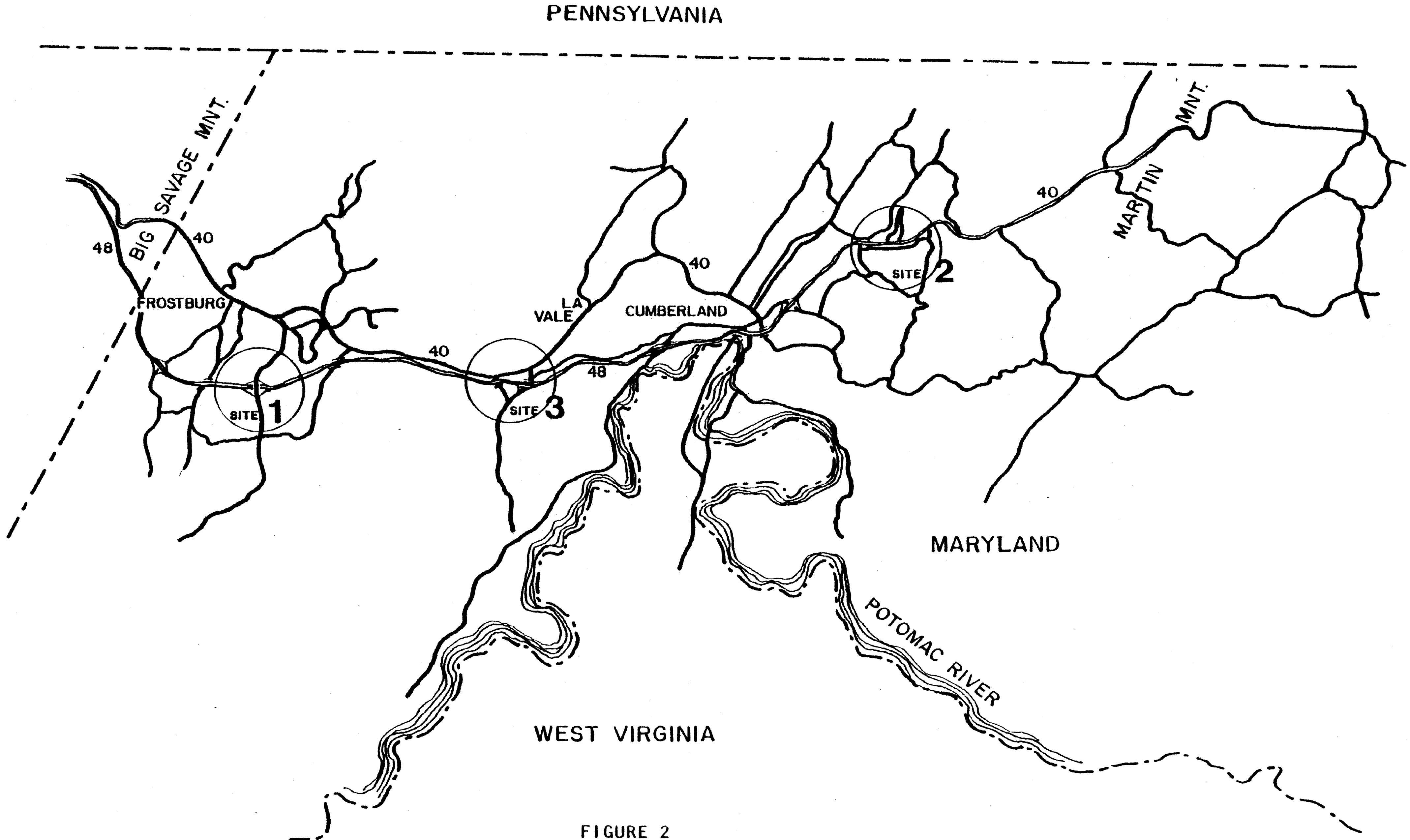
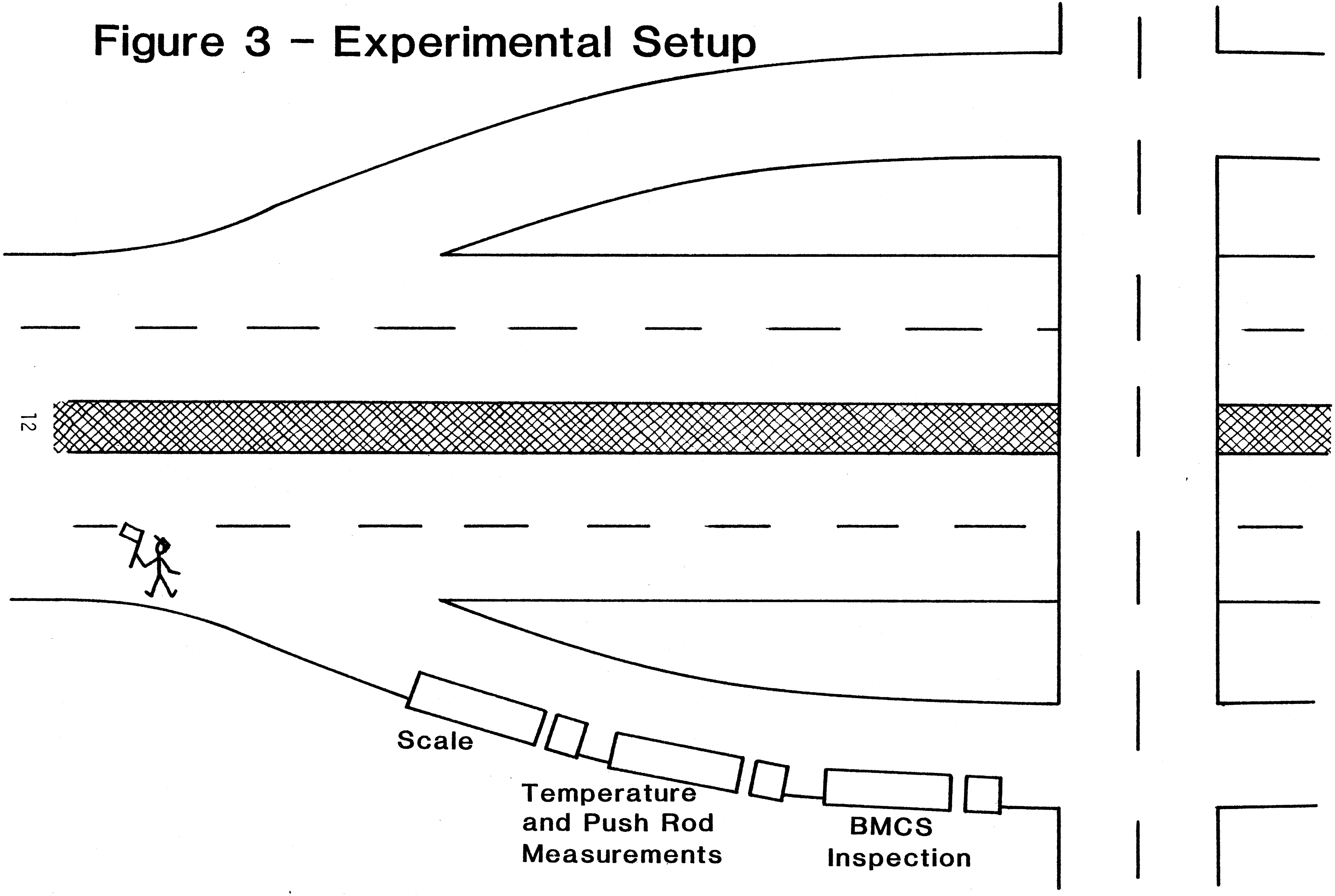


FIGURE 2

Portion of Allegany County, Maryland, in Which Observation Sites Were Located

Figure 3 – Experimental Setup



at each brake between zero and 100 psi of applied air pressure, and two, the measurement of brake drum temperature (by applying a thermocouple probe to the outside surface of the drum). At this same station, the operator was interviewed with regard to driving experience, horsepower, cargo, weight, etc. The form used for recording these data is included in Appendix B as Form 1. Brake pushrod travel measurements were recorded on Form 2, along with identification of the chamber size and manufacturer. Temperature measurements were recorded on Form 3, as were tire characteristics (tread type, carcass type, and size).

The various data elements are related in one way or another to the energy dissipation distribution in the downhill run. Radial tires, for example, exhibit lower rolling resistance, and would require that a larger share of the retardation would have to be taken up by the brake system. The presence or absence of an aerodynamic shield would have a similar effect.

2.4 Data Processing

During the field work, data were collected on three separate forms by different persons. Each form contained enough identifying information to permit matching at the end of the day, and the material for each case was assembled at that time.

While many recorded items were precoded on the forms, certain information such as tire size, transmission type, etc., were allowed free responses. These were subsequently coded, where possible, for inclusion in a computer file. The structure of the computer file is shown in Appendix D.

Two computer files were generated, the first containing all 117 cases observed, and the second restricted to five-axle tractor-trailers. The latter file is the basis for most of the analysis in this report.

2.5 Comparative Evaluations of the Temperature Observations

After each truck passed the scales, it was halted in order that the driver interview and brake temperature observations could be made. The total elapsed time before temperature measurements began varied from about one minute to as much as fifteen minutes, with an average of about five minutes. Temperature measurements were begun with the right-front drive wheel, and proceeded clockwise around the vehicle to the right-front steering wheel. The typical measurement time was about three minutes.

With few exceptions, the drum temperature was measured by inserting an Omega Model 68103K thermocouple probe on the drum exterior through a slot in the outside of the wheel. In rare instances, it was necessary to make this measurement from the inside of the wheel. Both the time delay in measurement and the observation at the outside of the drum result in a measured value somewhat lower than the lining temperature. Ambient temperature at the site varied from near 0°C to 15°C, and a time correction has been made to all temperatures assuming a 10°C ambient and a constant delay of six minutes (0.1 hour). This adjustment adds about 25°C when the measured temperature was near 200°C, 12° at 100°C, and 0° for temperatures close to ambient.

The NHTSA instrumented truck which participated in the experiment had thermocouples buried in the brake linings, and was able to record temperatures continuously. In general, the brake lining temperatures recorded were about 10 percent higher than the externally measured drum temperatures, but no adjustment has been made for that difference in this presentation.

The NHTSA test vehicle was instrumented with brake temperature recording devices for all wheels except those on the rear trailer axle. This vehicle was driven down the grades on which the observations of the other vehicles were made, and provides a set of reference temperatures which may be compared with those of other vehicles at the same weight. The NHTSA vehicle was loaded to 80,000 lbs, and was equipped with an engine brake. The temperatures recorded for this vehicle will be compared with other vehicles with and without retarders.

Table 4 displays the recorded temperatures for the front eight wheels of three 80,000-lb vehicles observed during the experimental program and the two conditions of the NHTSA test vehicle. As the NHTSA vehicle did not have instrumentation on the rear trailer wheels, data

Table 4

Measured Brake Drum Temperatures in °C for Selected Trucks

Wheel	Retarder #1		No Retarder		Retarder #2
	Flatbed	DOT Test Veh.	Van (Baked Goods)	DOT Test Veh.	Lowboy
Left Front	5	54	16	149	0
Right Front	5	38	14	116	0
Left Front Drive	52	27	190	60	9
Right Front Drive	56	38	148	99	8
Left Rear Drive	89	38	132	71	17
Right Rear Drive	28	88	148	160	16
Left Front Trailer	112	49	72	132	21
Right Front Trailer	132	82	108	149	29
Temperature Sums	479	414	828	936	100

are shown for eight wheels only. The "experimental" NHTSA truck was operated in either of two modes—with and without the retarder engaged. The temperatures at the bottom of a 3.6-mile descent are shown for the appropriate condition in the second and fourth data columns. The parallel column for retarder #1 shows the temperature readings for an 80,000-lb vehicle consisting of a cab-over tractor with a flatbed trailer carrying tobacco (case #55). And, the parallel column for no retarder shows an 80,000-lb vehicle having a van trailer carrying baking goods (case #87). The NHTSA test vehicle had made the hill descent at a controlled speed of 45 mph, and no measure of speed was available for the other vehicles. Thus, some of the variation may result from differences in travel speed.

The last column of Table 4 shows the measured temperature distribution for another 80,000-lb vehicle—this one equipped with another retarder. In this case, the temperature sum was only 100°C, suggesting that brakes were almost completely unused in the hill descent. This vehicle consisted of a conventional tractor and a low-boy trailer carrying an army personnel carrier.

Individual brake temperatures depend on the actual proportioning of brake pressures to the various wheels, as well as on the slack adjuster settings for each wheel, the actions of the driver (in applying trailer and tractor brakes), etc. A model has been devised to estimate wheel-by-wheel temperatures for the descent of any one of the hills used in this experiment. In the model*, the descent speed of the vehicle is assumed to be constant at 45 mph, and such factors as the presence of aerodynamic shields or radial tires are neglected. The observed slack adjustment for each wheel is taken into account, and the tractor versus trailer proportioning is estimated from the difference in average temperature of the tractor and trailer wheels.

The individual wheel differences noted between estimated and actual temperature were frequently substantial, although the average difference observed was near zero. The distributions of the differences for the four tractor drive wheels and the four trailer wheels are shown in Figure 4. Based on these results, it is concluded that individual brake

---

*See Appendix F.

```
TEMPERATURE     LEFT FRONT DRIVE AXLE
DIFFERENCE
  in C°

-250.00         0 +
-200.00         1 +X
-150.00         1 +X
-100.00        11 +XXXXXXXXXXX
-50.000        10 +XXXXXXXXXX
0.             16 +XXXXXXXXXXXXXXXX
 50.000         3 +XXX
 100.00         4 +XXXX
 150.00         1 +X
 200.00         0 +
 250.00         0 +

 MISSING       53
                1 < -250.00
 TOTAL        101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     RIGHT FRONT DRIVE AXLE
DIFFERENCE
  in C°

-250.00         1 +X
-200.00         1 +X
-150.00         1 +X
-100.00        10 +XXXXXXXXXX
-50.000         8 +XXXXXXXX
0.             16 +XXXXXXXXXXXXXXXX
 50.000         8 +XXXXXXXX
 100.00         3 +XXX
 150.00         0 +
 200.00         0 +
 250.00         0 +

 MISSING       53
 TOTAL        101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     LEFT REAR DRIVE AXLE
DIFFERENCE
  in C°

-250.00         1 +X
-200.00         2 +XX
-150.00         2 +XX
-100.00         8 +XXXXXXXX
-50.000        12 +XXXXXXXXXXXX
0.             17 +XXXXXXXXXXXXXXXXX
 50.000         5 +XXXXX
 100.00         1 +X
 150.00         2 +XX
 200.00         0 +
 250.00         0 +

 MISSING       51
 TOTAL        101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     RIGHT REAR DRIVE AXLE
DIFFERENCE
  in C°

-250.00         0 +
-200.00         2 +XX
-150.00         2 +XX
-100.00         8 +XXXXXXXX
-50.000        10 +XXXXXXXXXX
0.             15 +XXXXXXXXXXXXXXX
 50.000         7 +XXXXXXX
 100.00         4 +XXXX
 150.00         1 +X
 200.00         0 +
 250.00         0 +

 MISSING       51
                1 < -250.00
 TOTAL        101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     LEFT FRONT TRAILER AXLE
DIFFERENCE
  in C°

-250.00         0 +
-200.00         3 +XXX
-150.00         4 +XXXX
-100.00         8 +XXXXXXXX
-50.000         6 +XXXXXX
0.             13 +XXXXXXXXXXXXX
 50.000         9 +XXXXXXXXX
 100.00         6 +XXXXXX
 150.00         1 +X
 200.00         0 +
 250.00         0 +

 MISSING       51
 TOTAL        101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     RIGHT FRONT TRAILER AXLE
DIFFERENCE
  in C°

-250.00         1 +X
-200.00         3 +XXX
-150.00         4 +XXXX
-100.00         7 +XXXXXXX
-50.000         5 +XXXXX
0.             15 +XXXXXXXXXXXXXXX
 50.000        11 +XXXXXXXXXXX
 100.00         2 +XX
 150.00         2 +XX
 200.00         0 +
 250.00         0 +

 MISSING       51
 TOTAL        101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     LEFT REAR TRAILER AXLE
DIFFERENCE
  in C°

-250.00         0 +
-200.00         2 +XX
-150.00         2 +XX
-100.00         6 +XXXXXX
-50.000        10 +XXXXXXXXXX
0.             13 +XXXXXXXXXXXXX
 50.000        10 +XXXXXXXXXX
 100.00         3 +XXX
 150.00         1 +X
 200.00         1 +X
 250.00         0 +

 MISSING       52
                1 < -250.00
 TOTAL        101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     RIGHT REAR TRAILER AXLE
DIFFERENCE
  in C°

-250.00         0 +
-200.00         3 +XXX
-150.00         4 +XXXX
-100.00         5 +XXXXX
-50.000         9 +XXXXXXXXX
0.             12 +XXXXXXXXXXXX
 50.000         9 +XXXXXXXXX
 100.00         7 +XXXXXXX
 150.00         0 +
 200.00         0 +
 250.00         0 +

 MISSING       51
                1 < -250.00
 TOTAL        101  (INTERVAL WIDTH= 50.000)
```

Figure 4

Distributions of Computed Minus Measured Temperatures on Tractor and Trailer Wheels - 5-Axle Tractor Trailers Observed in Maryland temperatures often differ from predicted (anticipated) values for reasons such as lining friction variations, differences in pushout pressures, etc., which could not be determined in the field experiment. However, averages of the temperatures of all of the brakes installed on an axle set correspond to expected levels of temperature.

2.6 Brake Temperature Results

Figure 5 shows the time-adjusted temperature distributions for all five-axle tractor-trailers observed. A total of 101 trucks had valid data for these distributions, although this number was reduced by two for two tractors which had lift axles (for which temperature measurements were not made). Figure 6 shows the same distributions, but only for trucks which were not equipped with retarders. Figure 7 presents the temperature distributions for retarder-equipped trucks.

Although the number of retarder-equipped trucks was smaller than the others, it can be seen from the histograms that high temperatures in the retarder groups were rare. A small number of observations on the non-retarder trucks exceeded 300°C, including one which was actually on fire (burning grease) when the truck was stopped.

An alternative comparison of the brake temperatures is shown in Table 5. In this chart, tractor-trailers have been divided into two weight classes—less than 50,000 lbs versus 50,000 lbs and more. It can be seen that retarder-equipped trucks have consistently lower temperatures for both weight groups. Indeed, for the lighter weight category, retarder-equipped trucks exhibit temperatures close to ambient, indicating that little or no use of the foundation brakes was required on these hills. Although the number of cases is small, temperature differences between retarder-equipped trucks and non-retarder-equipped trucks are generally significant at the 0.3 percent level or better (for trucks over 50,000 lbs), and slightly significant (about the five percent level) for the lighter weight trucks.

TRACTOR DRIVE WHEELS

```
TEMPERATURE     COUNT FOR LEFT FRONT  (EACH X= 1)
  IN°C

 0.              19 +XXXXXXXXXXXXXXXXXXX
 50.000          41 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.00          15 +XXXXXXXXXXXXXXX
 150.00          12 +XXXXXXXXXXXX
 200.00           7 +XXXXXXX
 250.00           1 +X
 300.00           0 +
 350.00           0 +
 400.00           1 +X
 450.00           0 +
 500.00           0 +

 MISSING          2
                  3 < 0.
 TOTAL          101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     COUNT FOR RIGHT FRONT  (EACH X= 1)
  IN°C

 0.              18 +XXXXXXXXXXXXXXXXXX
 50.000          41 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.00          17 +XXXXXXXXXXXXXXXXX
 150.00          12 +XXXXXXXXXXXX
 200.00           4 +XXXX
 250.00           1 +X
 300.00           4 +XXXX
 350.00           0 +
 400.00           0 +
 450.00           0 +
 500.00           0 +

 MISSING          2
                  2 < 0.
 TOTAL          101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     COUNT FOR LEFT REAR  (EACH X= 1)
  IN°C

 0.              18 +XXXXXXXXXXXXXXXXXX
 50.000          35 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.00          20 +XXXXXXXXXXXXXXXXXXXX
 150.00          13 +XXXXXXXXXXXXX
 200.00           8 +XXXXXXXX
 250.00           1 +X
 300.00           1 +X
 350.00           1 +X
 400.00           0 +
 450.00           1 +X
 500.00           0 +

                  3 < 0.
 TOTAL          101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     COUNT FOR RIGHT REAR  (EACH X= 1)
  IN°C

 0.              20 +XXXXXXXXXXXXXXXXXXXX
 50.000          31 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.00          26 +XXXXXXXXXXXXXXXXXXXXXXXXXX
 150.00          13 +XXXXXXXXXXXXX
 200.00           5 +XXXXX
 250.00           1 +X
 300.00           1 +X
 350.00           1 +X
 400.00           0 +
 450.00           0 +
 500.00           0 +

                  3 < 0.
 TOTAL          101  (INTERVAL WIDTH= 50.000)
```

TRAILER WHEELS

```
TEMPERATURE     COUNT FOR LEFT FRONT  (EACH X= 1)
  IN°C

 0.              23 +XXXXXXXXXXXXXXXXXXXXXXX
 50.000          28 +XXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.00          28 +XXXXXXXXXXXXXXXXXXXXXXXXXXXX
 150.00          13 +XXXXXXXXXXXXX
 200.00           4 +XXXX
 250.00           3 +XXX
 300.00           1 +X
 350.00           0 +
 400.00           0 +
 450.00           0 +
 500.00           0 +

                  1 < 0.
 TOTAL          101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     COUNT FOR RIGHT FRONT  (EACH X= 1)
  IN°C

 0.              21 +XXXXXXXXXXXXXXXXXXXXX
 50.000          30 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.00          22 +XXXXXXXXXXXXXXXXXXXXXX
 150.00          18 +XXXXXXXXXXXXXXXXXX
 200.00           5 +XXXXX
 250.00           2 +XX
 300.00           1 +X
 350.00           0 +
 400.00           0 +
 450.00           0 +
 500.00           0 +

                  2 < 0.
 TOTAL          101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     COUNT FOR LEFT REAR  (EACH X= 1)
  IN°C

 0.              22 +XXXXXXXXXXXXXXXXXXXXXX
 50.000          39 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.00          20 +XXXXXXXXXXXXXXXXXXXX
 150.00           9 +XXXXXXXXX
 200.00           4 +XXXX
 250.00           4 +XXXX
 300.00           0 +
 350.00           0 +
 400.00           0 +
 450.00           0 +
 500.00           0 +

                  3 < 0.
 TOTAL          101  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     COUNT FOR RIGHT REAR  (EACH X= 1)
  IN°C

 0.              23 +XXXXXXXXXXXXXXXXXXXXXXX
 50.000          30 +XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.00          24 +XXXXXXXXXXXXXXXXXXXXXXXX
 150.00          12 +XXXXXXXXXXXX
 200.00           8 +XXXXXXXX
 250.00           1 +X
 300.00           2 +XX
 350.00           0 +
 400.00           0 +
 450.00           0 +
 500.00           0 +

                  1 < 0.
 TOTAL          101  (INTERVAL WIDTH= 50.000)
```

Figure 5. Temperature distributions for tractor and trailer brake drums: All 5-axle tractor-trailers observed in Maryland.

TRACTOR DRIVE WHEELS

```
TEMPERATURE    COUNT FOR LEFT FRONT  (EACH X= 1)
  IN°C

 0.             7 +XXXXXXX
 50.000        28 +XXXXXXXXXXXXXXXXXXXXXXXXXXXX
 100.00        11 +XXXXXXXXXXX
 150.00        10 +XXXXXXXXXX
 200.00         7 +XXXXXXX
 250.00         1 +X
 300.00         0 +
 350.00         0 +
 400.00         1 +X
 450.00         0 +
 500.00         0 +

 MISSING        2
                2 < 0.
 TOTAL         69  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE    COUNT FOR RIGHT FRONT  (EACH X= 1)
  IN°C

 0.             9 +XXXXXXXXX
 50.000        25 +XXXXXXXXXXXXXXXXXXXXXXXXX
 100.00        13 +XXXXXXXXXXXXX
 150.00        11 +XXXXXXXXXXX
 200.00         3 +XXX
 250.00         1 +X
 300.00         4 +XXXX
 350.00         0 +
 400.00         0 +
 450.00         0 +
 500.00         0 +

 MISSING        2
                1 < 0.
 TOTAL         69  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE    COUNT FOR LEFT REAR  (EACH X= 1)

 0.            11 +XXXXXXXXXXX
 50.000        24 +XXXXXXXXXXXXXXXXXXXXXXXX
 100.00        15 +XXXXXXXXXXXXXXX
 150.00         9 +XXXXXXXXX
 200.00         4 +XXXX
 250.00         4 +XXXX
 300.00         0 +
 350.00         0 +
 400.00         0 +
 450.00         0 +
 500.00         0 +

                2 < 0.
 TOTAL         69  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE    COUNT FOR RIGHT REAR  (EACH X= 1)
  IN°C

 0.            13 +XXXXXXXXXXXXX
 50.000        16 +XXXXXXXXXXXXXXXX
 100.00        19 +XXXXXXXXXXXXXXXXXXX
 150.00        11 +XXXXXXXXXXX
 200.00         7 +XXXXXXX
 250.00         1 +X
 300.00         2 +XX
 350.00         0 +
 400.00         0 +
 450.00         0 +
 500.00         0 +

 TOTAL         69  (INTERVAL WIDTH= 50.000)
```

TRAILER WHEELS

```
TEMPERATURE    COUNT FOR LEFT FRONT  (EACH X= 1)
  IN°C

 0.            10 +XXXXXXXXXX
 50.000        20 +XXXXXXXXXXXXXXXXXXXX
 100.00        21 +XXXXXXXXXXXXXXXXXXXXX
 150.00         9 +XXXXXXXXX
 200.00         4 +XXXX
 250.00         3 +XXX
 300.00         1 +X
 350.00         0 +
 400.00         0 +
 450.00         0 +
 500.00         0 +

                1 < 0.
 TOTAL         69  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE    COUNT FOR RIGHT FRONT  (EACH X= 1)
  IN°C

 0.             7 +XXXXXXX
 50.000        21 +XXXXXXXXXXXXXXXXXXXXX
 100.00        18 +XXXXXXXXXXXXXXXXXX
 150.00        13 +XXXXXXXXXXXXX
 200.00         5 +XXXXX
 250.00         2 +XX
 300.00         1 +X
 350.00         0 +
 400.00         0 +
 450.00         0 +
 500.00         0 +

                2 < 0.
 TOTAL         69  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE    COUNT FOR LEFT REAR  (EACH X= 1)
  IN°C

 0.             8 +XXXXXXXX
 50.000        21 +XXXXXXXXXXXXXXXXXXXXX
 100.00        18 +XXXXXXXXXXXXXXXXXX
 150.00        10 +XXXXXXXXXX
 200.00         7 +XXXXXXX
 250.00         1 +X
 300.00         1 +X
 350.00         1 +X
 400.00         0 +
 450.00         1 +X
 500.00         0 +

                1 < 0.
 TOTAL         69  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE    COUNT FOR RIGHT REAR  (EACH X= 1)
  IN°C

 0.            10 +XXXXXXXXXX
 50.000        20 +XXXXXXXXXXXXXXXXXXXX
 100.00        19 +XXXXXXXXXXXXXXXXXXX
 150.00        11 +XXXXXXXXXXX
 200.00         4 +XXXX
 250.00         1 +X
 300.00         1 +X
 350.00         1 +X
 400.00         0 +
 450.00         0 +
 500.00         0 +

                2 < 0.
 TOTAL         69  (INTERVAL WIDTH= 50.000)
```

Figure 6. Temperature distributions for tractor and trailer brake drums: 5-axle tractor-trailers observed in Maryland not equipped with retarders.

TRACTOR DRIVE WHEELS

```
TEMPERATURE     COUNT FOR LEFT FRONT  (EACH X= 1)               TEMPERATURE     COUNT FOR RIGHT FRONT  (EACH X= 1)
  IN°C                                                            IN°C

 0.             12 +XXXXXXXXXXXX                                 0.              8 +XXXXXXXX
 50.000         12 +XXXXXXXXXXXX                                 50.000         16 +XXXXXXXXXXXXXXXX
 100.00          3 +XXX                                          100.00          3 +XXX
 150.00          2 +XX                                           150.00          1 +X
 200.00          0 +                                             200.00          1 +X
 250.00          0 +                                             250.00          0 +
 300.00          0 +                                             300.00          0 +
 350.00          0 +                                             350.00          0 +
 400.00          0 +                                             400.00          0 +
 450.00          0 +                                             450.00          0 +
 500.00          0 +                                             500.00          0 +

                 1 < 0.                                                          1 < 0.
 TOTAL          30  (INTERVAL WIDTH= 50.000)                     TOTAL          30  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     COUNT FOR LEFT REAR  (EACH X= 1)                TEMPERATURE     COUNT FOR RIGHT REAR  (EACH X= 1)
  IN°C
                                                                 0.             10 +XXXXXXXXXX
 0.             11 +XXXXXXXXXXX                                  50.000         14 +XXXXXXXXXXXXXX
 50.000         13 +XXXXXXXXXXXXX                                100.00          3 +XXX
 100.00          5 +XXXXX                                        150.00          1 +X
 150.00          0 +                                             200.00          1 +X
 200.00          0 +                                             250.00          0 +
 250.00          0 +                                             300.00          0 +
 300.00          0 +                                             350.00          0 +
 350.00          0 +                                             400.00          0 +
 400.00          0 +                                             450.00          0 +
 450.00          0 +                                             500.00          0 +
 500.00          0 +
                                                                                 1 < 0.
                 1 < 0.                                          TOTAL          30  (INTERVAL WIDTH= 50 000)
 TOTAL          30  (INTERVAL WIDTH= 50.000)
```

TRAILER WHEELS

```
TEMPERATURE     COUNT FOR LEFT FRONT  (EACH X= 1)               TEMPERATURE     COUNT FOR RIGHT FRONT  (EACH X= 1)
  IN°C                                                            IN°C

 0.             13 +XXXXXXXXXXXXX                                0.             14 +XXXXXXXXXXXXXX
 50.000          8 +XXXXXXXX                                     50.000          8 +XXXXXXXX
 100.00          6 +XXXXXX                                       100.00          4 +XXXX
 150.00          3 +XXX                                          150.00          4 +XXXX
 200.00          0 +                                             200.00          0 +
 250.00          0 +                                             250.00          0 +
 300.00          0 +                                             300.00          0 +
 350.00          0 +                                             350.00          0 +
 400.00          0 +                                             400.00          0 +
 450.00          0 +                                             450.00          0 +
 500.00          0 +                                             500.00          0 +

 TOTAL          30  (INTERVAL WIDTH= 50.000)                     TOTAL          30  (INTERVAL WIDTH= 50.000)
```

```
TEMPERATURE     COUNT FOR LEFT REAR  (EACH X= 1)                TEMPERATURE     COUNT FOR RIGHT REAR  (EACH X= 1)
  IN°C                                                            IN°C

 0.             10 +XXXXXXXXXX                                   0.             10 +XXXXXXXXXX
 50.000         13 +XXXXXXXXXXXXX                                50.000         11 +XXXXXXXXXXX
 100.00          2 +XX                                           100.00          5 +XXXXX
 150.00          2 +XX                                           150.00          2 +XX
 200.00          1 +X                                            200.00          1 +X
 250.00          0 +                                             250.00          0 +
 300.00          0 +                                             300.00          0 +
 350.00          0 +                                             350.00          0 +
 400.00          0 +                                             400.00          0 +
 450.00          0 +                                             450.00          0 +
 500.00          0 +                                             500.00          0 +

                 2 < 0.                                                          1 < 0.
 TOTAL          30  (INTERVAL WIDTH= 50.000)                     TOTAL          30  (INTERVAL WIDTH= 50.000)
```

Figure 7. Temperature distributions for tractor and trailer brake drums: 5-axle tractor-trailers observed in Maryland equipped with retarders.

Table 5

Average Brake Drum Temperatures for Drive and Trailer Wheels of 5-Axle Tractor Trailers

Wheel and Axle Measured	Temperatures in Degrees Celsius					
	GVW less than 50,000 lbs.			GVW=50,000 lbs. and more		
	Retarder (N=6)	No Retarder N=24	Both N=30	Retarder (N=22)	No Retarder N=42	Both N=64
Left Front Drive	12.3	47.0	38.8	49.6	106.8	87.4
Std. Dev.	(7.8)	(39.1)	(33.1)	(41.2)	(76.2)	(71.7)
Right Front Drive	21.3	52.1	44.4	56.1	116.5	95.8
Std. Dev.	(19.4)	(46.7)	(43.3)	(45.7)	(80.2)	(76.1)
Left Rear Drive	13.4	43.3	36.4	50.3	106.7	87.7
Std. Dev.	(9.5)	(35.9)	(34.1)	(34.8)	(68.6)	(65.2)
Right Rear Drive	17.2	56.4	47.4	54.8	116.2	96.7
Std. Dev.	(17.0)	(50.4)	(47.7)	(45.2)	(69.5)	(68.3)
Tractor Average	16.0	49.8		52.7	111.6	
Left Front Trailer	8.1	45.6	37.0	64.8	114.2	99.2
Std. Dev.	(4.4)	(41.5)	(39.6)	(46.0)	(64.6)	(63.4)
Right Front Trailer	12.6	46.5	38.7	62.8	123.2	104.5
Std. Dev.	(11.2)	(44.0)	(41.4)	(50.5)	(62.3)	(64.8)
Left Rear Trailer	6.8	45.7	36.8	63.1	131.6	110.3
Std. Dev.	(6.7)	(38.0)	(37.2)	(49.3)	(85.8)	(81.9)
Right Rear Trailer	8.7	39.2	32.2	70.0	118.4	103.0
Std. Dev.	(5.5)	(30.1)	(29.4)	(54.1)	(72.4)	(69.9)
Trailer Average	9.1	44.3		65.2	121.8	

Because of the small sample size for the retarder-equipped trucks in the less-than-50,000-lb category, the observed differences wheel-by-wheel are barely significant in a t-test. Aggregating over all tractor wheels and all trailer wheels, however, makes these differences quite significant. For tractor-trailers at GVW of 50,000 lbs or more, the brakes on retarder-equipped vehicles average about 60°C cooler.

2.7 Brake Pushrod Travel Measurements

One measure sought from this experiment was the relationship between brake condition and the presence of retarders. For a majority of the trucks the extent of pushrod travel at 100 psi of applied air pressure was recorded for each brake, and the number of brakes adjusted beyond the manufacturer's recommended limits is used as a measure of condition.

Of a total of 117 observations (trucks), 101 are categorized as five-axle (i.e., three tractor axles, two trailer axles) units. Two of these units had a lift axle on the tractor, the remaining 99 will be the basis for this comparison.

For 69 out of 99 five-axle tractor-trailers, pushrod measurements were made for each of eight wheels (the four tractor drive wheels, and the four trailer wheels).* For the type 30 brake system, the recommended maximum pushrod travel is 2 inches, with the brake force falling to about 90 percent of its maximum value at this point. The pushrod measurements are divided into two groups—2 inches or less versus more than 2 inches, and this dichotomy is used to indicate the state of maintenance of the vehicles in question. Table 6 shows the number of vehicles observed by presence of a retarder and by the number of brakes with pushrod travel greater than 2 inches.

Table 7 presents the same data in summarized form—i.e., trucks being divided simply into those with at least one brake out of specification versus the remainder. While the distributions in Table 6 were not significantly different (in a Chi-square test), the presence of

---

*Front (steering) axle pushrod travel was measured where possible, but the number of valid measurements was so limited that statistics are not presented here.

Table 6

Distribution of Brake Adjustment for
Retarder-equipped and Non-Retarder Equipped Tractor Trailers

Number of Brakes Beyond Specification	Not Retarder Equipped	Cum. %	Cum. %	Retarder Equipped	Total	Cum. %
None	17	34	25	5	22	32
One	5	45	45	4	9	45
Two	5	55	55	2	7	55
Three	8	71	70	3	11	71
Four	7	86	75	1	8	83
Five	5	96	80	1	6	91
Six	2	100	90	2	4	97
Seven	0	-	95	1	1	99
Eight	0	-	100	1	1	100
Total	49			20	69	

Table 7

Two-by-Two Tabulation of Brake Adjustment
and Presence of Retarders

Number of Brakes Beyond Specification	Not Retarder Equipped	Retarder Equipped	Total
None	17	5	22
Column Percent	35%	25%	32%
Some	32	15	47
Column Percent	65%	75%	68%
Total	49	20	69

Chi-Square (with one degree of freedom) = 0.246, sig. at .6146 empty cells suggests that aggregated data (Table 7) might be more appropriate for testing. In the latter case, we conclude that retarder-equipped trucks have not been proven to have significantly "better" brake adjustment. In fact, the column percentages suggest the opposite, although the number of cases is not large enough to provide statistical significance to such a conclusion. The firmest conclusion that can be drawn is that the brakes of retarder-equipped trucks in this population are rather certainly not twice as good as those of non-retarder trucks. In the present data, 35 percent of the non-retarder trucks had all brakes within specification. If as many as 60 percent of the retarder-equipped trucks had presented the same condition, we could have concluded that they were more likely to be "well-maintained." In fact, only 25 percent of the retarder-equipped trucks were in this condition.

Generally, the drums were cooler at the time of the pushrod measurements than they were when the temperature was determined, since the pushrod observations came later in the inspection process. Observations made by the DOT [5] indicate a relatively linear relationship between pushrod travel measurements and the difference between drum temperature and ambient temperature, with an additional pushrod travel of about 0.3 inches for 200°C of temperature rise. Pushrod travel was reported to the nearest eighth of an inch, and subsequently translated into decimal values for computation. It is possible to adjust the pushrod measurements by assuming a linear relationship with temperature based on the numbers given here, and that will have a slight effect on the "above and below two-inch" figures used for comparison.

The effect of this adjustment should be to lower slightly the proportion of vehicles considered out of adjustment, since, for example, a pushrod travel of 2-1/8 inches and a temperature elevation of 100°C would actually represent a cold travel of slightly less than two inches. Figure 8 shows parallel histograms of the adjusted and unadjusted pushrod travel distributions, and indicates that the difference in the number beyond the two-inch mark is quite small. Fewer than 10 percent of the over-two-inch values would change to two inches or less.

```
                Left Front Drive Axle

PUSHROD TRAVEL   Unadjusted              Adjusted
in inches x .01

0.               0 +               0 +
10.000           0 +               0 +
20.000           0 +               0 +
30.000           0 +               0 +
40.000           0 +               0 +
50.000           0 +               0 +
60.000           0 +               0 +
70.000           0 +               3 +XXX
80.000           4 +XXXX           0 +
90.000           4 +XXXX           4 +XXXX
100.00           5 +XXXXX          4 +XXXX
110.00           5 +XXXXX          5 +XXXXX
120.00           1 +X              8 +XXXXXXXX
130.00           8 +XXXXXXXX       1 +X
140.00           3 +XXX            3 +XXX
150.00           4 +XXXX           4 +XXXX
160.00           7 +XXXXXXX        7 +XXXXXXX
170.00           1 +X              5 +XXXXX
180.00           6 +XXXXXX         2 +XX
190.00           1 +X              1 +X
200.00           2 +XX             2 +XX
210.00           1 +X              1 +X
220.00           2 +XX             2 +XX
230.00           0 +               0 +
240.00           2 +XX             2 +XX
250.00           2 +XX             2 +XX
260.00           1 +X              1 +X
270.00           0 +               0 +
280.00           1 +X              0 +
290.00           0 +               0 +
300.00           0 +               0 +

                9>2"              8>2"
```

```
                Right Front Drive Axle

PUSHROD TRAVEL   Unadjusted.             Adjusted.
in inches x .01

0.               0 +               0 +
10.000           0 +               0 +
20.000           0 +               0 +
30.000           0 +               0 +
40.000           1 +X              1 +X
50.000           1 +X              1 +X
60.000           0 +               0 +
70.000           0 +               3 +XXX
80.000           5 +XXXXX          1 +X
90.000           3 +XXX            2 +XX
100.00           9 +XXXXXXXXX      9 +XXXXXXXXX
110.00           2 +XX             2 +XX
120.00           0 +               7 +XXXXXXX
130.00           8 +XXXXXXXX       1 +X
140.00           3 +XXX            3 +XXX
150.00           5 +XXXXX          5 +XXXXX
160.00           4 +XXXX           4 +XXXX
170.00           0 +               3 +XXX
180.00           4 +XXXX           1 +X
190.00           3 +XXX            3 +XXX
200.00           2 +XX             2 +XX
210.00           2 +XX             2 +XX
220.00           1 +X              4 +XXXX
230.00           3 +XXX            0 +
240.00           2 +XX             2 +XX
250.00           1 +X              1 +X
260.00           0 +               0 +
270.00           0 +               0 +
280.00           0 +               0 +
290.00           0 +               0 +
300.00           0 +               0 +

                9>2"              9>2"
```

```
                Left Rear Drive Axle

PUSHROD TRAVEL   Unadjusted.             Adjusted.
in inches x .01

0.               0 +               0 +
10.000           0 +               0 +
20.000           0 +               0 +
30.000           0 +               0 +
40.000           0 +               0 +
50.000           0 +               0 +
60.000           2 +XX             2 +XX
70.000           1 +X              2 +XX
80.000           1 +X              0 +
90.000           3 +XXX            3 +XXX
100.00           6 +XXXXXX         6 +XXXXXX
110.00           6 +XXXXXX         5 +XXXXX
120.00           1 +X              7 +XXXXXXX
130.00           6 +XXXXXX         0 +
140.00           4 +XXXX           4 +XXXX
150.00           4 +XXXX           4 +XXXX
160.00           5 +XXXXX          5 +XXXXX
170.00           1 +X              6 +XXXXXX
180.00           5 +XXXXX          0 +
190.00           2 +XX             2 +XX
200.00           3 +XXX            3 +XXX
210.00           2 +XX             2 +XX
220.00           0 +               6 +XXXXXX
230.00           7 +XXXXXXX        1 +X
240.00           0 +               0 +
250.00           0 +               0 +
260.00           1 +X              1 +X
270.00           0 +               0 +
280.00           0 +               0 +
290.00           0 +               0 +
300.00           0 +               0 +

                10>2"             10>2"
```

```
                Right Rear Drive Axle

PUSHROD TRAVEL   Unadjusted.             Adjusted.
in inches x .01

0.               0 +               0 +
10.000           0 +               0 +
20.000           0 +               0 +
30.000           0 +               0 +
40.000           0 +               0 +
50.000           1 +X              1 +X
60.000           0 +               0 +
70.000           0 +               2 +XX
80.000           3 +XXX            1 +X
90.000           3 +XXX            3 +XXX
100.00           6 +XXXXXX         6 +XXXXXX
110.00           7 +XXXXXXX        7 +XXXXXXX
120.00           1 +X              5 +XXXXX
130.00           6 +XXXXXX         1 +X
140.00           4 +XXXX           4 +XXXX
150.00           1 +X              1 +X
160.00           4 +XXXX           4 +XXXX
170.00           3 +XXX            7 +XXXXXXX
180.00           4 +XXXX           0 +
190.00           3 +XXX            3 +XXX
200.00           3 +XXX            3 +XXX
210.00           3 +XXX            3 +XXX
220.00           1 +X              4 +XXXX
230.00           3 +XXX            0 +
240.00           1 +X              1 +X
250.00           2 +XX             2 +XX
260.00           0 +               0 +
270.00           0 +               0 +
280.00           0 +               0 +
290.00           0 +               0 +
300.00           0 +               0 +

                10>2"             10>2"
```

```
                Left Front Trailer Axle

PUSHROD TRAVEL   Unadjusted.             Adjusted.
in inches x .01

0.               0 +               0 +
10.000           0 +               0 +
20.000           0 +               0 +
30.000           0 +               0 +
40.000           0 +               0 +
50.000           1 +X              1 +X
60.000           0 +               0 +
70.000           0 +               0 +
80.000           0 +               0 +
90.000           3 +XXX            3 +XXX
100.00           1 +X              1 +X
110.00           2 +XX             2 +XX
120.00           1 +X              6 +XXXXXX
130.00           5 +XXXXX          0 +
140.00           4 +XXXX           4 +XXXX
150.00           8 +XXXXXXXX       8 +XXXXXXXX
160.00           5 +XXXXX          5 +XXXXX
170.00           4 +XXXX          11 +XXXXXXXXXXX
180.00          10 +XXXXXXXXXX     3 +XXX
190.00           3 +XXX            3 +XXX
200.00           2 +XX             2 +XX
210.00           2 +XX             2 +XX
220.00           1 +X              2 +XX
230.00           2 +XX             1 +X
240.00           4 +XXXX           4 +XXXX
250.00           3 +XXX            3 +XXX
260.00           1 +X              1 +X
270.00           0 +               2 +XX
280.00           2 +XX             0 +
290.00           1 +X              1 +X
300.00           0 +               0 +

                16>2"             16>2"
```

```
                Right Front Trailer Axle

PUSHROD TRAVEL   Unadjusted.             Adjusted.
in inches x .01

0.               0 +               0 +
10.000           0 +               0 +
20.000           0 +               0 +
30.000           1 +X              1 +X
40.000           1 +X              1 +X
50.000           1 +X              1 +X
60.000           0 +               0 +
70.000           0 +               2 +XX
80.000           2 +XX             0 +
90.000           1 +X              1 +X
100.00           4 +XXXX           4 +XXXX
110.00           0 +               0 +
120.00           2 +XX             6 +XXXXXX
130.00           5 +XXXXX          1 +X
140.00           7 +XXXXXXX        7 +XXXXXXX
150.00           3 +XXX            3 +XXX
160.00           3 +XXX            3 +XXX
170.00           1 +X             11 +XXXXXXXXXXX
180.00          12 +XXXXXXXXXXXX   2 +XX
190.00           5 +XXXXX          5 +XXXXX
200.00           3 +XXX            3 +XXX
210.00           4 +XXXX           4 +XXXX
220.00           0 +               6 +XXXXXX
230.00           7 +XXXXXXX        1 +X
240.00           1 +X              1 +X
250.00           1 +X              1 +X
260.00           2 +XX             2 +XX
270.00           0 +               0 +
280.00           0 +               0 +
290.00           0 +               0 +
300.00           0 +               0 +

                15<2"             15<2"
```

```
                Left Rear Trailer Axle

PUSHROD TRAVEL   Unadjusted.             Adjusted.
in inches x .01

0.               0 +               0 +
10.000           0 +               0 +
20.000           0 +               0 +
30.000           0 +               0 +
40.000           0 +               0 +
50.000           0 +               0 +
60.000           1 +X              0 +
70.000           0 +               1 +X
80.000           1 +X              0 +
90.000           3 +XXX            3 +XXX
100.00           2 +XX             2 +XX
110.00           2 +XX             2 +XX
120.00           1 +X              6 +XXXXXX
130.00           5 +XXXXX          0 +
140.00           5 +XXXXX          5 +XXXXX
150.00           5 +XXXXX          5 +XXXXX
160.00           2 +XX             2 +XX
170.00           2 +XX             8 +XXXXXXXX
180.00           8 +XXXXXXXX       2 +XX
190.00           5 +XXXXX          5 +XXXXX
200.00           3 +XXX            3 +XXX
210.00           7 +XXXXXXX        7 +XXXXXXX
220.00           1 +X              7 +XXXXXXX
230.00           7 +XXXXXXX        1 +X
240.00           3 +XXX            3 +XXX
250.00           1 +X              1 +X
260.00           2 +XX             1 +X
270.00           0 +               0 +
280.00           0 +               0 +
290.00           0 +               0 +
300.00           0 +               0 +

                21>2"             20>2"
```

```
                Right Rear Trailer Axle

PUSHROD TRAVEL   Unadjusted.             Adjusted.
in inches x .01

0.               0 +               0 +
10.000           0 +               0 +
20.000           0 +               0 +
30.000           0 +               0 +
40.000           0 +               0 +
50.000           0 +               0 +
60.000           0 +               0 +
70.000           0 +               1 +X
80.000           1 +X              0 +
90.000           3 +XXX            3 +XXX
100.00           2 +XX             2 +XX
110.00           4 +XXXX           4 +XXXX
120.00           0 +               6 +XXXXXX
130.00           7 +XXXXXXX        1 +X
140.00           2 +XX             2 +XX
150.00           7 +XXXXXXX        7 +XXXXXXX
160.00           3 +XXX            3 +XXX
170.00           1 +X              6 +XXXXXX
180.00           6 +XXXXXX         1 +X
190.00           2 +XX             2 +XX
200.00           4 +XXXX           4 +XXXX
210.00           6 +XXXXXX         6 +XXXXXX
220.00           0 +               4 +XXXX
230.00           7 +XXXXXXX        3 +XXX
240.00           3 +XXX            3 +XXX
250.00           5 +XXXXX          5 +XXXXX
260.00           0 +               0 +
270.00           0 +               0 +
280.00           2 +XX             0 +
290.00           0 +               0 +
300.00           0 +               0 +

                23>2"             21>2"
```

FIGURE 8

Push Rod Travel at 100 PSI, Unadjusted Measurements Compared
With Measurements Adjusted for Brake Drum Temperature
5-Axle Tractor Trailers Observed in Maryland

2.8 Summary

The two principal questions addressed were (1) Do retarder-equipped trucks have better-maintained brakes? and (2) Is the effect of retarders a reduction in temperature, an increase in descent speed, or some of each?

The quantity of data available from the observations was inadequate to give a very solid answer to question number 1. Based on the small sample, there was some indication that retarder-equipped trucks actually had brakes in poorer condition. However, there is little statistical confidence in this finding. There is certainly no strong evidence, however, that the retarder-equipped trucks had much better brakes, and at least a hint that they might be poorer.

With the slopes present in this part of Maryland, the effect of the retarders was to reduce brake usage while maintaining the same speed as non-retarder-equipped trucks. Trucks with a gross vehicle weight less than 50,000 lbs and a retarder evidently descended these hills with almost no brake application. For heavier trucks (more than 50,000 lbs GVW), there was some brake usage, but drum temperatures averaged about 60°C cooler (i.e., 60°C compared with 120°C) than on trucks without retarders.

Nearly 30 percent of the 117 trucks observed were equipped with retarders. On these Maryland roads, retarders were more likely to be associated with private carriers, with short range (< 200 miles) trips, with conventional tractors, and with heavy (particularly bulk) cargos. Clearly, the results obtained reflect the influences of the characteristics of the types of service and vehicles encountered in Western Maryland. (See Appendix E.)

3. EXPERIMENTAL MEASUREMENTS AND ANALYTICAL PREDICTIONS OF TRUCK RETARDATION

A method for predicting the performance of retarders in controlling the speed of heavy vehicles operating on steep downgrades is presented in this section. In addition to obtaining in-service data pertaining to the use of retarders (see Section 2), the development of a proposed recommended practice for predicting truck retardation was a primary objective of the Phase II work.

3.1 Operating Principles of an Over-the-Road Dynamometer for Testing Tractors Equipped with Retarders

A mobile dynamometer (the "MRD") [2] has been constructed and employed in this study of the retardation properties of heavy vehicles. The reasons for developing a mobile device are (a) the construction cost is small compared to the cost of a laboratory dynamometer, (b) the retarder is tested in a typical operating environment, and (c) the device can be used to measure natural retardation (rolling resistance and aerodynamic drag) and engine drag in addition to retarder performance. For this project, the ability to examine the performance of a vehicle operating on a highway was the primary factor supporting the choice to use a mobile dynamometer.

Using a mobile dynamometer is not the only suitable method of characterizing retarder performance. Laboratory dynamometers having well-controlled test conditions can provide accurate data describing retarder performance. Retarder and engine manufacturers usually employ laboratory dynamometers in evaluating their products. The calculation procedures presented in Section 3.3 require information on retarder horsepower as a function of the rotational speed of the retarder. In these calculations, any accurate method of measuring retarder horsepower as a function of retarder speed is suitable for predicting vehicle retardation.

The MRD, shown in Figure 9, consists of a 45-foot flat-bed semitrailer equipped with (a) a load cell for measuring longitudinal force at the fifth wheel connection between the tractor and the semitrailer and (b) a closed-loop system for controlling velocity by applying

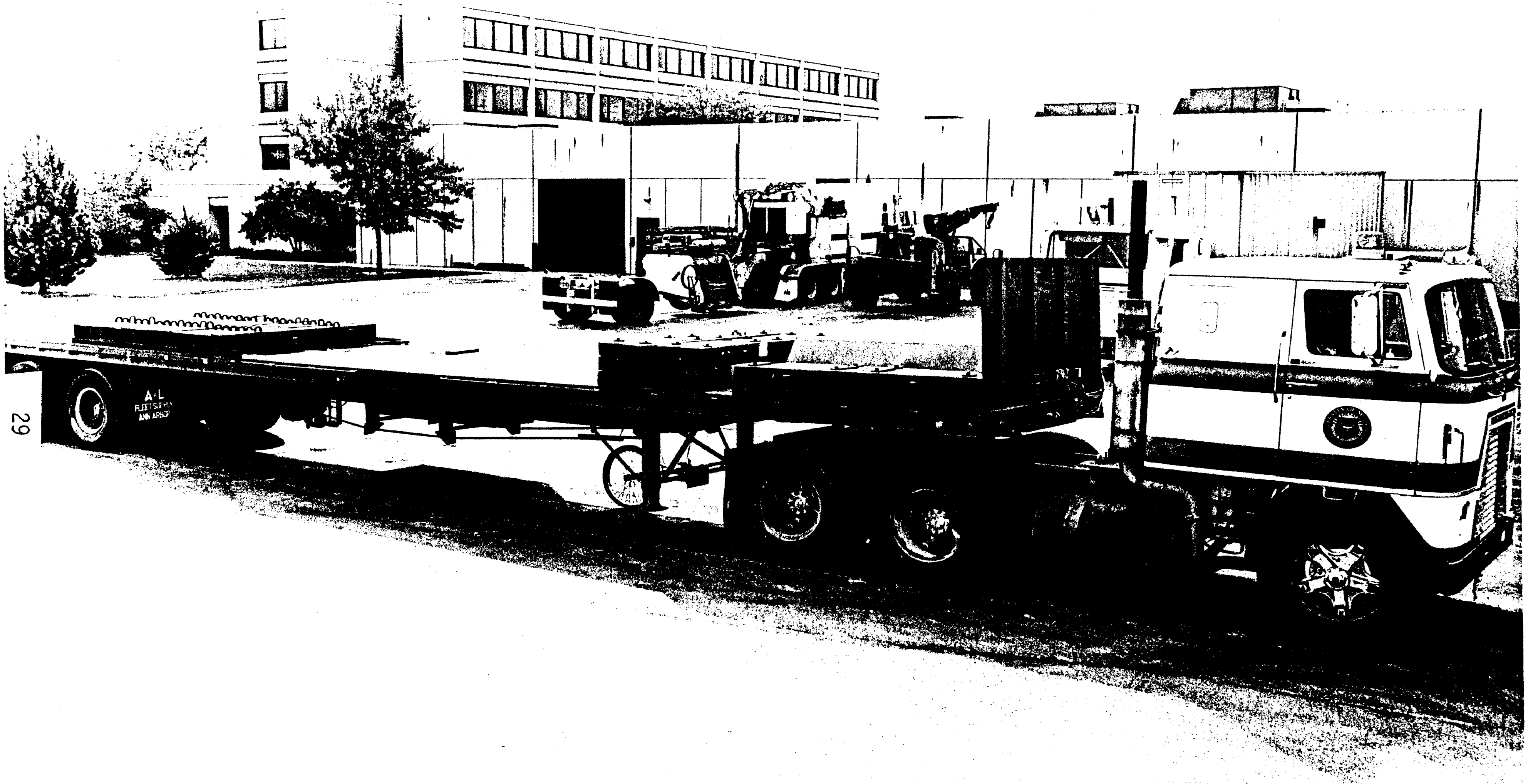


Figure 9. The Mobile Retarder Dynamometer (MRD) [2].

retarding torque to the semitrailer's wheels. When coupled to a tractor and operated on a sufficiently severe downgrade, this semitrailer can be used to measure the horsepower absorbed by the retarder, the engine, and/or the natural retardation present in the tractor.

Speed control is obtained by the action of two electrical retarders mounted on the drive shaft of a tandem axle set that has been mounted on the semitrailer. These retarders are actuated by a velocity control system in order to maintain a constant vehicle speed during tests on downgrade sections of highway. (The velocity control system is described in Reference [2].)

The basic theory of operation of the mobile dynamometer may be understood by examining the free-body diagrams and associated symbols illustrated and defined in Figures 10 and 11). At constant velocity, the equilibrium forces in the x-direction for the entire vehicle (see the free-body diagram in Figure 10) may be used to obtain the following expression for the drag from the retarders installed on the semitrailer.

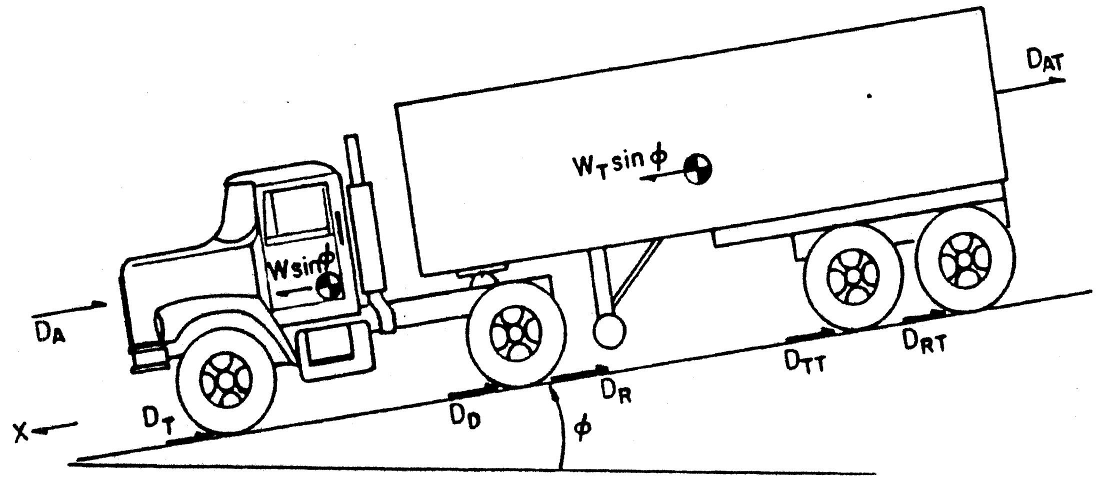
$$D_{RT} = (W_1+W_2)\sin\phi - (D_A + D_T + D_D + D_{AT} + D_{TT}) - D_R \tag{1}$$

The quantity D_{RT} (the drag from the semitrailer's retarders) cannot be negative nor can it exceed the capability of the semitrailer's retarders. Hence, the grade (ϕ) of the hill used for testing must meet the following requirements:

a) ϕ must be large enough so that $D_{RT} \geqq 0$, that is, the right side of (1) is greater than zero. (This implies that the semitrailer should be heavily loaded also.)

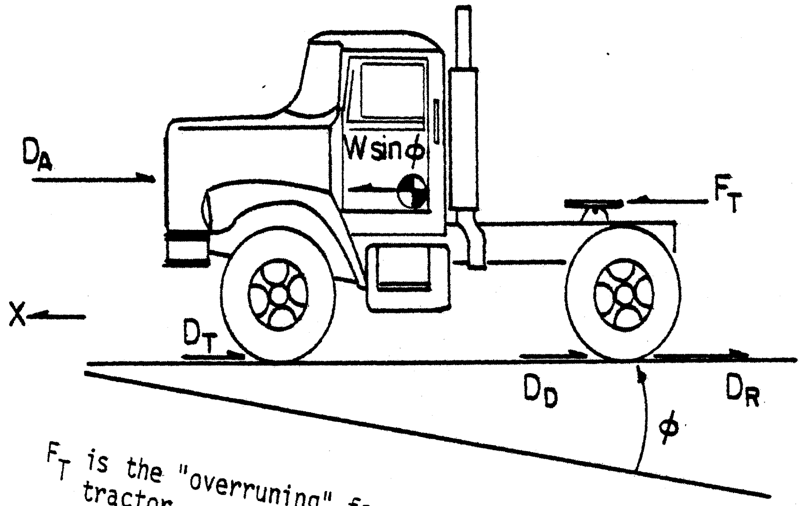
b) ϕ must be small enough so that the right side of (1) does not exceed the capability of the semitrailer's retarders. (In the MRD, the semitrailer's retarders have capabilities of 1500 horsepower when they are cool and 400 horsepower when they are very hot.)

Within these limits, ϕ may vary during a test. An accelerometer is used to measure ϕ throughout a test run—a feature which is needed to assure a



D_A	is aerodynamic drag on the tractor
D_T	is total tire rolling resistance drag on the tractor
D_D	is the drive train drag (exclusive of retarder) on the tractor
D_R	is the drag from the tractor retarder (the "test specimen")
W_1	is the weight of the tractor
D_{AT}	is aerodynamic drag on the trailer
D_{TT}	is total tire resistance drag on the trailer
D_{RT}	is the drag from the "drive" axles and the control retarders on the trailer
W_2	is the weight of the trailer
ϕ	is the angle of downhill incline

Figure 10. Free-body diagram: Steady-state grade descent of tractor-semitrailer vehicle [2].



F_T is the "overruning" force from the trailer acting on the tractor

Figure 11. Free-body diagram: Steady-state grade descent of a tractor [2].

viable test method on typical downgrade sections of highway with varying slope along the length of the hill.

Now consider the free-body diagram of the tractor alone (see Fig. 11). The equilibrium equation for the forces acting in the x-direction may be expressed as follows.

$$D_A + D_T + D_D + D_R = W_1 \sin \phi + F_T \tag{2}$$

The quantities on the left side of (2) are all functions of velocity. At a selected speed, V, they are all constants, depending upon V. To formalize this observation and to aid in explaining how $D_R(V)$ is obtained, let

$$D_V = D_A(V) + D_T(V) + D_D(V) \tag{3}$$

Now consider the following method for obtaining D_R:

1) Perform an initial test down the hill at a selected velocity, V, with the tractor's retarder turned off ($D_R = 0$) to determine D_V from measured values of ϕ and F_T and knowledge of the weight of the tractor, that is,

$$D_V = W_1 \sin \phi + F_T \tag{4}$$

where F_T is measured by the longitudinal force transducer. (See Reference [2] for a description of the device used for measuring F_T.)

2) Perform a second test down the hill at speed V with the tractor's retarder turned on. In this case,

$$D_R(V) = W_1 \sin \phi + F_T - D_V \tag{5}$$

where D_V was determined in the initial test run and F_T is measured on this trip down the hill.

3) Repeat steps (1) and (2) above for various velocities over the range of speeds applicable to all transmission gear selections of interest.

To obtain data in the form desired for the recommended prediction procedure (Section 3.3), it is necessary to measure (or determine) the rotational speed of the retarder also.

Note that this same type of "two-step" procedure can be used to obtain engine drag by operating with the retarder off—first with the transmission in neutral (the clutch disengaged) and then in gear with the clutch engaged. Natural retardation from rolling resistance combined with aerodynamic drag is obtained when operating in neutral. (It is not easy or necessary to separate the influences of rolling resistance and aerodynamic drag, so these quantities are simply combined in the measurement of natural retardation.)

3.2 Retardation Results from Over-the-Road Tests

The MRD, discussed in Section 3.1, was used to measure all of the retardation mechanisms in effect on the two tractors described by the specifications presented in Tables 8 and 9. These tractors were tested on a downgrade, westbound section of US 48 east of Morgantown, West Virginia near Cheat Lake. This downgrade is approximately 4.5 miles long with an average slope of approximately 0.045. For a test vehicle weighing approximately 76,000 lbs, this grade is sufficient to require 500 horsepower to maintain 55 mph. Assuming no more than 300 horsepower of retardation from rolling resistance, aerodynamic drag, and engine drag at 55 mph, the MRD can be used on this hill to measure the performance of tractor-installed retarders with horsepower capabilities of at least 200 horsepower over and above the power due to normal engine drag and natural retardation.*

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*In testing large retarders, it is possible that the test retarder alone may be capable of decelerating the vehicle if the test site does not provide a sufficient grade. Since the velocity control system of the MRD cannot provide drive thrust, steady-state testing is not attainable in this situation. It remains possible to determine retarder horsepower, however, by including the longitudinal deceleration in the data analysis. For this purpose, the instrumentation system of the MRD allows for measurement of longitudinal deceleration through the differentiation of the vehicle velocity signal. (The accelerometer signal used to provide a measure of roadway slope must be appropriately corrected for the effects of deceleration [2].)

Table 8

Tractor #1 6 x 4 Weight 15,820 lbs
Freightliner Model No. WFT 10464
Engine: Cummins Model NTC-350
Cab: Cab-Over-Engine
Transmission: Fuller RTO-9513

Gear	Ratio
LL	12.51
1L	8.35
2L	6.12
3L	4.56
4L	3.38
1D	2.47
10	2.14
2D	1.81
20	1.57
3D	1.35
30	1.17
4D	1.00
40	.87

Drive Axle - Rockwell
Ratio 3.7

Accessory Power at 2100 RPM ≈ 3 hp
10x20 Radial Tires
No Aerodynamic Aids

Table 9

Tractor #2 6 x 4 Weight 16,720 lbs
1973 Freightliner I.D. #73826
Engine: Cummins Model NTC 350
Cab: Cab-Over-Engine
Transmission - Fuller RT-12509

Gear	Ratio
1	12.5
2	8.35
3	6.12
4	4.56
5	3.38
6	2.47
7	1.81
8	1.35
9	1.0

Drive Axle
Ratio 4.11

10x22 Bias Tires
No Aerodynamic Aids

Tractor number 1 was equipped with two different types of exhaust brakes. Separate tests were made for each of these retarders. The total retardation acting on the tractor was measured at several speeds between 20 and 50 mph. In addition, retardation measurements were made with (a) the retarders off and (b) the transmission in neutral in order to assess engine drag and natural retardation. The raw data, shown in Figure 12, have been fitted with polynomial functions in the form

$$HP = a_1V + a_2V^2 + a_3V^3 \tag{6}$$

where V is the vehicle velocity in mph. (These results are superimposed on Figure 12.) Note that for exhaust brake number 2, the form of Equation (6) does not fit the data well. An additional line (the dashed line in Figure 12) of the form

$$HP = a_0 + a_1V + a_2V^2 + a_3V^3 \tag{7}$$

has been used to characterize the performance of this device [2].

The results of the regression analyses for the coefficients in these polynomials are given in Table 10.

Given the ratio of retarder (engine) RPM to vehicle velocity for the transmission gear used, the retardation horsepowers of the retarders and the engine may be presented as functions of their rotational speeds (see Fig. 13).

The test data obtained for tractor number 2 are shown in Figure 14. This tractor was tested with an engine brake operating on either four or six cylinders of the engine. The results obtained by processing these data are summarized in Table 11 and Figure 15. As expected, even though a different type of engine speed retarder was tested in this case, this tractor's retardation due to rolling resistance, aerodynamic drag, and engine drag is roughly the same as that of the first tractor. This engine brake has a greater horsepower capacity than either of the exhaust brakes tested on the first tractor. Nevertheless, these results do not cause doubts concerning the basic notion of expressing retarder performance as a function of its rotational speed.

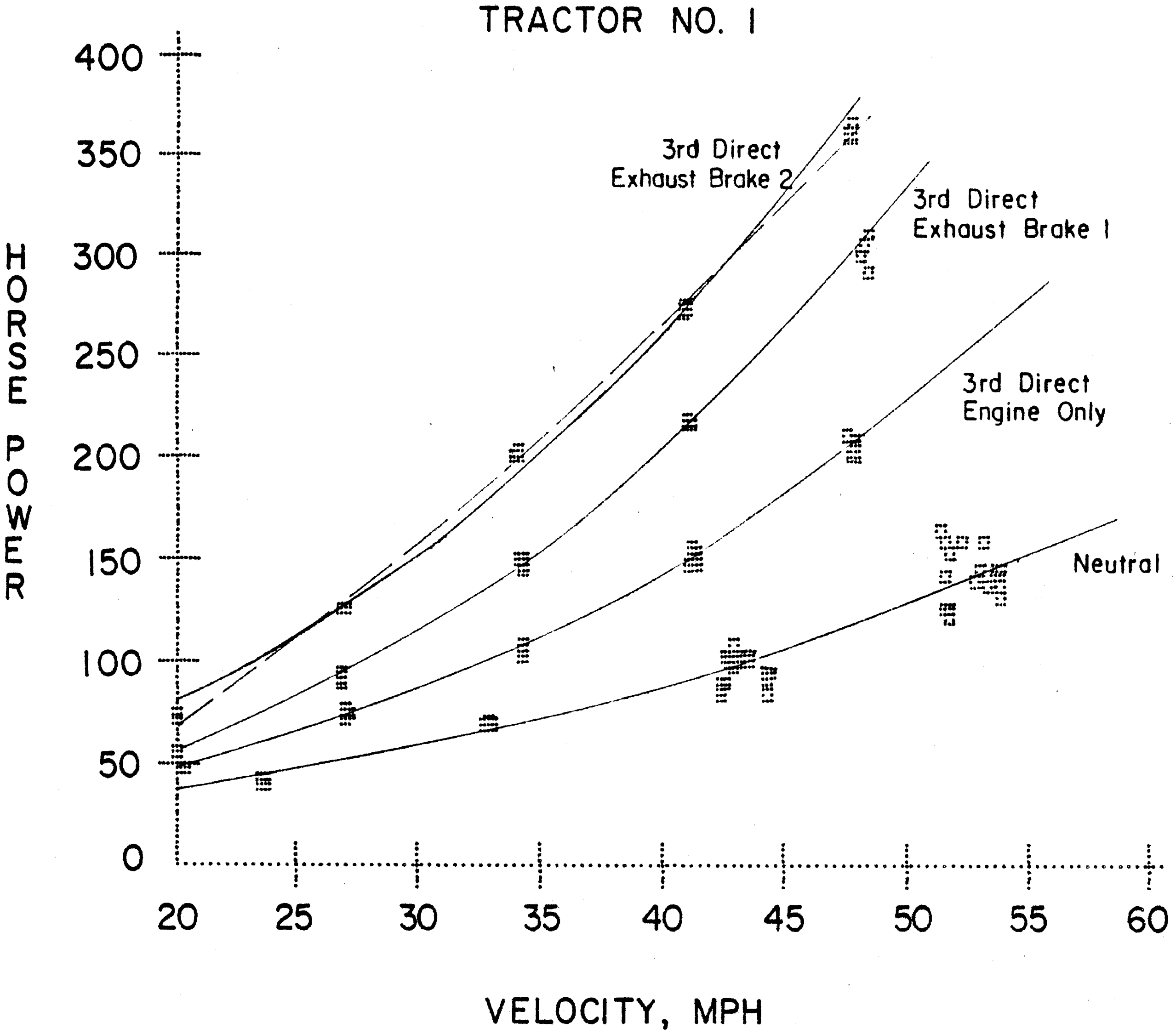


Figure 12. Test data points and fitted curves for Tractor No. 1 [2].

Table 10. Regression Analysis Constants for Equation 6 or 7, Tractor No. 1.

Data Set			Constants			
Gear Selected	Retarder	Applicable Equation	a_0	a_1	a_2	a_3
Neutral	None	6		1.46	-5.65×10^{-7}	4.33×10^{-4}
3rd Direct	(Engine)	6		1.87	-1.88×10^{-7}	1.04×10^{-3}
3rd Direct	Exhaust Brake #1	6		2.03	4.94×10^{-6}	1.87×10^{-3}
3rd Direct	Exhaust Brake #2	7	-21.4	1.42	.17	$-.697 \times 10^{-3}$

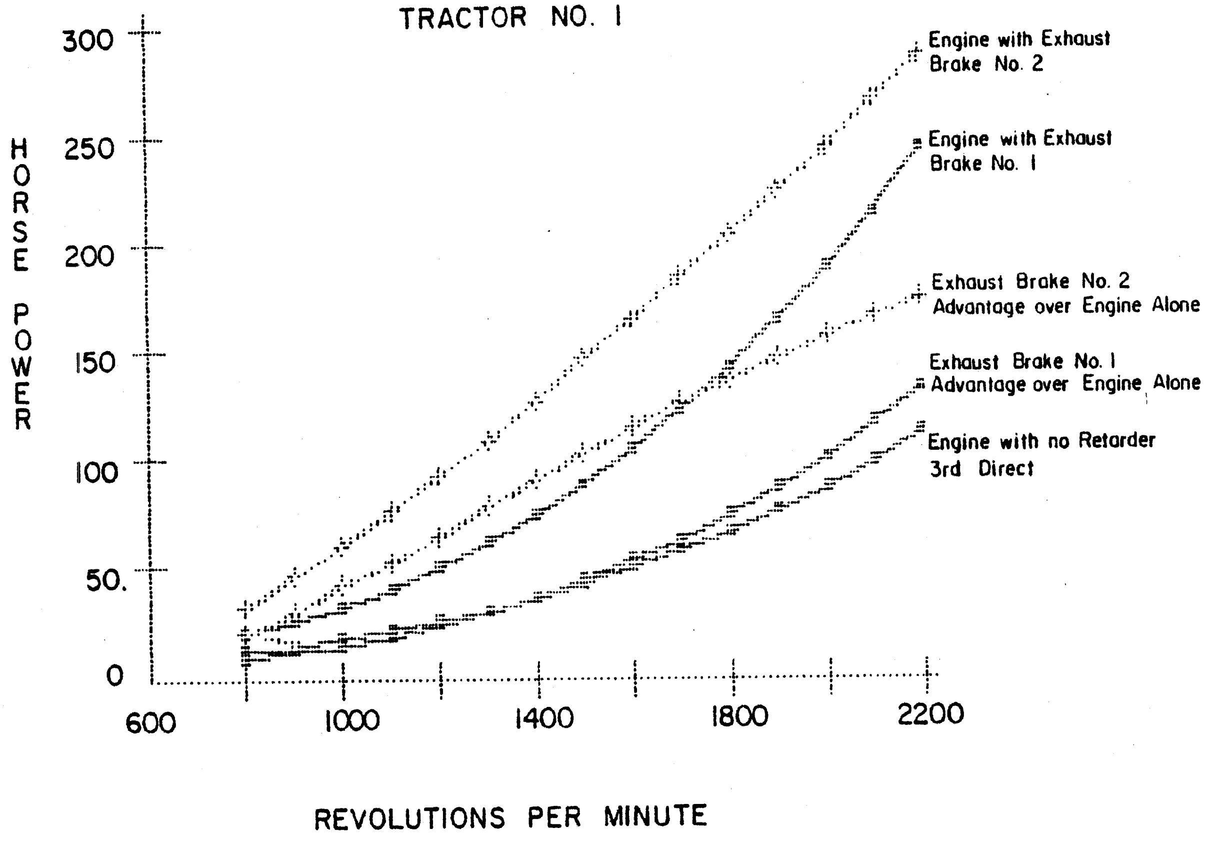


Figure 13. MRD test results, Tractor No. 1 [2].

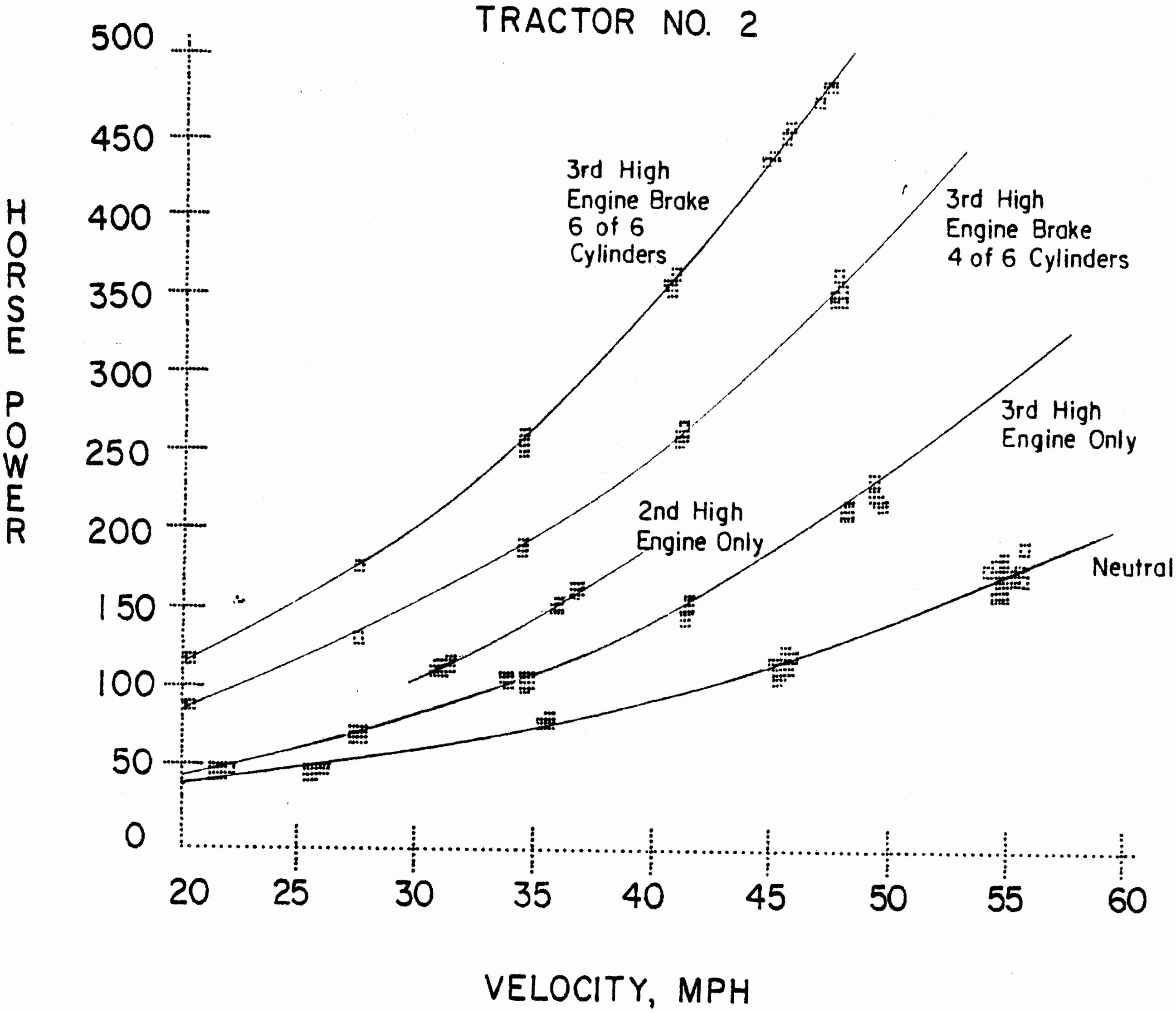


Figure 14. Test data points and fitted curves for Tractor No. 2 [2].

Table 11. Regression Analysis Constants, Tractor No. 2.

Data Set		Applicable Equation	Constants		
Gear Selected	Retarder		a_1	a_2	a_3
Neutral	None	6	1.49	-7.90×10^{-7}	5.26×10^{-4}
3rd High	(Engine)	6	1.58	1.44×10^{-6}	1.21×10^{-3}
2nd High	(Engine)	6	1.76	-3.24×10^{-8}	1.94×10^{-3}
3rd High	Engine Brake (All Cylinders Actuated)	6	4.55	-2.23×10^{-6}	2.54×10^{-3}
3rd High	Engine Brake (4 of 6 Cylinders Actuated)	6	3.57	-1.74×10^{-6}	1.64×10^{-3}

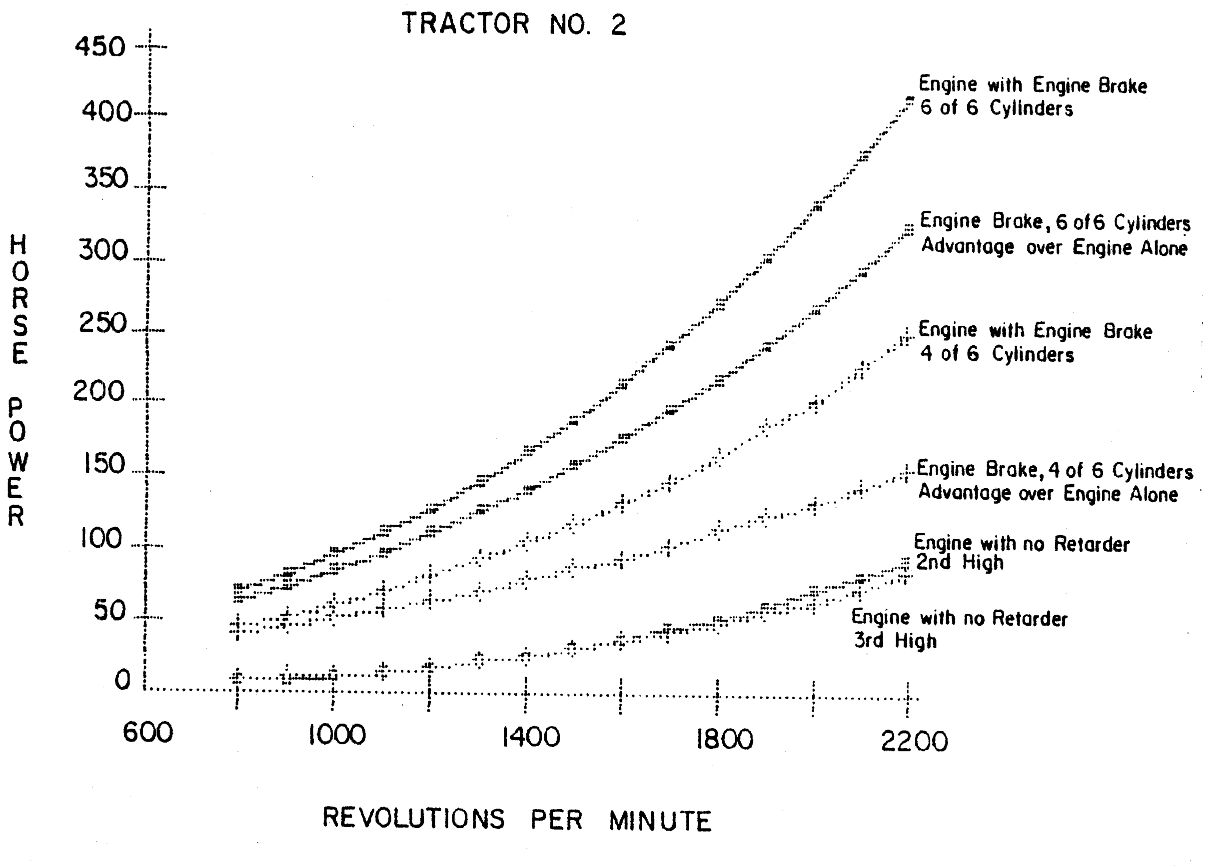


Figure 15. MRD test results, Tractor No. 2 [2].

The data presented here are related to retardation mechanisms that do not exhibit a significant sensitivity to the temperature of the retarder. However, electrical and some hydraulic retarders are sensitive to temperature changes taking place when they are used. Hence, the temperature, which relates to the energy absorbed by the retarder, is an important consideration in addition to the rotational speed of particular devices. The amount of heating that can take place during a test using the MRD is clearly limited by the length, as well as the slope, of the hill used for testing. Thus, the utility of the MRD for testing driveline retarders, that are high powered and temperature sensitive, is limited by both the slope and the length of the hill available.

Unfortunately, results for a driveline retarder were not obtained in this test program. Nonetheless, the performance of these devices is known from manufacturer's tests and specifications. The computational procedures described in the next section are arranged to employ manufacturer's data at the temperature conditions applicable to the measured data. Separate calculations can be made to predict truck retardation when the retarder is either hot or cold.

3.3 A Truck Retardation Prediction Procedure

This section presents a preliminary format for a "Truck Retardation Prediction Procedure." It is anticipated that professional organizations and trade associations may consider adopting a procedure of this type as a recommended practice.

Many of the quantities needed to predict retardation have received much attention in recent years. For example, rolling resistance and aerodynamic drag have been examined in connection with fuel economy studies. Similarly, engine drag and transmission efficiencies are matters of current concern. So-called "truck ability" calculations [3] entail items such as rolling resistance, aerodynamic drag, and transmission efficiencies. These items pertain to downhill speed control and deceleration as well as to acceleration and gradeability. Engine manufacturers have developed computer routines for performing "Vehicle Mission Simulations" [4]. These activities dealing with fuel economy and grade-climbing ability have contributed greatly to the development of this truck retardation prediction procedure in that parametric data in a usable form are generally available and reasonably well understood. The data formats for the procedure recommended here for predicting retardation are modeled after the data formats used in gradeability calculations.

However, the precision required for fuel economy studies is not believed to be necessary for retarder evaluation. Hence, simplified equations are employed to estimate natural retardation.

3.3.1 Overview of the Calculation Procedure. The calculation procedure is based on predicting a power balance between the available retarding power and either the power demand associated with traveling down a grade at constant velocity, or the instantaneous power associated with decelerating the vehicle on a level road. The available retarding power may come from three sources: natural retardation (rolling resistance and aerodynamic drag), engine drag, and retarders.

The rolling resistance force and aerodynamic drag are treated as functions of vehicle weight and velocity, respectively, using analytical expressions based on physical reasoning and empirical evidence. The power due to these sources of natural retardation is obtained by multiplying the force by the velocity of the vehicle, thereby resulting in a polynomial of the following form:

$$P_N = a_1 V + a_3 V^3 \qquad (8)$$

where P_N is the natural retardation

and V is the vehicle velocity

Note that the polynomials for natural retardation as derived from experimental measurements (see Tables 10 and 11) agree with Equation (8) in that the values of the "a_2V^2" terms in the measured expressions are very small compared to the values of the "a_1V" and "a_3V^3" terms. Since the coefficients, a_1 and a_3, in (8) can be estimated from either vehicle properties or test results with suitable accuracy, the calculation procedure employs Equation (8) with parameters depending upon tire and road surface properties, the vehicle weight, its cross-sectional area (height and width), and the presence or absence of aerodynamic devices for lowering drag.

The retarding powers due to engine drag and retarder performance are specified as functions of their rotational speeds. These functions are supplied as input information to the calculation procedure. It is intended that these functions be obtained from experimental measurements performed on the engines and retarders to be included in the calculations. These functions are expected to be specified in tabular form, thereby precluding the need for processing data to obtain analytical expressions describing the results in terms of common functions.

Clearly, the power balance computations are based on very simple equations once the sources of retarding power are determined. The only complexity of the calculation procedure relates to keeping track of the results for several speeds for each transmission gear. The details of the recommended prediction procedure are believed to be evident from the description of the preliminary format presented in the next section.

3.3.2 A Preliminary Format for a Proposed Recommended Practice. This subsection contains a formal statement of the recommended prediction procedure.

Truck Retardation Prediction Procedure

This procedure has been developed to provide a practical method for the prediction of retarder performance in a specified vehicle installation, using measured data describing retarder horsepower characteristics. It is designed to help anyone concerned with the problem of retarder selection.

1. Purpose. This recommended practice provides a uniform method for calculating the control speeds maintainable by either engine, driveline, or trailer-axle retarders employed on heavy vehicles operating on downgrades. It also provides predictions of vehicle deceleration resulting from retarder use on level roadways.

2. Scope. This procedure covers the estimation of the total retardation capability available to a specified vehicle from the following sources:

-natural retardation (rolling resistance, aerodynamic drag, etc.)
-engine drag
-engine, driveline, or trailer-axle retarders

(It does not cover the use of the foundation brakes for maintaining speed on long mountain descents.)

Retardation is rated in terms of the maximum grades at which stable control speeds can be maintained for each gear over the range of highway speeds appropriate to that gear.

For each gear, the calculation procedure determines maximum grades for four values of control speed ranging from the vehicle velocity (V_{1i}) corresponding to rated engine RPM to the vehicle velocity (V_{4i}) corresponding to the engine RPM at maximum torque.

In addition, the calculation procedure provides information on (a) the total retarding power available and (b) the vehicle deceleration capability on a level road using the retarder. This information is also presented for V_{1i} through V_{4i} for each gear.

(The deceleration capability is important for use in estimating the brake savings that may be obtained for vehicles such as buses or delivery trucks that make frequent stops. Also, the deceleration capability serves as an indicator of situations where retarder use could lead to directional control difficulties on very slippery roads.)

3. Symbols and Definitions

Weight Factors

W	total vehicle weight in lbs
GVW/GCW	same as W

Vehicle Dimensions

w	vehicle width in ft
h	vehicle height in ft
R_M	number of tire revolutions per mile of travel (establishes the rolling radius of the tires)

Dimensionless Coefficients

C_A	air resistance coefficient (used in determining aerodynamic drag)
C_e	equivalent weight coefficient (used in determining the influence of decelerating the rotating components of the vehicle)
C_R	road surface coefficient (used in determining the influence of road surface properties on rolling resistance)
C_T	rolling resistance coefficient (used in determining the influence of tire properties and other factors on rolling resistance)

Subscripts

i	subscript used to denote each gear with $i=1$ corresponding to the highest gear ratio (i.e., the lowest gear)

Velocities

V_e	engine speed in revolutions per minute (rpm)
V_{er}	rated engine speed (rpm)
V_{ep}	engine speed at peak torque (rpm)
V	vehicle velocity in miles per hour (mph)
V_{1i}	vehicle velocity corresponding to rated engine speed with the transmission in gear i (mph)
V_{4i}	vehicle velocity corresponding to the engine speed at maximum engine torque with the transmission in gear i (mph)
V_{2i}	an intermediate velocity between V_{1i} and V_{4i}, $V_{2i} = V_{4i} + 2/3(V_{1i}-V_{4i})$ (mph)
V_{3i}	an intermediate velocity between V_{1i} and V_{4i}, $V_{3i} = V_{4i} + 1/3(V_{1i}-V_{4i})$ (mph)
V_d	driveline speed (rpm)
V_t	trailer retarder speed (rpm)
V_C	control speed (equilibrium speed on a downgrade (mph)

Gear Ratios

G_i	transmission gear ratio for the i^{th} gear
A_R	drive axle gear ratio
A_{RT}	trailer axle ratio (gear ratio determining the rotational speed of a retarder installed on a trailer axle)

Efficiencies

η_D	drive axle efficiency
η_T	trailer axle efficiency
η_{E_i}	overall drive system efficiency for the i^{th} gear

Power

P_N	natural retardation in horsepower (hp)
P_E	engine retarding power (hp)
P_{RE}	retarder power from an engine-speed retarder (hp)
P_{RD}	retarder power from a driveline-speed retarder (hp)
P_{RT}	retarder power from a trailer axle retarder (hp)
P_S	total retarding power available (hp)
P_G	grade power demand (hp)

Retardation Numerics

D	deceleration capability in g units
G	grade of the hill used in determining P_G
G_M	maximum grade allowable for a given set of values for P_S, W, and V_C

4. Input Data and Information. The recommended form for entering the input data is listed below in Table 12. This list is arranged as it might appear if the calculation procedure were to be implemented in an interactive computer program. (Even if the calculation procedure is not implemented on a computer, the following format for documenting the input information is recommended to provide a uniform pattern for communicating the results of applying the calculation procedure.)

The user is expected to reply to the computer after each colon (:) appearing in the list. Some of the information to be entered is descriptive in nature. For example, after the statement "Vehicle Code:" is printed at the computer terminal, the user of the program is expected to type a statement describing the vehicle. The content of this statement does not have to be "6x4-2S" as shown in the example list. It can be any short description that is meaningful to the program user.

In the first section of input data (entitled "Vehicle Description") the calculation procedure only employs the number listed after "GVW/GCW (lbs)," "Equivalent Weight Coefficient," "Width (ft)," "Height (ft)," and "Air Resistance Coefficient." These numbers pertain to the parameters W, C_e, w, h, and A_R as defined in Part 3. The remainder of the entered information is for documentation purposes. However, a knowledgeable person should be able to use this descriptive information to judge the reasonableness of the parametric data provided to the calculation procedure.

Under the heading "TIRES," the first entry (after "TIRE TYPE") is a general description of the nature of the tires to be considered. The following entries are equated to R_M, C_R, and C_T, respectively, in the calculation procedure. (The manner in which these parameters, and all other parameters, are to be used is determined by the equations given in Part 5 of this procedure.)

The value of the coefficient C_R describes the influence of road surface characteristics on rolling resistance. The value 0.012 represents a very smooth concrete highway. Other types of roads are expected to correspond to larger values of C_R for truck tires.

The value of 0.7 for C_T, as shown in the example, is characteristic of a radial-ply truck tire. For a bias-ply truck tire, C_T is approximately 1.0.

Table 12. Example Input Data.

Vehicle Description

Vehicle Code: 6x4-2S
Cab Type: Highway Tilt Cab-Over-Engine
Trailer Body: Flatbed
GVW/GCW (Lbs): 75880
Equivalent Weight Coefficient: 0.05
Width (Ft): 8.0
Height (Ft): 10.5
Length (Ft): 55.0
Aeroaids: None
Air Resistance Coefficient: 1.0

Tires

Tire Type: 10.00x20, Radial
No. of Rev. Per Mile: 498
Road Surface Coefficient: 0.012
Rolling Resistance Coefficient: 0.7

Engine

Engine Type:

At Rated Engine Speed (RPM): 2100
(HP): 350
(Ft-Lb): 875

At Peak Torque Speed (RPM): 1300
(HP): 277
(Ft-Lb): 1120

Accessory Power at Rated Speed (HP): 3.2

Drive Train

Drive Axle Type:
Drive Axle Ratio: 3.7
Drive Axle Efficiency: .97

Transmission Data

Transmission Type:
Number of Gears: 13

Gear 1 Ratio and Overall Efficiency: 12.51, .909
" 2 " " " " : 8.35, .908
" 3 " " " " : 6.12, .906
" 4 " " " " : 4.56, .904
" 5 " " " " : 3.38, .919
" 6 " " " " : 2.47, .915
" 7 " " " " : 2.14, .893
" 8 " " " " : 1.81, .908
" 9 " " " " : 1.57, .885

Gear 10 Ratio and Overall Efficiency: 1.35, .899
" 11 " " " " : 1.17, .876
" 12 " " " " : 1.00, .907
" 13 " " " " : 0.87, .879

Trailer Axle

Trailer Axle Ratio: 4.0
Trailer Axle Efficiency: 1.0

Engine Drag Power
Closed Throttle, Retarder Off
(Including Accessory Power)

No. of Data Points: 4

Engine Speed (RPM) and Power (HP): 832., 16.9
" " " " " " : 1248., 30.8
" " " " " " : 1663., 51.7
" " " " " " : 2100., 85.5

Retarder Power

1st Location: Engine Speed Retarder
No. of Data Points: 4

Engine Speed (RPM) and Retarder Power (HP): 832., 6.9
" " " " " " " : 1248., 23.6
" " " " " " " : 1663., 52.2
" " " " " " " : 2100., 87.3

2nd Location: No Driveline Speed Retarder
No. of Data Points: 0

3rd Location: No Trailer Axle Retarder
No. of Data Points: 0

Additional example of

Retarder Power

1st Location: No Engine Speed Retarder
No. of Data Points: 0

2nd Location: Driveline Retarder
No. of Data Points: 4

Driveline RPM and Retarder Power (HP): 200., 80.
" " " " " " : 600., 220.
" " " " " " : 1200., 420.
" " " " " " : 2800., 700.

3rd Location: Trailer Axle Retarder
No. of Data Points: 2

Retarder RPM and Retarder Power (HP): 0., 0.
" " " " " " : 3000., 500.

The product of C_T with C_R determines the level of rolling resistance for a vehicle of given weight traveling at a known speed. (See Equation (D) in Part 5 of this procedure.)

Information on the engine is given in two places. First, rated speed (V_{er}) and peak torque speed (V_{ep}) are specified for use in establishing the velocity range for each gear. Other items entered after the prompting phrases, "Engine Type," "(HP)," "(Ft-Lb)," and "Accessory Power at Rated Speed (HP)," are not used in the calculations, but if they are entered, they can be used to evaluate the reasonableness of the second set of engine data given after the heading "Engine Drag Power."

Gear ratios and efficiencies are entered in a straightforward manner for the drive axle and the transmission. For vehicles with retarders connected to the trailer axles, the gear ratio and efficiency of this connection are entered. If a trailer-axle retarder is not present on the vehicle, the entries after the prompting statements pertaining to the trailer axle will be ignored once the program recognizes that there are no data points for retarder power at the "3rd Location."

Under the heading "Retarder Power" the prompting remarks, "1st Location," "2nd Location," and "3rd Location," are used to separate tabular functions pertaining to engine speed, driveline speed, and trailer axle retarders. An entry of "0" after the prompting statement "No. of Data Points" indicates that there is not a retarder at that location. See the example specifying only an engine speed retarder.

To calculate retardation due to natural retardation plus engine drag, without any retarder in use, simply enter 0 for the number of data points for all three locations, or if more than one retarder is to be used, include the appropriate tabular functions as illustrated in the additional example.

The tabular functions for engine drag power and retarder power should reflect appropriate consideration of the efficiencies of the gears involved. That is, the total power absorbed by rotating these devices is increased over and above the tabulated values according to the efficiencies of the gears involved (see Equation (I) in Part 5). Hence, the data entered in these tabular functions are intended to represent the performance of the device alone and are not intended to include the influences of the efficiencies of any gearing arrangements used in testing engines or retarders.

5. Basic Variables and Equations. The following equations define the computations to be made in this calculation procedure.

Vehicle Speeds:

For each gear (denoted by the subscript i)

V_{1i} = Vehicle velocity corresponding to rated engine speed = $V_{er}60/R_MA_RG_i$

V_{4i} = Vehicle velocity corresponding to the engine RPM at maximum torque = $V_{ep}60/R_MA_RG_i$

V_{2i} = An intermediate vehicle velocity between V_{1i} and V_{4i}, specifically, $V_{2i} = V_{4i} + 2/3(V_{1i} - V_{4i})$

V_{3i} = Same as V_{2i} except $V_{3i} = V_{4i} + 1/3(V_{1i} - V_{4i})$

The calculations are done at each of these speeds, but the basic equations are the same regardless of the speed used. Hence, the symbol V is used to represent vehicle velocity in the following equations.

Rotational Speeds:

a) V_e = engine speed in RPM

$$V_e = \frac{V\ R_MA_RG_i}{60} \qquad (A)$$

where

V = vehicle velocity in mph
R_M = tire revolutions per mile
A_R = rear (drive) axle ratio
G_i = ratio for the i^{th} gear

b) V_d = driveline speed in RPM

$$V_d = \frac{V\ R_M A_R}{60} \tag{B}$$

c) V_t = trailer retarder speed in RPM

$$V_t = \frac{V\ R_M A_{RT}}{60} \tag{C}$$

where A_{RT} = trailer axle ratio

<u>Retardation Variables</u>:

a) P_N = natural retardation in horsepower

$$P_N = \frac{W\ C_R\ C_T\ V}{375} + \frac{w(h - 0.75)0.002\ C_A\ V^3}{375} \tag{D}$$

where

W = GVW/GCW in lbs
C_R = road surface coefficient
C_T = tire rolling resistance coefficient
V = vehicle velocity in mph
w = vehicle width in ft
h = vehicle height in ft
C_A = air resistance coefficient

b) P_E = engine retarding power in horsepower

$$P_E = f_E(V_e) \tag{E}$$

where

$f_E(V_e)$ is a tabular function

c) P_{RE} = retarder power from an engine speed retarder

$$P_{RE} = f_{RE}(V_e) \tag{F}$$

where

$f_{RE}(V_e)$ is a tabular function

d) P_{RD} = retarder power for a driveline retarder (horsepower)

$$P_{RD} = f_{RD}(V_d) \qquad (G)$$

where

$f_{RD}(V_d)$ is a tabular function

e) P_{RT} = retarder power from a trailer axle retarder (horsepower)

$$P_{RT} = f_{RT}(V_t) \qquad (H)$$

where

$f_{RT}(V_t)$ is a tabular function

f) P_S = total retarding power available

$$P_S = \frac{P_E}{\eta_{E_i}} + \frac{P_{RE}}{\eta_{E_i}} + \frac{P_{RD}}{\eta_D} + \frac{P_{RT}}{\eta_T} \qquad (I)$$

where

η_{E_i} = overall drive system efficiency for the gear applicable to the calculation

η_D = rear (drive) axle efficiency

η_T = trailer axle efficiency

Deceleration Capability:

D = deceleration in g units

$$D = \frac{P_S\ 375}{V\ W_e} \qquad (J)$$

where

$W_e = W + C_e W$

with C_e equal to the coefficient determining the influence of decelerating the rotating components of the vehicle. (C_e is the "equivalent weight coefficient.")

Grade vs. Control Speed:

P_G = grade power demand

$$P_G = \frac{W\ G\ V}{375} \qquad (K)$$

where G is the grade (G is the sine of the angle of the hill)

By equating P_G and P_S and solving for the maximum grade, G_M, at which V is the control speed, one obtains:

$$G_M = \frac{P_S\ 375}{W\ V_c} \qquad (L)$$

where V_c is the selected control speed.

Note: The program calculates G_M for the speeds V_{1i} through V_{4i} for each gear. These speeds are control speeds for the grades determined by Equation (L). (Clearly Equation (L) is similar to Equation (J) except W_e is used in (J).)

6. Output Tables and Graphs. For each transmission gear, tables showing total retarding power, P_S, deceleration capability, D, and maximum grade allowable, G_M, versus vehicle velocities (V_{1i}, V_{2i}, V_{3i}, and V_{4i}) are to be constructed using the equations given in Part 5 and the parameters described in Part 4. For example, the following tables show results at V_{4i} and V_{1i} for a vehicle described by the parametric values given in Part 4 (using an engine brake only).

Graphical presentation of the calculated information is desirable. A graph of the form shown in Figure 16 may be used to display G_M (or D) versus control speeds applicable to each transmission gear.

Another interesting graph (Figure 17) displays P_S versus velocity with lines of constant grade, G, or deceleration, D, superimposed. (Polar coordinate paper is convenient for reading information from this type of graph.)

Table 13

Gear	MPH at Minimum Speed, V_{4i}	HP at Minimum Speed, P_S	Decel. Capacity, D (g units)	Max. Grade G_M
i=1	3.38	74.49	0.1036	0.109
2	5.07	77.47	0.0719	0.076
3	6.92	80.85	0.0550	0.058
4	9.28	85.22	0.0432	0.045
5	12.52	90.08	0.0339	0.036
6	17.14	99.50	0.0273	0.029
7	19.78	106.80	0.0254	0.027
8	23.39	113.87	0.0229	0.024
9	26.96	124.57	0.0217	0.023
10	31.36	135.61	0.0204	0.021
11	36.18	152.51	0.0198	0.021
12	42.33	172.38	0.0192	0.020
13	48.66	201.69	0.0195	0.020

Table 14

Gear	Rated Speed, V_{1i} (mph)	HP at Rated Speed, P_S	Decel. Capacity, D (g units)	Max. Grade G_M
i=1	5.47	206.16	0.1775	0.186
2	8.19	211.16	0.1214	0.127
3	11.17	217.02	0.0914	0.096
4	15.0	224.78	0.0705	0.074
5	20.23	232.49	0.0541	0.057
6	27.68	251.39	0.0427	0.045
7	31.95	268.21	0.0395	0.041
8	37.78	283.66	0.0353	0.037
9	43.56	310.54	0.0336	0.035
10	50.65	339.15	0.0315	0.033
11	58.45	386.61	0.0311	0.033
12	68.38	446.48	0.0307	0.032
13	78.60	539.11	0.0323	0.034

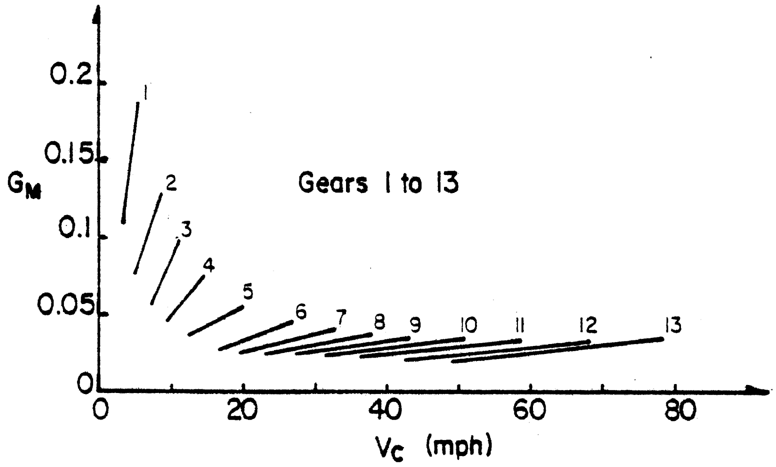


Figure 16. Maximum grades over the range of control speeds applicable to each gear.

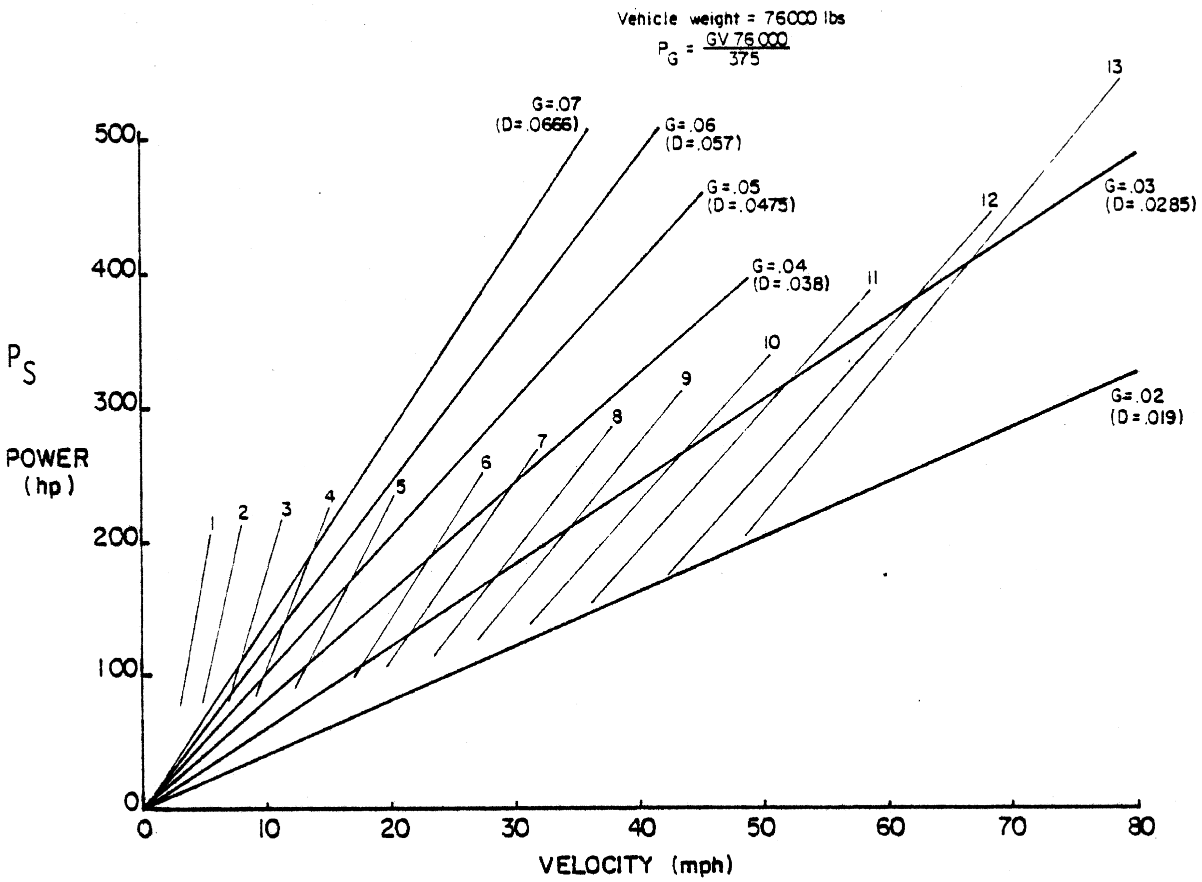


Figure 17. Retarding power, P_S, versus velocity with lines of constant grade or deceleration capability superimposed.

3.3.3 Example Calculations Using the Prediction Procedure. As a first example, consider the vehicle described in Table 8 equipped with exhaust brake No. 2 with performance characteristics as shown in Figure 12 (see Section 3.1). Furthermore, the engine, transmission, and drive axle information given in Part 4 of the prediction procedure (as defined in Section 3.3.2) apply to this vehicle. Hence, many of the example values given in Part 4 describe this vehicle.

However, parametric entries differing from some of the example values will be made here to illustrate more fully the use of test data for natural retardation, engine drag, and retarder power as obtained from the MRD.

The values of the coefficients C_A, C_T, and C_R can be selected to match the test results for natural retardation. For example, examination of the results obtained during tests in neutral (line 1, Table 10) indicate that, since $|a_2V^2|$ is very much less than $a_1V + a_3V^3$ for $0 < V \leq 70$ mph,

$$P_N \approx 1.46V + (4.33)10^{-4}V^3 \tag{9}$$

where

P_N is the natural retardation in horsepower

and V is the vehicle velocity in mph

By comparing Equation (9) with Equation (D) in Part 4, the following equalities result:

$$\frac{W\ C_R\ C_T}{375} = 1.46 \tag{10}$$

and

$$\frac{w(h-.74)0.002C_A}{375} = (4.33)10^{-4} \tag{11}$$

However, (10) only applies to the tractor wheels, that is, the rolling resistances of the trailer wheels are not included in the result given by (9). Estimating the additional influence of the trailer wheels yields the following result for the C_RC_T product.

$$C_R C_T = \frac{375\ (1.46)}{(75{,}880 - 33{,}500)} = 0.013$$

where 33,500 lbs are carried on the trailer wheels and the total vehicle weighs 75,880 lbs.

Assuming that C_T is set at 0.7 to represent radial tires, C_R then equals 0.019 to yield a product of 0.013. (Since the product of C_R with C_T is the important factor, the breakdown between C_R and C_T is not important numerically, but these coefficients have been treated separately in traditional analyses of vehicle performance in order to separate the influences of different types of roads from the influences of different types of tires.)

Solving Equation (11) for C_A, using h = 10.5 ft and w = 8 ft, indicates that $C_A = 1.04$. Again it should be noted that this is the drag on the tractor without including the influence of the trailer. However, in this case the influence of the trailer may be very small, depending upon the details of the aerodynamic situation. As a first approximately, C_A is selected to be equal to 1.0 for the entire vehicle.

Clearly, the value of C_A can be modified to account for an improved understanding of the aerodynamics of the vehicle. Nevertheless, for vehicles with no aerodynamic aids, 1.0 is a reasonable choice for the value of C_A, while C_A might range from 0.9 to 0.75 for vehicles with various improvements for reducing drag.

Now consider engine drag. Examination of Figure 13 yields the following values of engine drag as a function of engine speed.

V_e (RPM)	P_E (HP)
1300	30
1567	47
1833	70
2100	100

These values include the influences of the drive system's efficiencies. "Third direct (high)" as indicated in Figure 13, corresponds to the 10th gear. This gear has an efficiency of 0.899. Removing the efficiency of this gear from the raw data yields the following table for engine drag power. (These values contain the influence of accessory power, but if they did not, the accessory power could be added in.)

V_e (RPM)	P_E (HP)
1300	27
1567	42
1833	63
2100	90

Similarly, the measured retarder power characteristics need to be adjusted for the efficiency of the drive system; viz., for exhaust brake No. 2,

V_e (RPM)	Raw Data (HP)	P_R (HP)
1300	77	69
1567	108	97
1833	137	123
2100	163	147

To shorten the calculations for this example, it is assumed that results for gears corresponding to a minimum speed (peak torque speed) greater than 30 mph are desired. In this case, results for gears 10 through 13 are calculated using the basic equations given in Part 5 of the prediction procedure. The following levels of retardation capability are predicted for speeds V_{1i} through V_{4i} for i=10 through 13.

$P_E = 90 \quad P_R = 147$

Gear	V_{1i}	P_N	P_S	D	G_M
10	50.65	190.4	454.2	.042	.044
11	58.45	240.4	510.9	.041	.043
12	68.38	317.0	578.3	.040	.042
13	78.60	413.5	683.1	.040	.043

$P_E = 42 \quad P_R = 97$

Gear	V_{3i}	P_N	P_S	D	G_M
10	37.79	124.2	278.8	.035	.036
11	43.60	151.8	310.4	.034	.035
12	51.01	192.5	345.7	.032	.033
13	58.64	241.7	399.9	.032	.034

$P_E = 27 \quad P_R = 69$

Gear	V_{4i}	P_N	P_S	D	G_M
10	31.36	97.2	204.0	.031	.032
11	36.18	117.1	226.7	.029	.031
12	42.33	145.5	251.4	.028	.029
13	48.66	178.9	288.1	.028	.029

The results shown in Figure 18 indicate that, as speed increases, a maximum grade of about 0.043 is predicted regardless of the gear selected. The influence of changing gears is to allow higher speeds on the maximum grade. In this example, for this type of retarder, the additional retarding power capability available due to speed increases is offset by the increase with speed of the power demand of the hill. According to these predictions, this vehicle can maintain speeds up to 78 mph using this retarder as long as the grades do not exceed 0.043. At 55 mph in 11th gear, the equilibrium grade is 0.041.

As a second example, consider the same vehicle with the same engine, transmission, rear axle, etc., except with an electrical driveline speed retarder. In this case, driveline speed is computed for each vehicle velocity to allow retarder power to be determined from characteristics measured in the laboratory. Performance data for a typical electrical retarder that might be employed on vehicles weighing from 35 to 38 tons are presented in Figure 19. Clearly, this retarder has a much higher horsepower capability when it is cold. At 2800 rpm, it can absorb 700 hp when it is cold, while after 20 minutes of operation it can only absorb 200 hp at 2800 rpm. For this example, the lower curve, corresponding to the situation after extreme service, will be employed.

Upon applying the calculation procedure, the results shown in Figure 20 are obtained for gears 10 through 13. The main difference between these results and the previous results for the other retarder (Fig. 18), is the decrease in speed sensitivity at each gear. The maximum grade is nearly the same as in the previous case because the maximum retarder horsepower is nearly the same. The reason for the reduced speed sensitivity is that the power being absorbed by the retarder at low speed (i.e., V_{4i}) is greater in this case than it was in the previous case.

As a matter of interest, predicted results (shown in Figure 21) for gears 10 and 13 when the electrical retarder is cold are similar in form to those shown in Figure 20 for a hot retarder. (Clearly, the grades involved in the cold condition are very much larger, as is to be expected.)

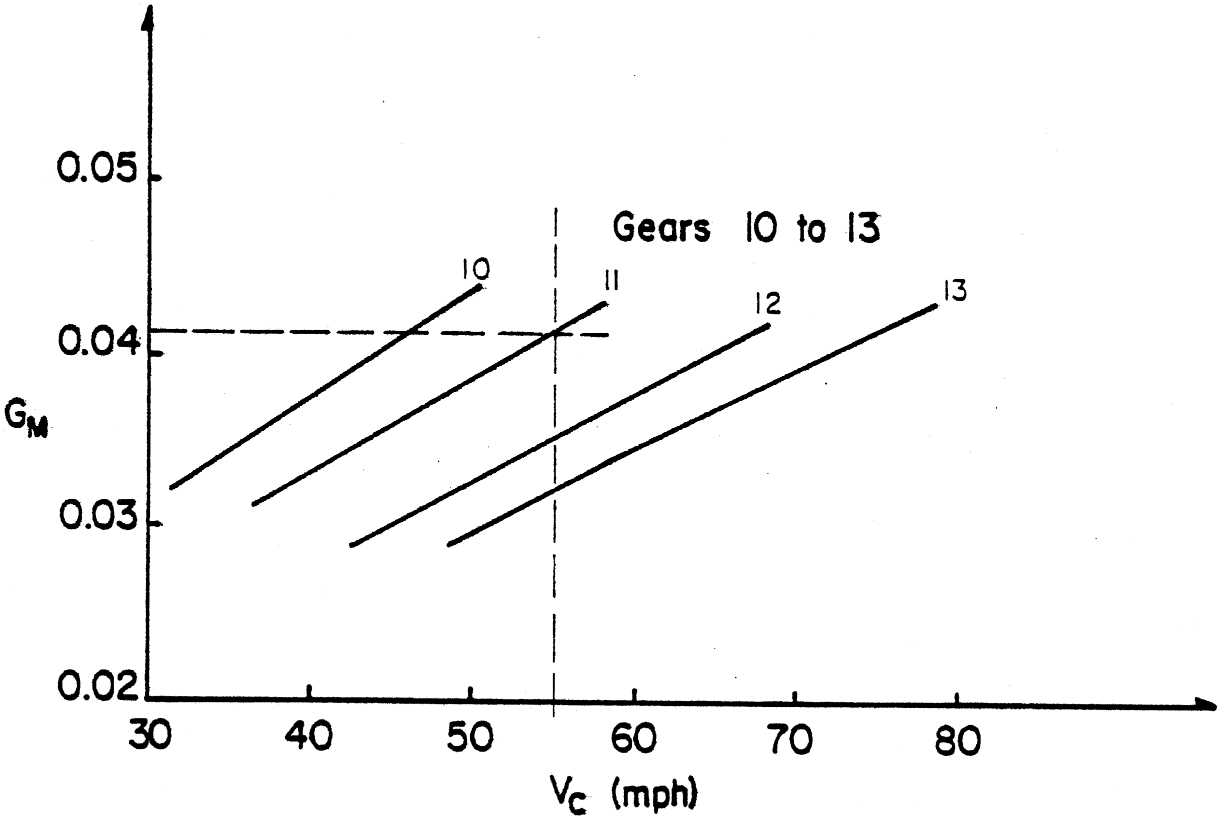


Figure 18. Example predictions of maximum grades for speeds above 30 mph.

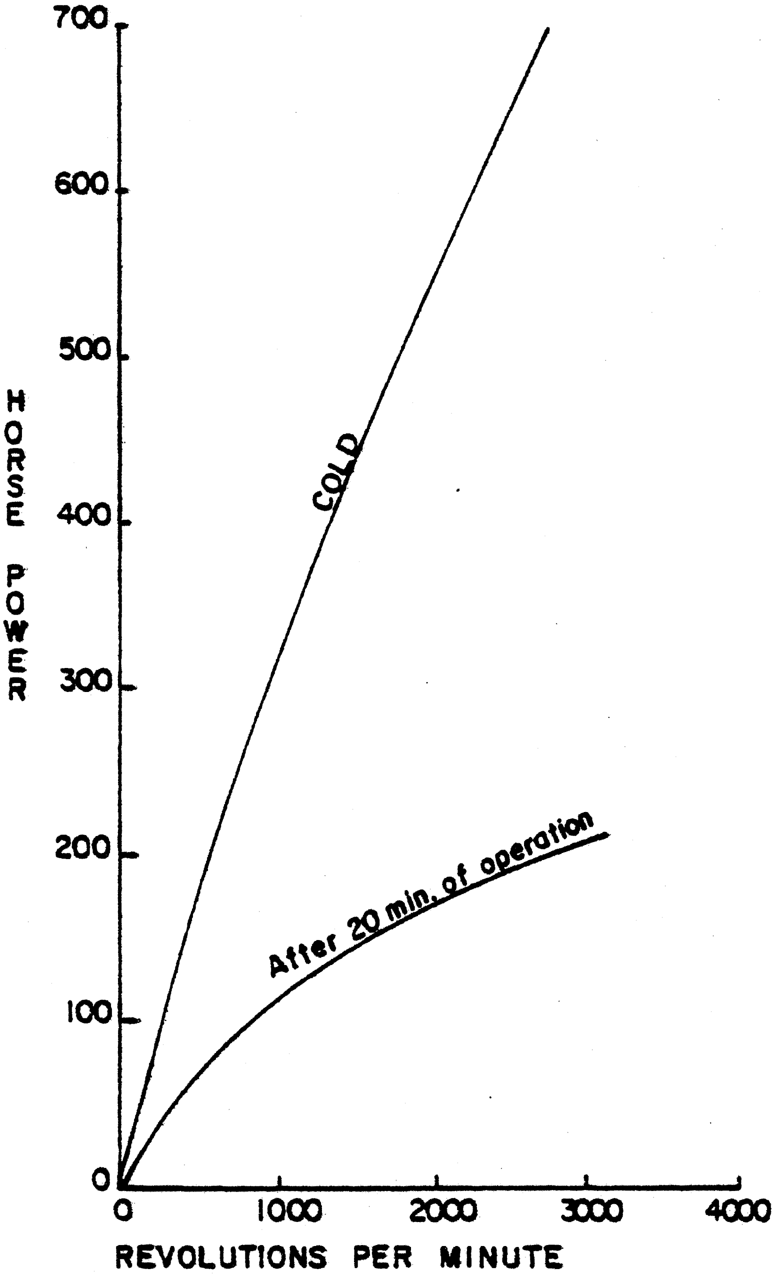


Figure 19. Typical performance data for an electrical retarder [6].

Gear	V_{1i}	Vd	P_S	D	G_M
10	50.65	1555	445.1	.041	.043
11	58.45	1795	508.0	.041	.043
12	68.38	2100	596.6	.041	.043
13	78.60	2414	711.8	.043	.045
10	31.36	963	240.6	.036	.038
11	36.18	1111	271.6	.035	.037
12	42.33	1300	314.5	.035	.037
13	48.66	1494	364.2	.035	.037

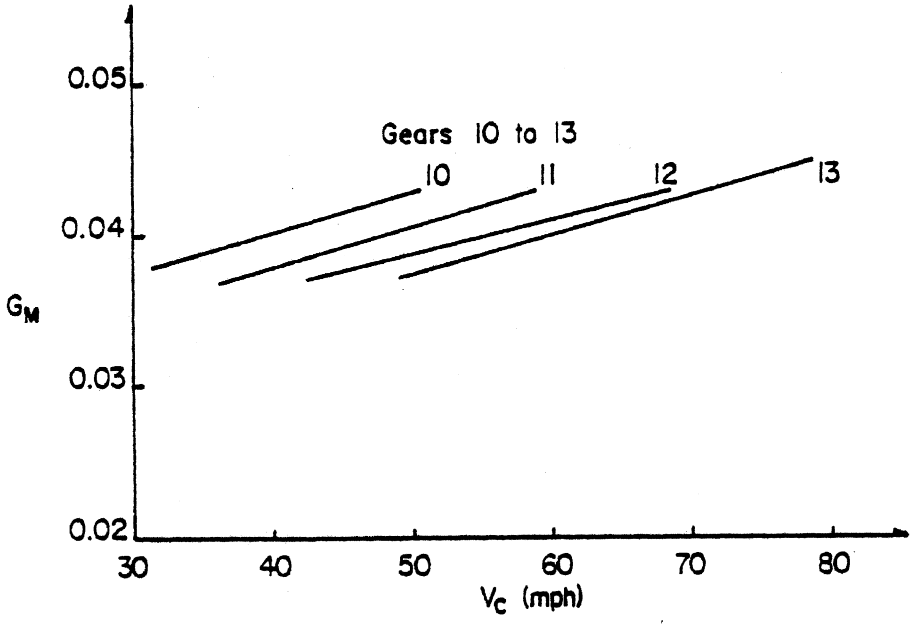


Figure 20. Example predictions for a "hot" electrical retarder.

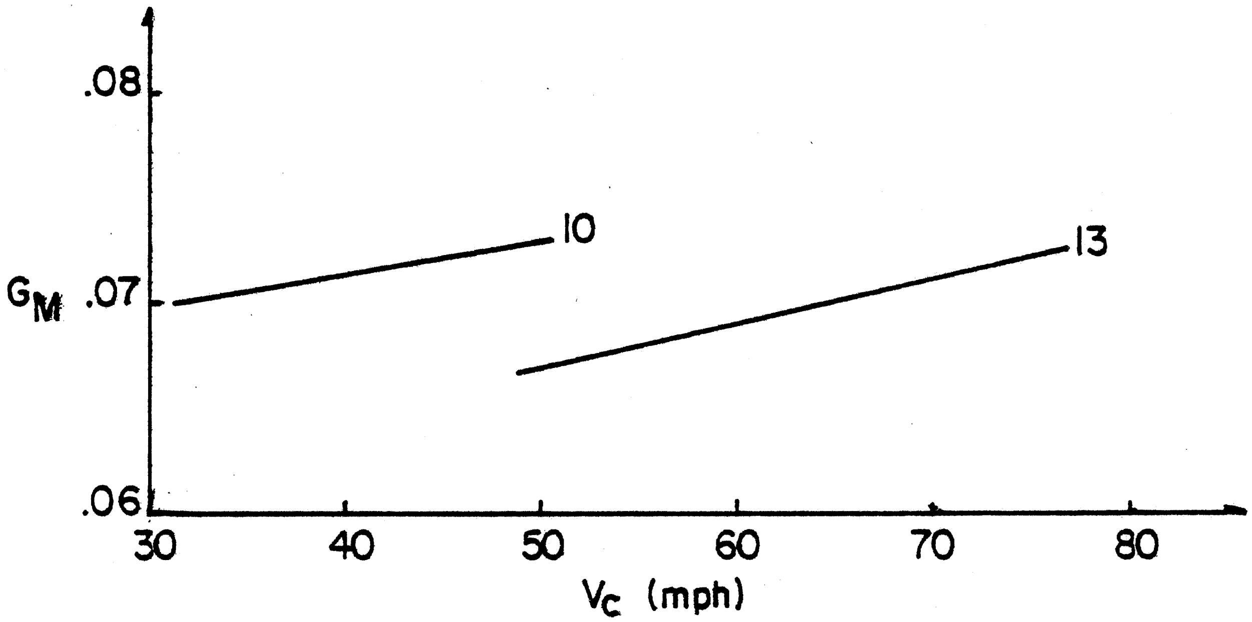


Figure 21. Example predictions for a "cold" electrical retarder.

To illustrate differences between engine-speed and driveline-speed retarders, consider the performance of the same vehicle again, but in this case the results are for gear 5 covering the speed range from 12.5 to 20.2 mph. As shown in Figure 22, the exhaust brake can maintain speed on steeper grades than the (hot) electrical retarder even though retarding capabilities at higher speeds are nearly equal. The trend of higher grade capability at lower speeds for an engine-speed retarder is due to the retarder speed (and hence power capability) remaining high while the retarding power demand decreases as the vehicle speed decreases. In the case of the driveline-speed retarder, the retarder power does not have much of an increasing trend in grade capability at low speeds because the speed of the driveline retarder is directly dependent upon vehicle velocity regardless of the gear selected.

It should be noted that the example results given in this section are significantly influenced by natural retardation. Newer vehicles with fuel-efficient engines, aerodynamic aids, and low rolling resistance might have as much as 100 hp less natural retardation at high speed than the example vehicle examined here [1]. This 100 hp translates into approximately a 0.01 decrease in the maximum grades and deceleration capabilities. Nevertheless, the examples presented do illustrate the basic nature of the results obtained by applying the calculation procedures to engine and driveline retarders.

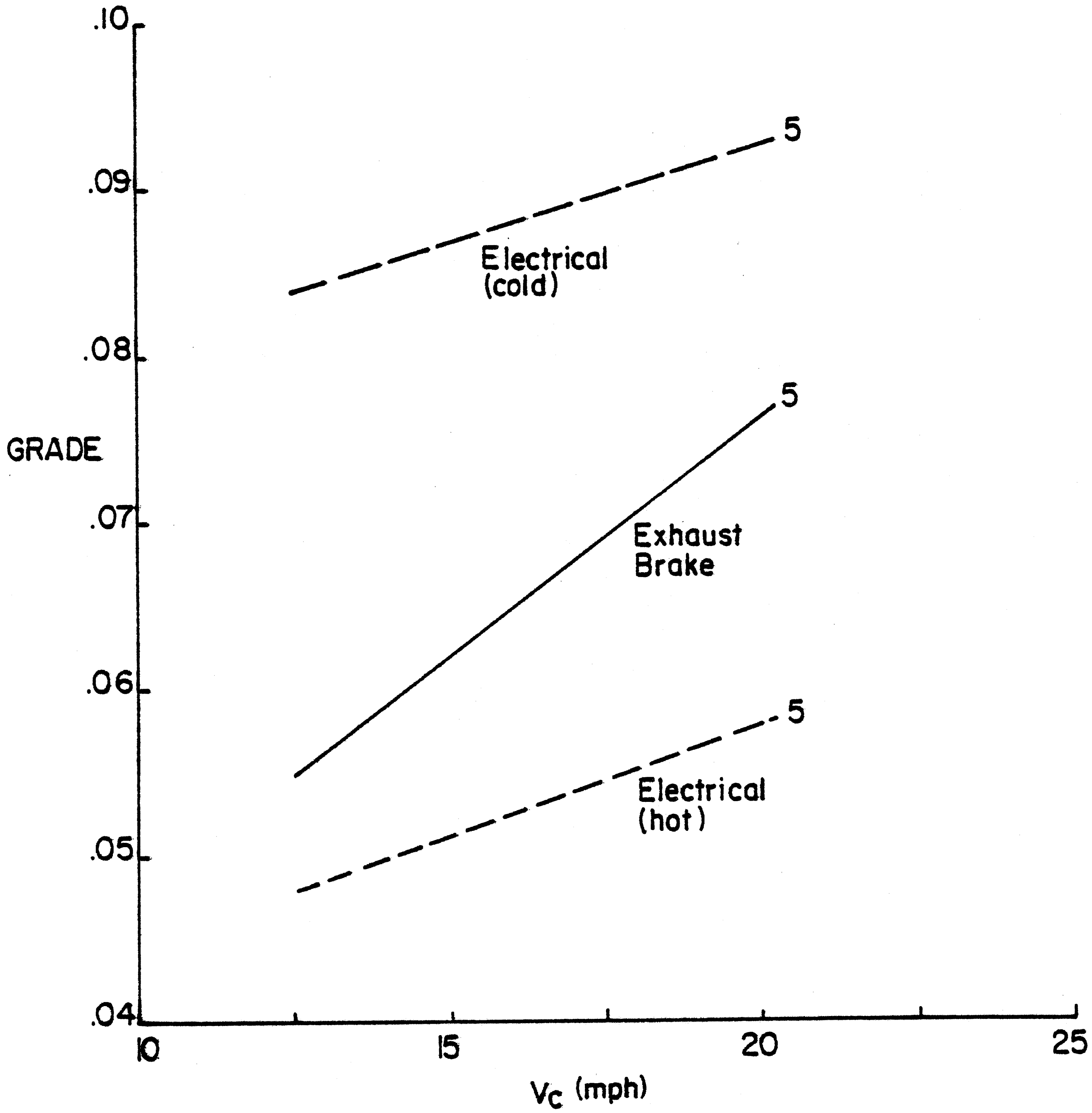


Figure 22. Example predictions in Gear 5 for velocities from 12.5 to 20.2 mph.

4. CONCLUSIONS AND RECOMMENDATIONS

1. Based on an in-service survey of 117 trucks operating on downgrades near Cumberland, Maryland, it appears that retarder-equipped trucks do not have better-maintained brakes than trucks without retarders. Hence the hypothesis that better brake maintenance accounts for part of the improvement in reducing runaway events for retarder-equipped trucks is not supported by the evidence gathered in this study. It appears reasonable to assume that the level of brake maintenance and the presence or not of a retarder are independent factors with respect to predicting runaway events.

2. For vehicles weighing more than 50,000 lbs, the drum temperatures for retarder-equipped vehicles averaged approximately 60°C cooler than on trucks without retarders (that is, 60°C versus 120°C) at the three downgrade sites involved in the in-service survey. At these sites, most heavy vehicles were traveling at approximately 45 mph, the speed limit for heavy trucks. Assuming that brake temperature is a suitable surrogate for predicting brake wear, it is estimated that, on the average, the retarders used under these conditions on these vehicles provide a brake life extension factor of 2 or greater. Verification of this estimate for vehicles operating in this area would provide evidence supporting the idea of using temperature measurements to expeditiously estimate brake life extension factors without having to wait long periods of time for brakes to wear on retarder-equipped vehicles. In addition, temperature measurements can be obtained for many vehicles (and various drivers) in a matter of days, thereby providing the breadth of data needed for averaging out the influences of wide variations in (a) the mechanical properties and adjustments of brake system components and (b) the different braking techniques employed by drivers.

3. A truck retardation prediction procedure has been developed. This prediction procedure is based on a power balance between (1) the rate of change of potential energy occurring during a descent at constant speed on a constant downgrade and (2) the following sources of retardation,

viz., (a) natural retardation, (b) engine drag, and (c) retarders. The prediction procedure is recommended for use in comparing the performance of retarders installed on heavy vehicles making mountain descents. For a given vehicle, the performance achieved with various types and/or sizes of retarders can be compared in terms of the stable control conditions that can be maintained on various grades with the transmission in the appropriate gear for the speed range involved.

4. A mobile retardation dynamometer (MRD) has been developed and employed to measure the natural retardation, engine drag, and retarder power capability of highway tractors equipped with retarders. The MRD consists of a specially instrumented semitrailer whose velocity is controlled through the action of two electrical retarders. Although a substantial hill of appropriate length and grade is needed to challenge the capabilities of currently available retarders, the MRD, nevertheless, remains a convenient device to use, especially for measuring engine drag and natural retardation. Note, however, that carefully controlled laboratory measurements of retarder power characteristics (as functions of the retarder's rotational speed and temperature) are expected to be at least as accurate and as useful as results obtained with the MRD with regard to supplying information on a given retarder as needed for the truck retardation prediction procedure developed in this study.

REFERENCES

1. Fancher, P., et al. "Retarders for Heavy Vehicles: Evaluation of Performance Characteristics and In-Service Costs." Final (Phase I) Report, NHTSA Contract No. DOT-HS-9-02239, Highway Safety Research Institute, University of Michigan, February 1981.

2. Winkler, C.B. and Fancher, P. "Using an Over-the-Road Dynamometer to Test Tractors Equipped with Retarders." SAE Paper No. 811259, November 1981.

3. Truck Ability Prediction Procedure - SAE J688, SAE Recommended Practice.

4. Klokkenga, D.A. "Selecting Powertrain Components for Heavy Duty Trucks." SAE Paper No. 760830, November 1976.

5. Radlinski, R. Private Communication.

6. Telma Specifications CC220 Retarder.

7. Myers, T.T., Ashkenas, I.L., and Johnson, W.A. "Feasibility of a Grade Severity System." FHWA-RD-79-116, Contract No. DOT-FH-11-9253, prepared by Systems Technology, Inc., August 1979.

APPENDICES

APPENDIX A

Design Plan

The presence of a retarder on a large truck may affect the probability of an accident (either in the sense of a runaway, or in situations in which maximum braking effectiveness is called for, the life of the components in the foundation braking system, and/or the productivity of the trucking operation (as related to the allowable speed of the vehicle). We have pointed out in the Phase I report that these factors are likely to be interactive, and that individual operators will use the retarders in such a way as to maximize one factor more than another.

Data from Colorado, Pennsylvania, and California were interpreted to mean that there was considerable safety improvement resulting from the presence and use of retarders. With the data available, however, it could readily be ascertained what proportion of the safety gain (i. e., the lower probability of a runaway) came directly from the braking effect of the retarders, and what proportion came from better foundation brake conditions associated with the retarder presence or other factors.

Most users of retarders seem to have bought them because of their potential for safer operation. Truck drivers believe that retarders will reduce the probability of a runaway; and truck owners in such mountainous areas as Colorado will order them routinely when purchasing a new vehicle. There is a real problem in designing an informal experiment to measure the effectiveness of retarders, in that the trucks with retarders installed are likely to be those that need them most (because of their cargo weight, trips primarily involving steep descents, etc.). When this group is compared with those which chose not to install retarders, the two groups are not likely to have operated under the same environmental conditions.

What's Wrong with Counting Accidents in a Controlled Experiment?

One might consider the installation of retarders in a matched pair experiment--expecting the trip profiles to be exactly the same for the retarder-equipped and the non-retarder-equipped environments.

Ultimately the accident rate of each group could be compared with the other, and some conclusion drawn as to the efficacy of the retarder. If the experiment could be kept completely clean the two groups could be compared at the end of some time period with respect to their (downhill runaway) accident rate. From the data provided in Phase I of this program we had estimated an average runaway rate of the order of 1 in 5000 downhill trips, with the presence of a retarder providing about a 3:1 reduction in the probability of a runaway event (i.e., a ramp usage or worse). The observations that led to this conclusion are confounded to the extent that trucks with retarders might have a better brake maintenance program, that drivers with retarders are more (or less) careful, that trucks with retarders are typically carrying heavier loads, etc. In a controlled experiment it seems likely that the probability of a runaway would be lower than for the average (on the road) truck. Using an assumption of one runaway in 10,000[1] descents for non-equipped vs. one in 30,000 for retarder-equipped trucks, and an average of 100 hill-descents per year per truck, a matched pair experiment with about 5000 trucks would be expected to show a significant difference in performance at about the five percent level. If the effect of retarders alone is smaller than the 3:1 assumed, a much larger experiment would be necessary.

The Alternative Experiment

An attractive alternative to counting accidents for two such different treatments is to count some more frequent events which may differ and which can be related to the probability of a runaway or accident. There are a number of more or less measurable things which may change in a retarder-equipped population which can be indirectly related to the chance of an accident. Table 1 lists a number of these, along with a comment about the relationship to accident occurrence.

With appropriate instrumentation it should be possible to observe retarder- and non-retarder-equipped trucks in operation to determine the

---

[1] These rates are smaller than the 1/5000 reported earlier because it is assumed that such an experiment would be conducted with relatively new and well-maintained vehicles.

direction and magnitude of the kinds of changes listed in the table. It seems clear that retarder-equipped trucks will operate more safely (i.e., with a lower probability of a downhill runaway) based on the accident and runaway analyses presented in the Phase I report. What could not be ascertained in that study, however, was <u>why</u> the safety improvement occurred. There must be some tradeoff in increased speed, lower probability of brake fade, and less brake wear. The proposed experiment is intended to get data which will fill the gaps in our knowledge about these things.

Assume that instrumentation and personnel can be provided at a long steep hill so that the following sequence can take place:

(1) Actual travel speed of a vehicle descending the hill can be observed and recorded

(2) An inspection station at the bottom of the hill permits examination of the air brake pushrod travel, determination of brake type, temperature measurement of the drum, examination of the tires, and a brief interview with the driver to determine retarder presence, engine horsepower, etc.

Such an observational procedure would necessitate full cooperation from at least the state authorities, and probably from BMCS as well.

The actual number of vehicles to be inspected will ultimately be a tradeoff of desired precision of the measurements, time, money, and good will. We start with the assumption that we do not wish to delay a particular truck for more than ten minutes, that we wish to measure something on each wheel (or pair of wheels), and that we need a precision for comparison of about 5% (one-sigma) for a variable in the neighborhood of 40 percent--for example a determination that the proportion of trucks with more than one adjuster beyond the recommended setting at 40% would have a one-sigma range of 35% to 45%. Assuming that other factors would be the same, a total population of about 100 trucks in a sample would provide such precision.

Other factors are not likely to be the same. We can anticipate, for example, that trucks with heavier loads are more likely to have retarders, and, of course, total weight will affect brake temperatures. In analysis of the resulting data it may be necessary to partition the data into weight groups, and this would reduce the precision.

TABLE 1
Measurable Factors and Their Relationship to Safety

Item	Effect on Probability of Accident
Brake adjustment distribution changes (e.g., lower average stroke of actuator)	Less likelihood of brake fade caused by expanding drums, shorter stopping distance.
Truck goes down hills faster (shorter trip time, different trip profile)	Probably less heating of brakes, better stopping performance, better economy.
Reduced brake wear (per unit time)	Better stopping performance on the average. Lower operating costs (fewer relinings).
Lower average brake temperature, and perhaps lower peak temperatures	Better stopping performance, less fade, ability to negotiate longer descents.
Different brake proportioning when retarder is employed.	Changes braking characteristics, interacts with controllability of vehicle.
Different fuel consumption because of higher downhill speeds.	??
Different tire wear on axle with retarder.	May change braking, handling.
Different drive train wear--e.g., wear on backside of transmission gears.	Increased maintenance, potential for breakdown on the road.
Driver learning curve when first using retarders.	??
Frequency of making panic stops. Lower frequency of locked wheel stops.	Performance in panic stop (more controllable).
Cooling system changes, less cooling on downhill run.	??

In order to keep the unwanted variation to a minimum it may be best to concentrate on some particular style of truck--e.g., 18-wheelers, and perhaps with a limited selection of trailer types. Within the given constraints the selection should be random. The selection process probably could not identify retarder-equipped trucks in advance, so the proportion of those sampled would be determined by the proportion in the total population.

Expected Instrumentation and Personnel

Required instrumentation includes:

(1) Scales to measure weight

(2) Rulers or calipers to measure pushrod travel

(3) Thermometers to measure drum temperature

(4) Data recording forms

(5) Speed measurement devices

(6) Cameras

(7) Signs, barriers, etc. at inspection site

Manpower requirements include police assistance to weigh and direct trucks into the inspection area, persons to measure brake drum temperature and pushrod travel, and an interviewer.

Data Analysis

The analysis of data in the earlier study suggests that driver will actually choose to operate on some middle ground, taking advantage of the speed-increasing capabilities provided by the retarders but also making fewer demands on the foundation brakes. Some variation with different drivers may be expected, since it is clear from the Colorado data that the presence of retarders does not prevent all runaways.

The purpose of the experiment described here is to (1) obtain information which will tell how drivers actually trade off the three related factors in a typical downhill environment, and (2) provide insight as to what characteristics of retarders or what education/ training of drivers might lead to an optimal tradeoff of these factors.

Primary and secondary analysis activities are discussed below. Primary question to be addressed include:

(1) Is there a difference in brake adjustment between retarder-equipped and non-retarder-equipped trucks.

(2) Is there a difference in downhill travel speed (or time of travel) between the two types of trucks?

(3) Is there a difference in the brake drum temperature distribution between the two types of trucks?

Secondary questions of interest include:

(1) How is brake adjustment distributed across the various wheels on tractor trailers?

(2) How is brake temperature distributed across the various wheels?

(3) Is brake condition strongly related to some other factor, such as carrier type, product carried, fleet size, etc? Is this relationship so strong as to mask the effect of retarders?

(4) What is the distribution of different kinds of retarders (and does this relate to the primary variables)?

(5) Is there a relationship between driver experience, driver age, carrier type, cargo, other factors, and the trip speed profile?

Summary

Briefly, the intent of the whole experiment is to acquire some hard data on vehicle condition and travel practice for trucks with and without retarders in order to be able to estimate the likely safety improvements which will result from retarder installation and use. The real safety improvements, in terms of fewer runaway events or accidents, will not be measured directly, but will be estimated on the basis of measured changes in brake condition and a knowledge of braking capabilities as a function of that condition. Informal observation of how drivers actually make use of retarders may be expected to provide insight into both the training and legislative requirements related to retarders.

APPENDIX B

Data Collection Forms

Separate field data collection forms were provided for (1) the recording of interview and truck descriptive information, (2) the recording of temperature and tire information, and (3) the recording of brake information (type, size, pushrod travel, etc.). Copies of the forms are reproduced in this appendix.

Case No. ____________

Date ___/___/___

Time___/___/___/___

Company ______________________________ Velocity ________

Make ________________ Model ____________ Model Year ______

Carrier Type:
☐ Private
☐ Common
☐ Contract
☐ Exempt
☐ Intrastate
☐ Other ____________

Configuration:

☐ Straight Truck
☐ Straight Truck + Trailer
☐ Tractor + Trailer

Trip Length:

☐ Local
☐ Less than 200 miles
☐ More than 200 miles

Cabstyle:

☐ COE
☐ Short Conventional
☐ Medium Conventional
☐ Long Conventional
☐ Other ____________

Cargo Body Style:

☐ Van
☐ Tank
☐ Flatbed
☐ Other ____________

Number of Axles: ____________ ____________
Truck/Tractor Trailer

Aerodynamic Flair: ☐ Yes ☐ No

Retarder: None ☐
Type: Eng., Dr. Line, Exhaust ____________________
(Jac., Caterpiller [Brake Saver], Mack [Dynatard], Williams, Detroit Diesel [Allison Div.], Telma)

Engine: Make________________ Model ____________

HP Rating ______hp ______rpm

Transmission: Make________________ Model ____________

No. Axles ________ Rear Axle Ratio __________

Form 1

Rated GVW: ______________ Scale Weight______________

Cargo Description ____

Total Truck Driving Experience_______

Mountain Driving Experience:

[ ] None

[ ] Less than 1 Year

_________ Years

Over this route __________ Times

Total Brake Loss or Runaway on a Hill ______________________________

REMARKS: ____
(Weather, Traffic, etc.)

____

____

____

____

Form 1 (Cont.)

Case No.____________

Date ____/____/____

Time____/____/____/____

PUSH ROD TRAVEL MEASUREMENTS

(X out missing wheels, pencil in extra wheels.)

(1) ________ Chamber Size: 9 12 16 20 24 ________

0 (2) ________ Slack Adjust.: [ ] Auto [ ] Man ________ 0

(3) ________ Brand__________ ________

(1) ________ ________

0 0 (2) ________ Chamber Size: 24 30 ________ 0 0

(3) ________ ________

(1) ________ Slack Adjust.: [ ] Auto [ ] Man Brand__________ ________

0 0 (2) ________ ________ 0 0

(3) ________ ________

(1) ________ ________

0 0 (2) ________ Chamber Size: 24 30 ________ 0 0

(3) ________ ________

(1) ________ Slack Adjust.: [ ] Auto [ ] Man Brand__________ ________

0 0 (2) ________ ________ 0 0

(3) ________ ________

VEHICLE CHOCKED
ALL PARKING BRAKES RELEASED
APPLIED MEASUREMENTS AT 100 PSI

Form 2

Case No. ____________

Date ____/____/____

Time ____/____/____/____

TEMPERATURE MEASUREMENTS
(X out missing wheels, pencil in extra wheels.)

Temp. Meas. Sequence						Temp. Meas. Sequence
[ ]	0	Temp.	________	________	0	[ ]
		Wt.	________	________		
[ ]	0 0	Temp.	________	________	0 0	[ ]
		Wt.	________	________		
[ ]	0 0	Temp.	________	________	0 0	[ ]
		Wt.	________	________		
[ ]	0 0	Temp.	________	________	0 0	[ ]
		Wt.	________	________		
[ ]	0 0	Temp.	________	________	0 0	[ ]
		Wt.	________	________		

REMARKS: ____

____

Form 3

Case No.__________

Date ___/___/___

Time___/___/___/___

TIRE INFORMATION

(X out missing wheels, pencil in extra wheels.)

	[ ] Rib	[ ] Lug	[ ] Rib	[ ] Lug	
0	[ ] Bias	[ ] Radial	[ ] Bias	[ ] Radial	0
	Size__________		Size__________		
	[ ] Rib	[ ] Lug	[ ] Rib	[ ] Lug	
0 0	[ ] Bias	[ ] Radial	[ ] Bias	[ ] Radial	0 0
	Size__________		Size__________		
	[ ] Rib	[ ] Lug	[ ] Rib	[ ] Lug	
0 0	[ ] Bias	[ ] Radial	[ ] Bias	[ ] Radial	0 0
	Size__________		Size__________		
	[ ] Rib	[ ] Lug	[ ] Rib	[ ] Lug	
0 0	[ ] Bias	[ ] Radial	[ ] Bias	[ ] Radial	0 0
	Size__________		Size__________		
	[ ] Rib	[ ] Lug	[ ] Rib	[ ] Lug	
0 0	[ ] Bias	[ ] Radial	[ ] Bias	[ ] Radial	0 0
	Size__________		Size__________		

REMARKS: ____________________

____

Form 3 (Cont.)

APPENDIX C

Participants

Participants in the field effort included a large contingent from the Maryland State Police, a representative of the Maryland Department of Transportation, persons from several agencies of the Federal Department of Transportation, and those from the University of Michigan. They are listed in this appendix according to their organizational affiliations.

Maryland State Police

M. J. Zepp, Captain, Commander of Traffic Enforcement Division

B. Diehl, Captain, Automotive Safety Enforcement Division

Wm. Holley, Lieutenant, Weight Enforcement Division

K. Harry, Sargeant, Weight Enforcement

D. Goglio, Corporal, Supervisor, Weight Enforcement

R. Sivic, Trooper First Class, Head of Weigh Team, Western Roving 4

D. Buckalew, Trooper First Class, Cumberland Barracks

M. Rote, Trooper First Class, Head of Weigh Team, Western Roving 2

J. Buell, Cadet

T. Miller, Cadet

M. Bowen, Cadet

Federal Highway Administration
Bureau of Motor Carrier Safety

R. Ketenheim II, Agent-in-Charge (Baltimore)

J. Heinemann, Highway Safety Management Specialist

S. Spalla, Highway Safety Management Specialist

National Highway Traffic Safety Administration
Vehicle Research Test Center

R. Testerman, Mechanical Engineering Technician, Transportation Research Center (Ohio)

W. Meddles, Instrumentation Technician

Maryland Department of Transportation

G. Small, Regional Traffic Engineer

University of Michigan
Highway Safety Research Institute

James O'Day, Research Scientist

Paul Fancher, Research Scientist

Leslie Pettis, Research Assistant

Leda Ricci, Research Assistant

Don Foster, Senior Engineering Technician

Temperature measurements and driver interviews were done by the staff of The University of Michigan. Generally a two-person team worked together, one taking the reading from the probe and the second recording the data. Interviews were done at the same time by a third person.

Brake pushrod measurements were made by any of several persons. Captain Diehl of the Maryland State Police, Reeve Testerman of the NHTSA Ohio Test Center, and Robert Ketenheim of the Bureau of Motor Carrier Safety inspection team shared this duty assisted as necessary by their support staffs.

Finally, the Bureau of Motor Carrier Safety inspection officers under the direction of Mr. Ketenheim performed a more complete inspection of many of the vehicles, and, on occasion, placed vehicles out-of-service for failure to pass the inspection.

All participants in the effort worked to give priority to the temperature measurements, and this contributed much to the success of the venture. Because of the sequence of events and the intermittent arrival time of trucks into the sites there was some unavoidable queueing so that there was usually some cooling of the brake components before the temperature measurement was made. There was no individual determination made of the delay time, but a general adjustment of temperatures based on an average delay is made in the analysis. For future expeditions of this sort, it would be appropriate either to measure this time, or to minimize it by rearranging the inspection sequence, or both.

The most time-consuming measurement was that of determining the pushrod travel. This process involved someone crawling under the truck (without a dolly, since clearances were tight), marking the pushrods with zero air pressure at eight or ten wheels, repeating the process at 100 psi applied pressure with a ruler, and recording the readings. Some brakes were difficult to reach--particularly those on the front drive axle. There were occasions when the trucks could not be held long enough to get these measurements, and the proportion of vehicles with valid pushrod travel information constitutes about 70% of the total. Again, in a future operation of this sort, it would be worth the time and trouble to develop a more automated technique for this process.

APPENDIX D

Dictionary of Variables in Maryland 5-Axle File

Variable 1-25 derived from the interview form shown in Appendix B.

VARIABLE	N	MINIMUM	MAXIMUM	MEAN	STD DEV
1.CASE	101	1.0000	116.00	59.356	34.998
2.DATE	101	1.0000	4.0000	2.1386	.89476
3.MAKE	101	2.0000	89.000	75.257	28.373
4.MODYR	94	67.000	81.000	77.532	3.1545
5.CARRTYPE	99	1.0000	3.0000	1.9798	.79514
6.CONFIG	101	3.0000	3.0000	3.0000	
7.TRIPLN	98	1.0000	3.0000	2.6939	.56364
8.CABSTYLE	99	1.0000	4.0000	1.6566	.88250
9.CBDYSTYL	99	1.0000	4.0000	2.1414	1.2290
10.TRKAXLE	101	3.0000	3.0000	3.0000	
11.TRLRAXLE	101	2.0000	2.0000	2.0000	
12.FLAIR	100	1.0000	2.0000	1.7600	.42923
13.RETARDER	99	1.0000	4.0000	1.4040	.72730
14.ENGMAKE	98	1.0000	6.0000	3.6939	1.2633
15.ENGHP	95	230.00	549.00	336.25	57.532
16.TRNSMAKE	96	1.0000	6.0000	3.3021	.90751
17.TRNSPD	84	4.0000	15.000	9.7619	3.1302
18.AXRATO	40	270.00	463.00	404.20	36.545
19.WEIGHT	95	16000.	90000.	60330.	18838.
20.CARGO	99	1.0000	16.000	8.6465	5.0595
21.EXPNCE	74	2.0000	20.000	10.135	5.3053
22.MTNEXP	98	2.0000	4.0000	3.4184	.57299
23.ROUTE	97	1.0000	4.0000	3.1031	1.1132

24.RUNWAY	97	1.0000	2.0000	1.8351	.37306
25.REMRKS	97	1.0000	2.0000	1.8454	.36344

Variables 101-131 derived from the second form of Appendix B and provide the brake make, type, and adjustment information for each of up to 16 wheels.

101.CASE	101	1.0000	116.00	59.356	34.998
102.DATE	100	1.0000	4.0000	2.1300	.89505
103.CHAMBER	42	2.0000	4.0000	3.5714	.70340
104.SLACK	26	1.0000	2.0000	1.9615	.19612
105.BRAND	38	1.0000	6.0000	3.3947	1.9665
106.WHEEL1	65	6.0000	888.00	352.11	306.17
107.WHEEL2	64	25.000	888.00	354.47	306.04
108.CHAMBER2	53	1.0000	2.0000	1.8302	.37906
109.SLACK2	35	1.0000	2.0000	1.8857	.32280
110.BRAND2	39	1.0000	5.0000	2.3846	1.4976
111.WHEEL3	67	75.000	888.00	221.16	221.74
112.WHEEL4	67	37.000	888.00	221.25	227.55
113.WHEEL5	67	56.000	888.00	220.90	221.49
114.WHEEL6	68	50.000	888.00	231.69	226.98
115.CHAMBER3	57	1.0000	2.0000	1.9825	.13245
116.SLACK3	37	1.0000	2.0000	1.8649	.34658
117.BRAND3	51	1.0000	7.0000	2.2549	1.6952
118.WHEEL7	68	50.000	555.00	189.79	93.468
119.WHEEL8	68	31.000	555.00	174.75	84.057
120.WHEEL9	68	62.000	555.00	183.72	81.117
121.WHEEL10	68	75.000	555.00	189.06	83.543
122.CHAMBER4	4	1.0000	2.0000	1.2500	.50000
123.SLACK4	2	1.0000	2.0000	1.5000	.70711

124.BRAND4	67	5.0000	7.0000	6.9104	.41675
125.WHEEL11	69	137.00	777.00	733.81	155.82
126.WHEEL12	69	144.00	777.00	767.83	76.204
127.WHEEL13	69	125.00	777.00	767.55	78.492
128.WHEEL14	69	112.00	777.00	767.36	80.057
129.WHEEL15	69	125.00	777.00	767.55	78.492
130.WHEEL16	69	100.00	777.00	767.19	81.501
131.REMARKS	70	1.0000	2.0000	1.6714	.47309

Variables 201-251 derived from the third form of Appendix B and provide details on tire tread, carcass (radial or bias), and size for each wheel.

201.CASE	101	1.0000	116.00	59.356	34.998
202.DATE	101	1.0000	4.0000	2.1287	.90181
203.TREAD	99	1.0000	2.0000	1.1313	.33946
204.CARCASS	100	1.0000	2.0000	1.5000	.50252
205.SIZE	100	7.0000	24.000	14.880	6.4890
206.TREAD2	99	1.0000	2.0000	1.1313	.33946
207.CARCASS2	100	1.0000	2.0000	1.4900	.50242
208.SIZE2	100	7.0000	24.000	14.990	6.4986
209.TREAD3	101	1.0000	3.0000	1.7129	.47616
210.CARCASS3	101	1.0000	2.0000	1.5248	.50188
211.SIZE3	101	2.0000	24.000	14.772	6.3967
212.TREAD4	101	1.0000	2.0000	1.7327	.44477
213.CARCASS4	101	1.0000	2.0000	1.5149	.50227
214.SIZE4	101	2.0000	24.000	14.802	6.4312
215.TREAD5	101	1.0000	3.0000	1.7327	.48767
216.CARCASS5	101	1.0000	2.0000	1.5644	.49831
217.SIZE5	101	7.0000	24.000	14.861	6.3072

```
218.TREAD6      101   1.0000   2.0000   1.6931   .46352
219.CARCASS6    101   1.0000   2.0000   1.5446   .50049
220.SIZE6       101   7.0000   24.000   14.891   6.3291
221.TREAD7      101   1.0000   3.0000   1.2970   .55758
222.CARCASS7    101   1.0000   2.0000   1.2277   .42145
223.SIZE7       101   2.0000   22.000   11.455   6.2857
224.TREAD8      101   1.0000   3.0000   1.2277   .46650
225.CARCASS8    101   1.0000   2.0000   1.2376   .42775
226.SIZE8       101   2.0000   22.000   11.554   6.2777
227.TREAD9      101   1.0000   3.0000   1.1386   .37496
228.CARCASS9    101   1.0000   2.0000   1.2376   .42775
229.SIZE9       101   2.0000   22.000   11.188   6.0790
230.TREAD10     101   1.0000   3.0000   1.2079   .47575
231.CARCAS10    101   1.0000   2.0000   1.2376   .42775
232.SIZE10      101   2.0000   22.000   11.089   6.0483
233.TREAD11       4   1.0000   1.0000   1.0000
234.CARCAS11      4   1.0000   2.0000   1.5000   .57735
235.SIZE11        4   6.0000   11.000   8.2500   2.2174
236.TREAD12       3   1.0000   1.0000   1.0000
237.CARCAS12      3   1.0000   2.0000   1.6667   .57735
238.SIZE12        3   6.0000   11.000   8.0000   2.6458
239.TREAD13       1   1.0000   1.0000   1.0000
240.CARCAS13      1   2.0000   2.0000   2.0000
241.SIZE13        1   11.000   11.000   11.000
242.TREAD14       1   1.0000   1.0000   1.0000
243.CARCAS14      1   2.0000   2.0000   2.0000
244.SIZE14        1   11.000   11.000   11.000
```

245.TREAD15	1	1.0000	1.0000	1.0000
246.CARCAS15	1	2.0000	2.0000	2.0000
247.SIZE15	1	11.000	11.000	11.000
248.TREAD16	1	1.0000	1.0000	1.0000
249.CARCAS16	1	2.0000	2.0000	2.0000
250.SIZE16	1	11.000	11.000	11.000
251.REMARKS	101	2.0000	2.0000	2.0000

Variables 301-319 provide the measured temperature for each of up to 16 wheels.

301.CASE	101	1.0000	116.00	59.356	34.998
302.DATE	101	1.0000	4.0000	2.1287	.90181
303.TEMP1	77	3.0000	888.00	36.403	101.83
304.TEMP2	77	2.0000	888.00	36.519	101.77
305.TEMP3	99	4.0000	666.00	85.889	118.10
306.TEMP4	99	1.0000	666.00	78.980	86.257
307.TEMP5	101	4.0000	666.00	83.554	115.56
308.TEMP6	101	4.0000	666.00	79.772	82.297
309.TEMP7	101	4.0000	666.00	78.386	80.934
310.TEMP8	101	5.0000	666.00	88.337	100.10
311.TEMP9	101	5.0000	666.00	98.178	120.57
312.TEMP10	101	6.0000	666.00	93.238	116.58
313.TEMP11	101	26.000	777.00	749.74	135.51
314.TEMP12	101	25.000	777.00	749.66	135.83
315.TEMP13	101	163.00	777.00	770.92	61.095
316.TEMP14	101	153.00	777.00	770.82	62.090
317.TEMP15	101	155.00	777.00	770.84	61.891
318.TEMP16	101	159.00	777.00	770.88	61.493

319.REMARKS	101	1.0000	2.0000	1.9901	.99504 -1
1001.BIN.111	61	1.0000	2.0000	1.1967	.40082
1002.BIN.112	61	1.0000	2.0000	1.2131	.41291
1003.BIN.113	61	1.0000	2.0000	1.2295	.42401
1004.BIN.114	62	1.0000	2.0000	1.2581	.44114
1005.BIN.118	68	1.0000	2.0000	1.3088	.46544
1006.BIN.119	68	1.0000	2.0000	1.2941	.45903
1007.BIN.120	68	1.0000	2.0000	1.3824	.48958
1008.BIN.121	68	1.0000	2.0000	1.4412	.50022
3000.VALID	68	6.0000	8.0000	7.9559	.26954

Variable 3001 presents the number of wheels with pushrod travel greater than two inches.

3001.OVER200	46	1.0000	8.0000	3.3043	1.7872
4001.FAXTEMP	76	6.0000	1776.0	73.697	204.62
4002.DAXTEMP	99	18.000	2664.0	329.76	344.09
4003.TAXTEMP	101	22.000	2664.0	358.14	342.78

Variable 4004 is the average front (steering) axle drum temperature.

4004.FAXAVTEM	75	3.0000	126.00	25.240	26.208

Variable 4005 is the average tractor drive axle drum temperature.

4005.DAXAVTEM	99	4.5000	666.00	82.439	86.023

Variable 4006 is the average trailer axle drum temperature.

4006.TAXAVTEM	101	5.5000	666.00	89.535	85.695

Variables 5001-5010 are the temperatures for ten wheels computed from the energy model.

5001.V5001	51	1.0000	159.00	20.353	25.981
5002.V5002	51	1.0000	159.00	20.353	25.981
5003.V5003	51	10.000	272.00	85.529	62.873
5004.V5004	51	10.000	272.00	86.725	60.624

```
5005.V5005         51   10.000     269.00     88.255     61.793

5006.V5006         51   10.000     272.00     85.118     60.950

5007.V5007         51   8.0000     216.00     91.627     61.134

5008.V5008         51   8.0000     252.00     95.490     66.290

5009.V5009         51   8.0000     364.00     90.510     71.316

5010.V5010         51   8.0000     364.00     90.471     73.214

6001.DIFTEM1       36  -130.00     817.00     24.583     140.68

6002.DIFTEM2       35  -131.00     817.00     26.686     142.94

6003.DIFTEM3       49  -255.00     594.00    -20.633     119.03

6004.DIFTEM4       49  -228.00     594.00    -16.184     117.09

6005.DIFTEM5       51  -234.00     594.00    -20.608     118.53

6006.DIFTEM6       51  -252.00     594.00    -15.137     118.14

6007.DIFTEM7       51  -200.00     521.00    -10.745     115.11

6008.DIFTEM8       51  -238.00     521.00    -17.275     116.58

6009.DIFTEM9       51  -331.00     526.00    -.50980     139.43

6010.DIFTEM10      51  -336.00     526.00    -16.725     120.08
```

APPENDIX E

Descriptive Statistics of the Trucks Observed

The population of trucks which were expected to be weighed and otherwise observed were all heavy trucks (generally with a gross vehicle weight of 26,000 lbs. or more) traveling on the roads under study during the test hours of observation. Since a major purpose of the experiment was to observe brake temperature and condition differences among trucks with and without retarders, there was no specific emphasis on sampling to represent the true population of trucks on the road. However, since truck traffic was relatively light on these roads, essentially all large trucks in the traffic stream did pass over the scales, and most of these were further observed with regard to braking system components.

During the four days of operation data were recorded for 117 trucks, and since these constitute about 90% of the trucks passing some statistics will be presented regarding the characteristics of large trucks on this route. Whether these same statistics would result without the presence of the police weigh team is uncertain. On the first day a number of coal trucks evidently delayed coming through the check area until it was evident that the weighing operation was closing--suggesting that the proportion of very heavy trucks might have been less than on a normal day. It was further understood that knowledge of the weighing operation was available 100 miles or more to the west of Cumberland, so that some trucks may have diverted at that point to a different route. In the light of this discussion, the reader will have to judge how well the observed vehicles represent the usual population of trucks in this area. With these cautions some statistics of the observed population are presented.

Cross-tabulation of truck make and model year is shown in Table 1. Seven vehicles with missing model year or make data have been deleted from this table. It can be seen that the most common truck make was Mack with nearly one-quarter of the total, followed by International Harvester, White, and Ford. The largest group for a single production year are from 1979.

Table 1

Trucks Observed in Maryland, 1981
Make by Model Year*

Model Year	Ford	Brock way	Reo	Freight liner	GMC	IH	Ken worth	Mack	Peter bilt	White	Other	Total
1973 and earlier	0	0	1	0	2	3	3	1	0	3	0	13
1974	0	0	0	0	0	2	1	0	1	3	0	7
1975	1	0	0	0	1	1	0	1	0	1	1	6
1976	1	1	0	0	0	0	1	0	0	3	0	6
1977	2	0	0	0	1	1	0	2	0	2	0	8
1978	2	0	0	2	2	2	1	5	2	2	0	18
1979	5	0	0	2	3	5	1	4	2	2	0	24
1980	2	0	0	3	2	0	3	4	1	0	0	15
1981	1	0	0	1	1	3	0	7	0	0	0	13
TOTAL	14	1	1	8	12	17	10	24	6	16	1	110

*Seven trucks with missing data excluded.

Table 2 shows the relationship between the type (make) of retarder and carrier type. About one-third of the private carriers were equipped with some kind of retarder, but a substantially smaller proportion (22%) of common and contract (interstate) carriers were so equipped.

Table 2

Type of Carrier and Type of Retarder
Trucks observed in Maryland, 1981

Carrier Type	Retarder Type					Total	Percent with Retarder
	Missing Data	None	Jake Brake	Cater-pillar	Mack Dynatard		
Private	0	24	14	1	2	41	41
Common	1	31	5	0	2	39	18
Contract	1	23	7	2	0	33	28
Intrastate	0	0	1	0	0	1	100
Other	0	2	1	0	0	3	33
Total	2	80	28	3	4	117	30

Table 3 shows the relationship between truck configuration and retarder type. Although the number of straight trucks was quite small, they were more likely to have retarders than the combination vehicles in the observed group.

Table 4 indicates that retarders were more likely to be present on vehicles with a triplength under 200 miles. The area in Maryland in which these observations were made is coal country, and, while the specific cargo was not recorded, it was observed that a number of these vehicles were carrying coal on short trips.

Table 5 indicates that medium and long nose/hood conventional trucks and tractors were more likely to be retarder-equipped than were

Table 3

Truck Configuration and Type of Retarder Trucks Observed in Maryland, 1981

Configuration	Retarder Type					Total	Percent with Retarder
	Missing Data	None	Jake Brake	Cater-pillar	Mack Dynatard		
Straight Truck	0	3	3	0	0	6	50
Truck Trailer	0	0	1	0	0	1	100
Tractor Trailer	2	77	24	3	4	110	29
Total	2	80	28	3	4	117	30

Table 4

Triplength and Type of Retarder Trucks observed in Maryland, 1981

Triplength	Retarder Type					Total	Percent with Retarder
	Missing Data	None	Jake Brake	Cater-pillar	Mack Dynatard		
Local	0	5	3	1	0	9	44
Less than 200 miles	0	14	11	1	2	28	50
More than 200 miles	1	61	12	1	2	77	20
Missing Data	1	0	2	0	0	3	-
Total	2	80	28	3	4	117	30

the cabovers or short conventionals. More than half of the former were so equipped.

Table 5

Cabstyle and Type of Retarder
Trucks observed in Maryland, 1981

Cab Type	Retarder Type					Total	Percent with Retarder
	Missing Data	None	Jake Brake	Caterpillar	Mack Dynatard		
Cabover	1	50	13	2	0	66	23
Short Conventional	0	20	5	0	1	26	23
Medium Conventional	0	8	9	0	3	20	60
Long Conventional	0	1	1	1	0	3	66
Missing Data	1	1	0	0	0	2	-
Total	2	80	28	3	4	117	30

Table 6 relates cargo body style and retarders, and indicates that flatbeds and "other" (many of which were dump or open-top coal trucks) were more likely to have retarders.

Table 7 indicates that retarders were most common for "solids in bulk" cargoes, but also common for heavy machinery and metal products. They were generally not present for lighter-weight cargoes--household goods, general freight, etc.

Drawing general inferences from the tables presented in this appendix should be done with great caution, of course. While data were obtained for a large proportion of the trucks using these roads during the experimental period, the population observed is not likely to

Table 6

Cargo Body Style and Type of Retarder
Trucks observed in Maryland, 1981

Cargo Body Type	Retarder Type					Total	Percent with Retarder
	Missing Data	None	Jake Brake	Caterpillar	Mack Dynatard		
Van	0	48	5	2	0	55	13
Tank	0	8	1	0	1	10	20
Flatbed	0	13	9	0	1	23	43
Other	1	11	12	1	2	27	58
Missing Data	1	0	1	0	0	2	-
Total	2	80	28	3	4	117	30

represent other regions of the country, and perhaps not even this region on other days. Tables 1 through 7, then, provide some descriptive statistics for the population observed, and little more.

Table 7

Cargo Type and Type of Retarder
Trucks observed in Maryland, 1981

Cargo	Retarder Type					Total	Percent with Retarder
	Missing Data	None	Jake Brake	Caterpillar	Mack Dynatard		
General Freight	0	10	0	0	0	10	0
Household Goods	0	4	0	0	0	4	0
Metal Products	0	7	4	0	0	11	36
Machinery	1	6	4	0	1	12	45
Gases in Bulk	0	1	0	0	1	2	50
Solids in Bulk	0	5	13	1	1	20	75
Liquids in Bulk	0	6	2	0	0	8	25
Explosives	0	1	0	0	0	1	0
Logs	0	4	2	0	0	6	33
Empty	0	14	2	0	1	17	18
Refrigerated Food	0	3	0	0	0	3	0
Other	0	19	0	2	0	21	10
Missing Data	1	0	1	0	0	2	-
Total	2	80	28	3	4	117	30

APPENDIX F

A MODEL FOR ESTIMATING TEMPERATURES AT EACH BRAKE

The purpose of this model is to provide an analytical means for estimating the reasonableness of the temperature measurements and the extent to which individual temperature variations between brakes can be accounted for by differences in stroke. In the model, the power absorbed by each brake is calculated first. Then the temperature of the brake is computed. These calculations are made for each of the three survey sites.

The following equation is used to estimate the natural retardation, HP_N, of each vehicle:

$$HP_N = 48 + 0.00144(GVW) + 0.2(HP_E)$$

where

GVW is the gross vehicle weight

HP_E is the rated horsepower of the engine

The vehicles were all traveling at approximately 45 mph. The aerodynamic drag was set at 48 hp as a first approximation for all the vehicles.

For the three survey sites, their average slopes were used to express the horsepower requirement of each hill, HP_K, at 45 mph for each vehicle; viz., the HP_K's for K = 1,2,3 are evaluated as follows:

$$HP_1 = (0.0054)(GVW) \qquad \text{(first site)}$$

$$HP_2 = (0.00768)(GVW) \qquad \text{(second site)}$$

$$HP_3 = (0.00444)(GVW) \qquad \text{(third site)}$$

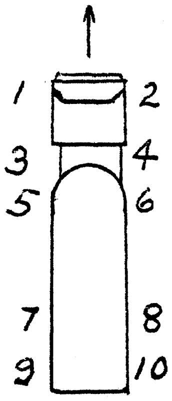
If the vehicle has a retarder, 150 hp is subtracted from the net horsepower absorbed by the brakes. The horsepower absorbed by the brakes, HP_{BK} (where K indexes the survey sites), is given by

$$HP_{BK} = HP_K - HP_N - HP_R$$

where

$$HP_R = \begin{cases} 150 \text{ hp with retarder} \\ 0 \text{ hp no retarder} \end{cases}$$

The horsepower absorbed by all the brakes is distributed amongst the individual brakes using the following equations and logical decisions. These expressions take into account the stroke of each brake and the proportioning of the braking system. The subscript i indicates the individual brakes using the following numbering system:



A factor, S_i, is used to indicate the state of brake adjustment. If the vehicle has front brakes, $S_1 = S_2 = 1.0$. If the vehicle has no front brakes, $S_1 = S_2 = 0.0$. For $i \geqq 3$, the stroke measurement in inches, I_i, is used to determine S_i. Specifically,

$$S_i = 1.0 \quad \text{for} \quad I_i \leqq 1.5$$

$$S_i = -0.26 + 1.68I_i - 0.56I_i^2 \quad \text{for} \quad I_i > 1.5$$

Since the proportioning of the braking system is not known, the estimation of individual brake temperatures requires some scheme for estimating the quantities P_f, P_D, and P_T corresponding to the percentages of the braking effort taking place at the tractor's front axle, the drive axles, and the trailer axles, respectively. The scheme used here for estimating proportioning is based on the temperatures measured. That is, for vehicles with no front brakes

$$P_f = 0 , \quad P_D = \frac{\Sigma T_D - 40}{\Sigma T - 80} ,$$

and $P_T = \dfrac{\Sigma T_T - 40}{\Sigma T - 80}$

where ΣT_D is the sum of the drive axle temperatures

ΣT_T is the sum of the trailer axle temperatures

and $\Sigma T = \Sigma T_D + \Sigma T_T$

The constant factors correspond to an ambient temperature of 10°C at each brake. If the vehicle has front brakes,

$$P_f = \frac{\Sigma T_f - 20}{\Sigma T - 100}$$

$$P_D = \frac{\Sigma T_D - 40}{\Sigma T - 100}$$

$$P_T = \frac{\Sigma T_T - 40}{\Sigma T - 100}$$

The gain of each brake, G_i, is determined by combining the stroke and proportioning factors as follows:

$$G_1 = P_f S_1/2$$

$$G_2 = P_f S_2/2$$

$$G_3 = P_D S_3/4$$

$$G_4 = P_D S_4/4$$

$$G_5 = P_D S_5/4$$

$$G_6 = P_D S_6/4$$

$$G_7 = P_D S_7/4$$

$$G_8 = P_D S_8/4$$

$$G_9 = P_D S_9/4$$

$$G_{10} = P_D S_{10}/4$$

The quantity $G_T = \sum_{i=1}^{10} G_i$ is used in computing the fraction, F_i, of the total power assigned to each brake, i.e., $F_i = G_i/G_T$, and, for the K^{th} site

$$HP_{iK} = HP_{BK} F_i$$

where HP_{ik} is the power absorbed by the i^{th} brake while the vehicle is operating on the K^{th} grade (site).

The temperature at each brake is then computed from the HP_{iK} using the brake temperature model developed in [7]. Specifically, for $i = 3$ to 10 on grades 1, 2, or 3, the temperatures, T_{iK}, are evaluated as follows:

Grades, K	Temperatures, T_{iK}
1	$T_{i1} = HP_{i1}(5.0) + 10$ °C
2	$T_{i2} = HP_{i2}(4.0) + 10$ °C
3	$T_{i3} = HP_{i3}(11.0) + 10$ °C

The different equations for the three sites reflect differences in the lengths of the hills at the three sites.