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Registration No.

24377



MOUNTAIN BRAKING TEST VENUE STUDY

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12-12-2013

U.S. Army Tank Automotive Research,
Development, and Engineering Center
Detroit Arsenal
Warren, Michigan 48397-5000

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 12-12-2013		2. REPORT TYPE Technical		3. DATES COVERED (From - To) 8-08-2013 to 11-05-2013	
4. TITLE AND SUBTITLE Mountain Braking Test Venue Study				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Norman, Kenneth D; Army TARDEC; 6501 E. 11 Mile Rd; MS 157; Warren, MI 48397 Lynett, Jeffrey W, PD-LTV Engineering; 6501 E. 11 Mile Rd; MS 245; Warren, MI 48397 Singh, Amandeep; US Army TARDEC; 6501 E. 11 Mile Rd; MS 157; Warren, MI 48397 Clark, Timothy, Alion Science and Technology, 31201 Chicago Rd, Warren, MI 48093 Mulder, Douglas A; US Army TARDEC; 6501 E. 11 Mile Rd; MS 268; Warren, MI 48397				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army TARDEC Analytics 6501 E. 11 Mile Rd Bldg 215, MS 157 Warren, Michigan 48397-5000				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) PD-LTV Engineering 6501 E. 11 Mile Rd BLDG 200, MS 245 Warren, Michigan 48397-5000				10. SPONSOR/MONITOR'S ACRONYM(S) SFAE - CSS - JL - LT	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT PD-LTV Engineering requested assistance with research that would enable the writing of an ATPD documenting a procedure for evaluating the brake system performance in a realistic mountain driving environment. A literature search was undertaken to identify test procedures and test sites that were utilized by automobile manufacturers, NATC, ATC, and the University of Michigan Transportation Research Institute (UMTRI). Potential mountain road test venues documented by R&R Publishing were examined for severity by estimating the brake temperatures resulting from the length and grade of the road, and the speed limit using a fundamental analysis documented by UMTRI. The severity of these roads was compared to the estimated temperature from executing the MRAP FoV CPD requirement to descend a 10 mile long 6% grade at 45 mi/h and to existing known Government and automotive industry test standards. Several candidate mountain roads for evaluation were recommended based upon estimated brake temperature and safety considerations. Guidelines for the evaluation of the test venues were also proposed. In addition, several automotive standards and Government test procedures were simulated and their brake temperature severity compared.					
15. SUBJECT TERMS Mountain Braking; Test Development; Simulation; Medium Truck; Heavy Truck; Heavy Vehicle; Brake Fade					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Unclassified Unlimited	18. NUMBER OF PAGES 32	19a. NAME OF RESPONSIBLE PERSON Kenneth D. Norman
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED			19b. TELEPHONE NUMBER 586-282-5157

Abstract

Product Director, Light Tactical Vehicles Engineering requested assistance with research that would enable the writing of an Army Tank Purchase Description documenting a procedure for evaluating the brake system performance in a realistic mountain driving environment. Ultimately a new lab test procedure that accurately simulates severe mountain braking is required. A literature search was undertaken to identify test procedures and test sites that were utilized by automobile manufacturers, Nevada Automotive Test Center, Aberdeen Test Center, and the University of Michigan Transportation Research Institute. Potential mountain road test venues documented by R&R Publishing were examined for severity by estimating the brake temperatures resulting from the length and grade of the road, and the speed limit using a fundamental analysis documented by UMTRI. The severity of these roads was compared to the estimated temperature from executing the Mine Resistant Ambush Protected Family of Vehicle Capabilities Production Document requirement to descend a 10 mile long 6% grade at 45 mi/h and to existing known Government and automotive industry test standards. Several candidate mountain roads for evaluation were recommended based upon estimated brake temperature and safety considerations. Guidelines for the evaluation of the test venues were also proposed. In addition, several automotive standards and Government test procedures were simulated and their brake temperature severity compared.

Contents

1.0 Summary	2
2.0 Introduction	3
3.0 Methods, Assumptions, and Procedures	4
3.1 Mountain Descent Power Balance Equations	4
3.2 Brake Temperature Estimation	6
3.3 Application of Power Balance Equation to Determine Brake Temperature	7
4.0 Results and Discussion	8
4.1 Results Overview	8
4.2 Study Part 1: Brake Temperature Estimates for Common Test Venues	8
4.3 Study Part 2: Mountain Descent Venue Review	9
4.4 Study Part 3: Mountain Braking Test Procedure Temperature Estimates	12
4.5 Study Part 4: Drive Cycle Optimization for Laurel Mountain and Union Pass	22
5.0 Conclusions	28
6.0 Recommendations	28
7.0 References	30
Appendix	32

1.0 Summary

Product Director, Light Tactical Vehicles (PD-LTV) Engineering requires a road test that adequately identifies the brake fade performance of its vehicles. The HMMWV has been uparmored and the additional weight has resulted in performance concerns with the legacy brake system. The existing lab tests that have been utilized, ATPD-2354A [1] and ATPD-2383 [2] were found to not sufficiently identify the limitations of the brake system. A road test measuring mountain braking performance that provides a significant and realistic brake fade challenge needs to be defined. However, the ultimate goal is to develop a lab test that accurately simulates such a mountain braking road test.

In this study, brake temperature estimates were made for several mountain highways and test procedures utilizing a simple analysis described in section 3.0, the Methods, Assumptions, and Procedures Required section of this report. The estimated brake temperatures calculated were based upon a number of assumptions regarding the vehicle and are only used to provide a comparison of the severity of the venues and procedures. Rank ordering of the severity could differ with different values for vehicle characteristics. This study provided estimates of the severity of real world mountain descents for generating high brake temperatures and comparison of those temperatures to those generated by Government and industry braking test procedures.

Brake temperature estimates were made for descending mountain highway grades commonly used for testing by the U.S. Government and the automotive industry. Maximum brake temperature was also estimated for descending a 10 mile long 6% grade at an average speed of 45 mph, the mission after which a Mine Resistant Ambush Protected (MRAP) vehicle is required to safely stop at GVW (threshold)/GVWR (objective). In addition, brake temperature estimates were made for several Government and industry laboratory and road brake test procedures. Two mountain highway venues used by the Government were studied in more detail to determine a braking schedule that maximized brake temperature.

To identify other potential mountain highway locations that were at least as severe as the MRAP requirement, characteristics of highways in the eastern and western U.S. mountain ranges were examined. A list of potential sites based upon grade, length, speed limit, and safety considerations was assembled. Those with sharp turns were singled out in the event that the special condition of brake decelerations being necessary during mountain descent was to be evaluated.

Two roadways in common use for mountain braking testing, Pikes Peak Highway and AZ-260 near Camp Verde, Arizona, have estimated brake temperatures very near that calculated for the MRAP requirement grade. Another venue in use by European high performance brake manufacturers, Grossglockner Mountain in Austria, has an average 12% grade over 9.9 miles. Estimated maximum brake temperature for this road far exceeded any of the other roads or the test procedures evaluated. Pikes Peak Highway, AZ-260, and thirteen other venues listed in section 4.0, the Results and Discussion section of this report, are recommended as having very good potential for evaluation of severe mountain descent brake temperatures.

If a new mountain grade braking test procedure is to be developed to meet the needs of PD-LTV, it is recommended that an Integrated Product Team be assembled to strategize the best method of evaluating and selecting a test venue. This IPT should include representatives from TARDEC Analytics, TARDEC Physical Simulation and Test, Program Executive Office (PEO) Combat Support & Combat Service Support (CS & CSS) to include PD-LTV, and the Army Test and Evaluation Center (ATEC).

2.0 Introduction

Product Director, Light Tactical Vehicles (PD-LTV) Engineering requested assistance with research that would enable the writing of an Army Tank Purchase Description (ATPD) documenting a procedure for evaluating the brake system performance in a mountain driving environment. Existing mountain braking performance assessments ATPD-2354A [1] and ATPD-2383 [2] mimic the Jennerstown Mountain Highway Brake System Test defined in US Army Developmental Test Command (DTC) Test Operations Procedure (TOP) 2-2-608 [3] with a prescribed number of repeated decelerations on a mountain grade. PD-LTV requires a road test that presents realistic severe conditions that is more representative of potential military mission profiles and brake temperatures. PD-LTV is aware of more severe mountain road environments utilized by the Nevada Automotive Test Center (NATC) for their "Mountain Descent Brake Fade Testing". Specifically those courses are referred to by NATC as Spooner, Hawthorne, Bishop Grade, and 88EB.

It is assumed that the severity of the test environment should at least be equivalent to the MRAP Family of Vehicles (FoV) Capability Production Document (CPD) [4] requirement that was developed to meet the needs of the warfighter in Afghanistan. This CPD requirement states that the vehicle should safely stop at GWV (threshold)/GVWR (objective) after descending a 10 mile long, 6% grade at an average speed of 45 mph. Because there are no U.S. Government facilities that have the grade and distance characteristics to evaluate this, it is necessary to investigate the characteristics of public roadways as potential braking performance evaluation sites.

A literature search was undertaken to identify test procedures and test sites that were utilized by automobile manufacturers, Nevada Automotive Test Center (NATC), Aberdeen Test Center (ATC), and the University of Michigan Transportation Research Institute (UMTRI). Potential mountain road test venues documented by R&R Publishing [5][6] were examined for severity by estimating the brake temperatures resulting from the length and grade of the road, and the speed limit using a fundamental analysis documented by UMTRI [7][8]. The severity of these roads was compared to the estimated temperature from executing the MRAP FoV CPD requirement. Maximum brake temperature estimates were also calculated for the ATPD-2354A and ATPD-2383, TOP 2-2-608, and known Society of Automotive Engineers (SAE) [9] and Japan Society of Automotive Engineers (JSAE) [10] brake fade test procedures. Because ATPDs 2354A and 2383 utilize identical brake test procedures, heretofore only ATPD-2354A will be referred to in this report.

In addition, an optimization was performed that showed in the limit, the higher the maximum vehicle speed and the more brake applies given specific distance, grade, and acceleration/deceleration rates, the higher the maximum brake temperature. In other words, frequent pulsing of the brakes while accelerating to the original speed between the brake applications should result in higher brake temperatures. In the real world that would suggest that high speed steep grades with multiple curves requiring hard braking could be worst case for brake temperatures. Pulsing or “snubbing” the brakes was also found by UMTRI to provide a more even distribution of temperatures among the brakes and to reduce hot spots.[11] Candidate roads for evaluation as mountain braking test sites were recommended based upon estimated brake temperature and safety considerations. Guidelines for the evaluation of the test venues were also proposed.

Brake temperature estimates were determined using the equations developed by UMTRI in their report, “Retarders for Heavy Vehicles: Evaluation of Performance Characteristics and In-Service Costs.”[7][8] These equations considered the effects of the road grade, vehicle and tire rolling resistance, aerodynamic drag, engine braking, vehicle speed, ambient and initial brake temperatures. The equations also take into account brake cooling that is a function of vehicle speed and brake mass. The estimated brake temperatures calculated were based upon a number of assumptions regarding the vehicle and are only used to provide a comparison of the severity of the venues and procedures.

3.0 Methods, Assumptions, and Procedures

3.1 Mountain Descent Power Balance Equations

To estimate the brake temperatures for various mountain conditions, the power required to control speed on a specified grade was considered. The braking power required to control speed is proportional to its weight, speed, and the grade and is reduced by the power consumed by aerodynamic drag, rolling resistance, and engine braking. The following equation shows this relationship:

$$P_B = W \cdot V \cdot \Theta - P_A - P_{RR} - P_E. \quad (1)$$

The engine braking power estimates used in this analysis are based upon engine friction measurements measured by TARDEC on a Caterpillar 3116 Diesel engine as shown in Figure 1. This engine is the predecessor of and similar to the Caterpillar C7 engine used in some MRAP vehicles. The engine braking horsepower based on a polynomial curve fit from 800 to 2800 rpm with closed throttle is:

$$P_E = 0.000006066 \cdot N^2 + 0.002297 \cdot N \text{ (HP)}, \quad (2)$$

where N is engine RPMs.

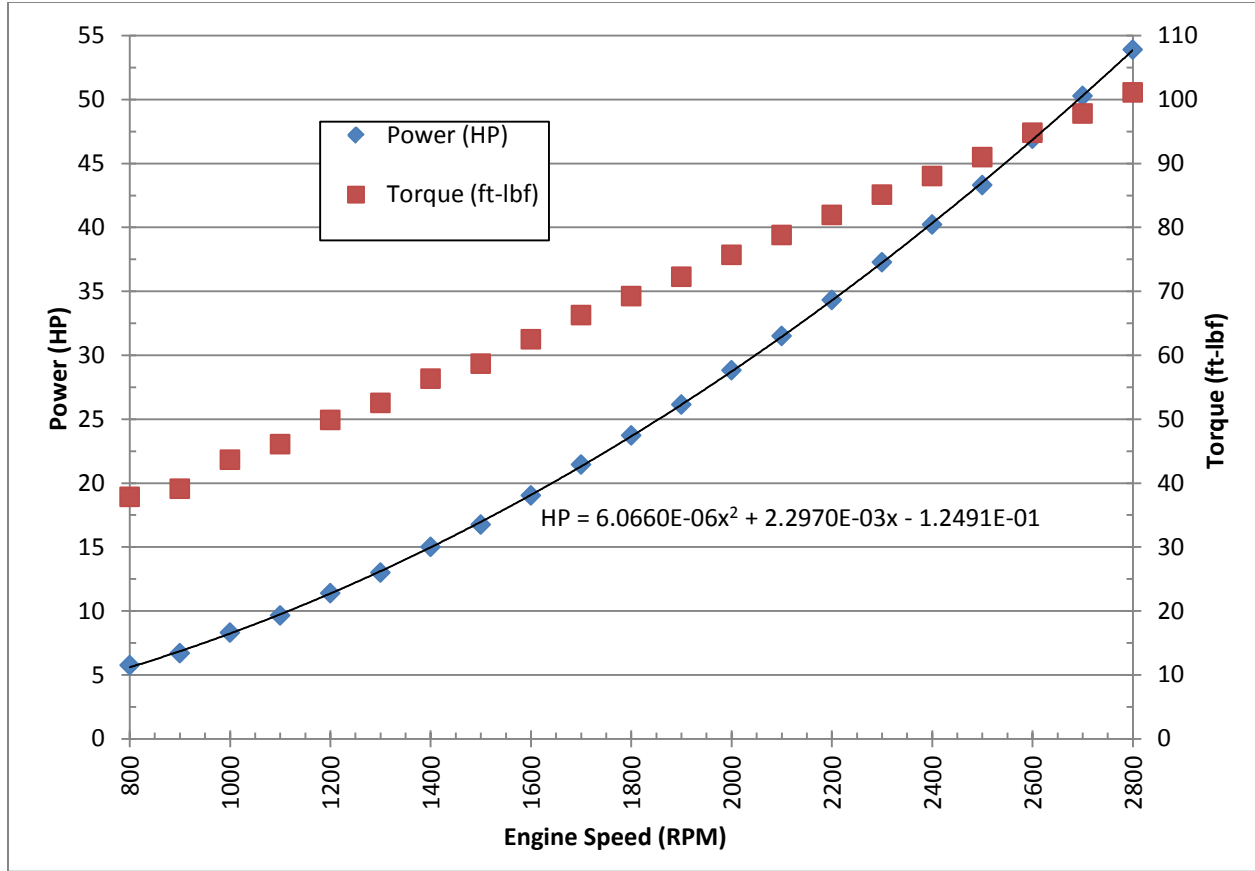


Figure 1: Caterpillar 3116 Diesel Engine Horsepower and Torque

Seventy-five to eighty percent of the power absorbed by vehicle rolling resistance is due to tires and can be characterized as:

$$P_{RR} = C_{RR} \cdot W \cdot V \cdot C_T / 375 \text{ (HP)}, \quad (3)$$

where C_{RR} is the tire-road interface related rolling resistance coefficient, W is vehicle weight in lb, V is vehicle speed in mi/h, and C_T is a tire construction coefficient.

The empirical coefficient C_{RR} was determined by UMTRI [7][8] to be 0.012, and C_T as 1.0 for bias tires and 0.7 for radial tires. Data from UMTRI for power absorbed by tire rolling resistance is shown in Figure 2 for an 80,000 lb four axle tractor-trailer. Fitting this data and recognizing that rolling resistance is proportional to tire load results in the following equation:

$$P_{RR} = (0.0002455 \cdot V^2 + 1.784 \cdot V) \cdot W / 80,000 \text{ (HP)}. \quad (4)$$

The power absorbed by vehicle body aerodynamics can be characterized by:

$$P_A = C_A \cdot A \cdot V^3 / 375 \text{ (HP)}, \quad (5)$$

where C_A is the drag coefficient and A is frontal area in ft^2 , reported by UMTRI to be 0.75 and 100 ft^2 , respectively. Data from UMTRI for power absorbed by aerodynamic drag is shown in Figure 2 for an 80,000 lb four axle tractor-trailer. Fitting this data and recognizing that aerodynamic drag is proportional to frontal area results in the following equation for the horsepower absorbed:

$$P_A = (0.000003597 \cdot V^3 + 0.00003254 \cdot V^2 - 0.0005801 \cdot V) \cdot A / 100 \text{ (HP)}. \quad (6)$$

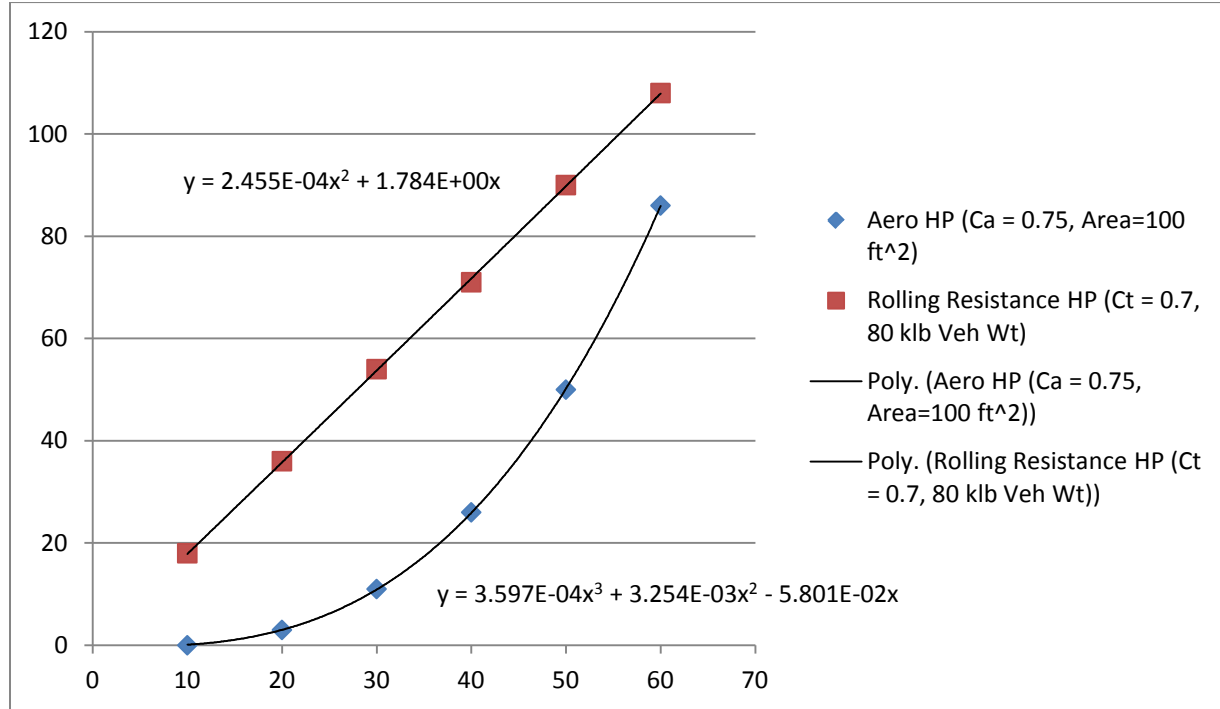


Figure 2: Rolling Resistance and Aerodynamic Coefficients for Semi-Tractor Trailer

3.2 Brake Temperature Estimation

UMTRI's report, "Retarders for Heavy Vehicles: Evaluation of Performance Characteristics and In-Service Costs,"[7][8] presents an equation for calculation of brake temperature as a function of the required braking horsepower, the vehicle speed and distance over which the brakes are applied, the brake heat capacitance, and their thermal time constant. The relationship between brake temperature and these variables is shown here:

$$T_f = T_i \cdot e^{-L/V\tau} + \left(\frac{P_B}{h(V)} + T_a \right) \cdot (1 - e^{-L/V\tau}) \text{ (deg F)}, \quad (7)$$

Where T_i and T_f are the initial and final brake temperatures respectively, T_a is ambient temperature, τ is the thermal time constant of the brakes, $h(V)$ is the brake cooling coefficient as a function of the vehicle speed, and L is the length of the grade over which the brakes are applied.

The brake thermal time constant can be determined from:

$$\tau = \frac{m_B \cdot C_P}{h(V)}, \quad (8)$$

where m_B is the mass of the brakes and C_P is the heat capacity of the brakes. Note that the vehicle speed, V , is assumed to be constant for this relationship.

UMTRI determined the brake cooling coefficient and the brake thermal time constant for the tractor-trailer combination from empirical data. The brake cooling coefficient was found to be

$$h(V) = 0.1 + 0.00208 \cdot V \text{ (deg F/HP)}. \quad (9)$$

Because the thermal time constant is a function of brake mass, if it can be roughly assumed that brake system mass is proportional to total vehicle mass, the empirical time constant equation can be altered to make it a function of vehicle weight:

$$\tau = 1/(1.23 + 0.0256 \cdot V \cdot W/80,000 \text{ (s)}). \quad (10)$$

3.3 Application of Power Balance Equation to Determine Brake Temperature

Given some assumptions, it is possible to estimate brake temperatures for particular road and vehicle characteristics in combination with the braking drive cycle. As mentioned before, it has been assumed that the brake system mass that is responsible for storing the heat generated by the brakes is proportional to the total vehicle mass. This allows us to use UMTRI's empirical relationship for vehicles of a weight that varies from the 80,000 lb tractor-trailer combination used in their study. A similar assumption is made for the total rolling resistance of the tires on the vehicle. While these assumptions may not be accurate, they should allow for relative rankings of road characteristics as they impact brake system temperatures.

Another assumption was that the brake cooling coefficient and therefore the brake thermal time constant, which are linear functions of vehicle speed, could be approximated by using the average speed for constant deceleration events.

In addition to the losses considered from tire rolling resistance, aerodynamics, and engine braking there are other sources not included in the power balance estimates. Those would include other drivetrain losses and brake drag. Given the expected degree of accuracy of these calculations and the primary intent to only rank order mountain braking venues, those other sources that were neglected by UMTRI are also not included in this study.

4.0 Results and Discussion

4.1 Results Overview

There were four basic parts to this study:

- 1) Maximum brake temperature estimates for mountain grades commonly used for brake temperature assessment.
- 2) Mountain descent venue review based upon severity relative to the MRAP CPD requirement.
- 3) Maximum brake temperature estimates for several test procedures that utilize a brake apply drive cycle.
- 4) Optimization to determine drive cycles that produce maximize brake temperatures for two mountain braking venues.

4.2 Study Part 1: Brake Temperature Estimates for Common Test Venues

The mountain grades evaluated for this part of the study include:

- 1) US-30 eastbound down Laurel Mountain near Jennerstown, PA. This venue is specified for the Laurel Mountain Brake Fade Test in TOP 2-2-608, "Braking, Wheeled Vehicles".[3] ATC Global Positioning System measurements of this venue indicate an average grade of 7.5 percent over 1.3 miles.
- 2) AZ-68 Union Pass between Bullhead City and Kingman, AZ near Davis Dam. This route is in common use by automotive OEMs to evaluate powertrains in the ascending direction.[12] However its length, grade, speed limit, and safe environment suggest it has good potential as an evaluation site.
- 3) Pikes Peak Highway in Cascade CO. This venue is used by General Motors for passenger cars, multipurpose passenger vehicles and light- trucks.[13] The Pikes Peak International Hill Climb Course Map reports the elevation change and course length showing the average grade as 7.2 percent and length of 12.4 miles.[14]
- 4) Grossglockner Mountain in Austria may be the most severe brake testing venue in common use for high performance brake systems. It has an average 12 percent grade over its 9.9 mi length.
- 5) AZ-88 eastbound near Roosevelt, AZ, Bishop Grade on US-395 in California, and Hawthorne Grade in Arizona are all used by NATC for brake testing. They range from 4.4 to 5.5 percent in grade and 13.2 to 8.4 miles in length according to NATC.
- 6) UMTRI listed a number of mountain grades that had high truck ramp usage and accident rates.[7] I-80 at Donner Summit in California and Parley's Canyon in Utah were included in the evaluation because of their combination of length and grade. Other steeper grades that were shorter in length would have lower brake temperatures and were not evaluated.

Table 1 shows the estimated maximum brake temperatures for the mountain grades mentioned above. For this study a vehicle weight of 26,000 lb and a frontal area of 50 ft². A constant value 24 HP of engine braking is used that is the amount generated by the Caterpillar 3116 Diesel

engine at 1800 rpm. This engine braking is a representative value recognizing that there can be significant variation from this value depending upon gearing and engine characteristics. The initial brake temperature is within the range commonly specified within test procedures. The ambient temperature of 90 deg F was chosen as a representative high value. No decelerations on the descent that would result from curves or other obstructions were considered here.

Grade Location	Temperature (deg F)			Course Characteristics			
	Final	Initial	Ambient	Road Slope (%)	Course Length (mi)	Worst Case Vehicle Speed (mi/h)	Speed Limit (mi/h)
Requirement	594	150	90	6	10	45.0	45
Grossglockner Mountain, Austria	1427	150	90	12	9.9	60.0	60
Pikes Peak Highway, Cascade, CO	609	150	90	7.2	12.42	25.0	25
AZ-260, AZ-87 to Camp Verde, AZ	587	150	90	5.74	11	54.4	65
US-395, Bishop Grade, CA	507	150	90	5.5	8.4	52.0	65
I-80, Parley's Canyon, UT	500	150	90	5.25	10	57.5	65
AZ-68, Union Pass/Davis Dam Bullhead City, AZ	483	150	90	5	11	52.0	70
Hawthorne	464	150	90	5	9.6	51.3	70
Laurel Mountain, PA	370	150	90	7.5	2	45.6	65
I-80 Donner Summit, CA	364	150	90	4	15	49.5	65
AZ-88 EB, AZ-CA	279	150	90	4.1	13.2	25.0	25

Table 1: Estimated Maximum Brake Temperature for Common Mountain Test Venues

Note in Table 1 that the vehicle speed used in the brake temperature calculation differs among the various roads, but in no case is it above the posted speed limit. In the absence of speed related cooling and motion resistance factors, higher vehicle speeds require higher braking horsepower to constrain the speed when descending a grade. This generates more heat and higher temperatures. However, higher speeds result in higher rolling and aerodynamic resistance and reduce the power requirement from the brakes. Higher speeds also increase cooling. So, there is an optimum speed that generates maximum brake temperatures based upon grade magnitude and length.

The row labeled Requirement lists the calculated maximum brake temperature given the road slope, length, and speed specified in the MRAP FoV CPD requirement. The bolded Grade Locations are those venues for which the estimated maximum brake temperature is within 20 percent of the estimated brake temperature for the Requirement characteristics. US-395 at Bishop Grade, I-80 at Parley's Canyon and Donner Summit, and AZ-68 at Union Pass are all multi-lane highways that could be expected to offer good opportunities for brake evaluations and less likely to be interrupted by traffic.

4.3 Study Part 2: Mountain Descent Venue Review

The East [5] and West [6] volumes of the Mountain Directory for Truckers, RV, and Motorhome Drivers were examined to recommend viable mountain braking test venues. These references provide reviews of roadways that may present braking or powertrain challenges to heavy vehicles or combination vehicles. They summarize grade lengths and posted grade

magnitudes. They do not have specific altitude change or accurate grade information, but primarily rely upon direct experience of driving the roadways. To determine the roadways with the greatest potential for brake temperature performance evaluation, the published grade length and magnitudes were compared to a table of grade characteristics that produce estimated brake temperatures that are equivalent to the temperature calculated for the MRAP FoV Requirement grade. This study utilized the same assumptions and characteristics as for the Brake Temperature Estimate for Common Test Venues study, including a vehicle weight of 26,000 lb and frontal area of 50 ft². The equivalent grade magnitudes and lengths are shown in Table 2 and plotted in Figure 3.

	Temperature (deg F)			Course Characteristics		
	Final	Initial	Ambient	Road Slope (%)	Course Length (mi)	Worst Case Vehicle Speed (mi/h)
MRAP FoV CPD Requirement	591	150	90	6.0	10.0	45.0
	590	150	90	6.0	9.4	54.1
	592	150	90	6.5	7.2	53.6
	589	150	90	7.0	5.8	53.1
	589	150	90	7.5	4.9	52.8
	592	150	90	8.0	4.3	52.7
	591	150	90	8.5	3.8	52.5
	590	150	90	9.0	3.4	52.3
	592	150	90	9.5	3.1	52.3
	587	150	90	10.0	2.8	52.1
	590	150	90	10.5	2.6	52.0
	588	150	90	11.0	2.4	51.9
	597	150	90	11.5	2.3	51.7
	588	150	90	12.0	2.1	51.8

Table 2: Equivalent MRAP FoV CPD Road Slope Magnitudes and Lengths

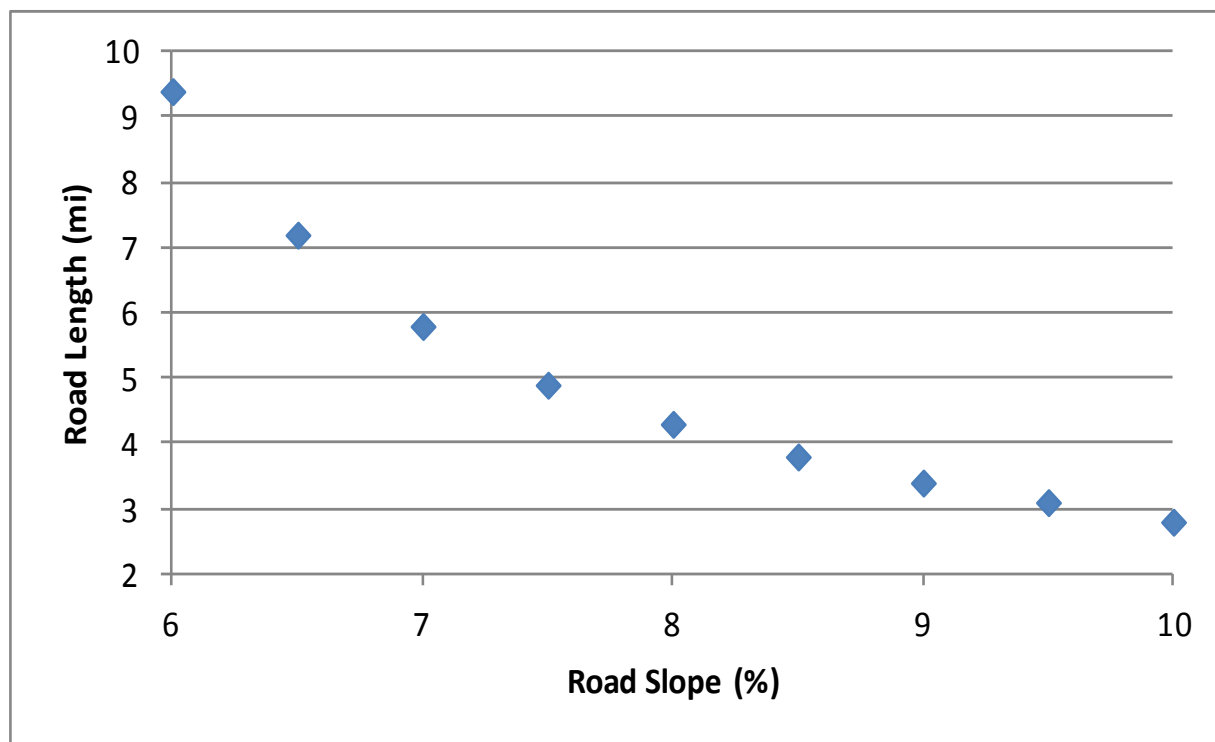


Figure 3: Equivalent MRAP FoV CPD Road Slope Magnitudes and Lengths

The Mountain Directory for Truckers, RV, and Motorhome Drivers West volume reviews 441 mountain grade locations in 11 western states. The East volume reviews 302 mountain grade locations in 11 eastern states. The grade magnitudes and lengths in Table 2 were compared to the descriptions of the various grade locations in the Mountain Directories to identify which locations appeared to offer at least as severe a braking challenge as the MRAP FoV CPD requirement. After accumulating a list based upon severity, the selections were pared to include those with multiple lanes in each direction as most promising for such evaluations. This list is presented in Table 3. While these may not be the only viable mountain braking performance evaluation sites, based upon the information available they would seem to have the greatest potential.

Here is a description of the locations listed in Table 3. Union Pass is the westbound section of AZ 68 between Kingman and Bullhead City, AZ. Sherwin Summit is the southbound section of US 395 north of Bishop, CA. Prather-Shaver Lake is the section of CA 168 northeast of Fresno, CA between Prather and Shaver Lake. Vail Pass is the westbound section of I70 east of Vail, CO. Cedaredge-Mesa is the southbound section of CO 65 between Cedaredge and Mesa, CO. Lewiston Hill is on US 95 just north of Lewiston, ID. Parley's Summit is at milepost 140 in I-80 east of Salt Lake City, UT, which is about 10 miles east of I-80 junction with I-218. Deep Gap is southbound from the Blue Ridge Parkway on US 421 near Deep Gap. Daylight Pass is the southbound section of CA 374 just south of the California-Nevada state line in Death Valley National Monument, CA. Brandywine is US 33 westbound near Brandywine, WV. Franklin-

Judy Gap is the section of US 33 between Franklin and Judy Gap, WV. Onego-Harmann is eastbound US 33 from the summit that is midway Between Onego and Harmann, WV.

	Location	Road	Grades (%)	Length (mi)	Curves	Lanes	Speed Limit
4+ Lane Highways	Union Pass Bullhead City-Kingman, AZ	AZ 68 WB	6	10	One 45 mi/h	4-Lane	70 mi/h
	Sherwin Summit Bishop, CA	US 395 SB	6	8	Few	4-Lane	65 mi/h, Trucks 35 mi/h
	Prather-Shaver Lake Fresno, CA	CA 168	7	11	45 mi/h	2, 4-Lane	55 mi/h
	Vail Pass, CO	I70 WB	7	7		4-Lane	65 mi/h, >30Klb 45 mi/h
	Cedaredge-Mesa, CO	CO 65 SB	5-7	20	Very Curvy, 25-45 mi/h	4-Lane Divided Highway	50 mi/h
	Lewiston Hill Lewiston, ID	US 95	7	6	45 mi/h	4-Lane Divided Highway	65 mi/h
	Parley's Summit Salt Lake City, UT	I-80 WB	6	9	Few	6-Lane	65 mi/h
	Frostburg, MD	I-68 EB	6	13	40 mi/h Near Bottom	4-Lane Divided Highway	65 mi/h, Trucks 45 mi/h
	Deep Gap, NC	US 421 SB	7-10	5		4-lane Divided and undivided highway	55 mi/h, Trucks 30 mi/h
2-Lane, Curvy Roads	Daylight Pass Death Valley National Monument, CA	CA 374 SB	6-8	13	Winding, 25, 30, 45 mi/h	2-Lane	45 mi/h, No Commercial Trucks
	Brandywine, WV	US 33 WB	9	4.5	Continuous Sharp & Hairpin Curves	2-Lane	55 mi/h
	Franklin-Judy Gap, WV	US 33	9	5	Continuous Sharp & Hairpin Curves	2-Lane	55 mi/h
	Onego-Harmann, WV	US 33 EB	10	3.5	25, 30 mi/h	2-Lane	55 and 45 mi/h

Table 3: Potential Mountain Descent Braking Evaluation Venues

4.4 Study Part 3: Mountain Braking Test Procedure Temperature Estimates

Seven brake test procedures were simulated by combining successive decelerations and cooling period cycles as prescribed by the test procedures. Output temperatures from each cycle were input to the next cycle successively until the entire procedure was represented. Again, the same vehicle characteristics for weight and resistance were used as in the earlier parts of the study.

The test procedures simulated include:

- 1) SAE J1247 Road Test, "Simulated Mountain-Brake Performance Test Procedure," August 2002.[9]
Scope is "light-duty trucks and multipurpose passenger vehicles up to and including 4500 kg (10 000 lb) GVW and all classes of passenger cars."
- 2) JASO C438 Road Test, "Road vehicles - Service brake - Vehicle simulated mountain brake fade test procedure," 2002.[10]

Scope is broken into multiple categories for passenger cars, trucks, and busses with no ultimate bound on GVW. Procedure is adjusted based upon vehicle class.

- 3) TOP 2-2-608 Road Test, "Braking, Wheeled Vehicles; Brake Fade Test," May 20, 2008. Scope is broken into three categories with no ultimate bound on GVW.[3]

- 4) TOP 2-2-608 Road Test, "Braking, Wheeled Vehicles; High Temperature Endurance Test," May 20, 2008.[3]

Scope is broken into three categories with no ultimate bound on GVW.

- 5) ATPD-2354A Lab Test, "Off-Vehicle Brake Testing for Military and Militarized Commercial Ground Wheeled Vehicles Over 3,500 kg (7,716 U.S. Lbs.) Gross Vehicle Weight Rating (GVWR); Laurel Mountain Fade Snubs and Hot Stop," November 27, 2007.[1]

Scope is "ground wheeled vehicles exceeding 7,716 US lbs. Gross Vehicle Weight Rating (GVWR)."

- 6) ATPD-2354A Lab Test, "Off-Vehicle Brake Testing for Military and Militarized Commercial Ground Wheeled Vehicles Over 3,500 kg (7,716 U.S. Lbs.) Gross Vehicle Weight Rating (GVWR); Laurel Mountain Cross Country Cycle," November 27, 2007.[1]

Scope is "ground wheeled vehicles exceeding 7,716 US lbs. Gross Vehicle Weight Rating (GVWR)."

- 7) SAE J2684 Lab Test, "FMVSS 105 Inertia Brake Dynamometer Test Procedure for vehicles above 4 540 kg GVWR; FMVSS Test Sequence, 2nd Fade Section," November 2011.(15)

Scope is "two-axle multipurpose passenger vehicles, trucks and buses with a GVWR above 4,540 kg (10,000 lbs) equipped with hydraulic service brakes."

Table 4 Summarizes the estimated peak brake temperatures and test duration for the seven procedures evaluated. These tests will be described in more detail, however note that the highest temperature generated was for an SAE mountain braking road test procedure that is not valid for the 26,000 lb vehicle simulated. It was included for comparison, but the Recommended Practice scope is applicable only for vehicles up to 10,000 lb GVWR.

Procedure Simulated	Estimated Test Length (hrs)	Estimated Peak Brake Temperature (deg F)
SAE J1247 Road Test (10 Klb Vehicle Weight Limit)	1 Hr 2 Min	566
JASO C438 Road Test	2 Hr 3 Min	286
TOP 2-2-608 Road Test; Brake Fade Test	4 Min	365
TOP 2-2-608 Road Test; High Temperature Endurance Test	6 Min	371
ATPD-2354A Lab Test; Laurel Mountain	8 Min	257
ATPD-2354A Lab Test; Cross Country Cycle	1 Hr 53 Min	261
SAE J2684 Lab Test (FMVSS 105 Emulation)	10 Min	376

Table 4: Braking Test Procedure Summary

SAE Recommended Practice J1247 is a road test intended to simulate a mountain descent brake test on level ground. There is no current SAE Recommended Practice with a mountain braking procedure for vehicles of GVWR greater than 10,000 lb. The J1247 braking drive cycle would therefore be considered aggressive for a vehicle weighing 26,000 lb. As a result, the estimated maximum temperature of 566 deg F is highest among the procedures examined. Simulating the J1247 procedure with a 10,000 lb vehicle, and reducing the frontal area and engine braking levels to half of the values for the 26,000 lb vehicle reduces maximum brake temperature to 295 deg F.

Figure 4 illustrates the test procedure drive cycle of vehicle decelerations and cooling periods represented by plotting the simulated vehicle speed versus time in red. The resultant temperature time history is displayed in blue. Following a brake burnish, the procedure begins with the brake temperatures between 150 deg F and 200 deg F. 150 deg F was chosen for the simulation. Then three cold effectiveness stops are conducted from 60 mi/h at 15 ft/s² (4.6 m/s²) with 200 s cooling intervals at 60 mi/h (97 km/h) between stops. Next the vehicle is driven at 35 mi/h (56 km/h) for 15 s and eighty 8 ft/s² (2.4 m/s²) brake snubs from 35 mi/h to 17 mi/h (27 km/h) commence with cooling intervals of 15 s. At this point, the vehicle is driven at 60 mi/h for 50 s followed by three hot effectiveness stops conducted as the previous cold effectiveness. After the hot effectiveness stops the vehicle is driven at 40 mi/h (64 km/h) for 120 s and a recovery procedure commences with ten 40 mi/h stops with 120 s cooling intervals between them. Following this recovery, eighty brake snubs are conducted in the same manner as was done previously. The highest temperatures would be recorded some time up to this point as a cool down soak is immediately conducted following the brake snubs.

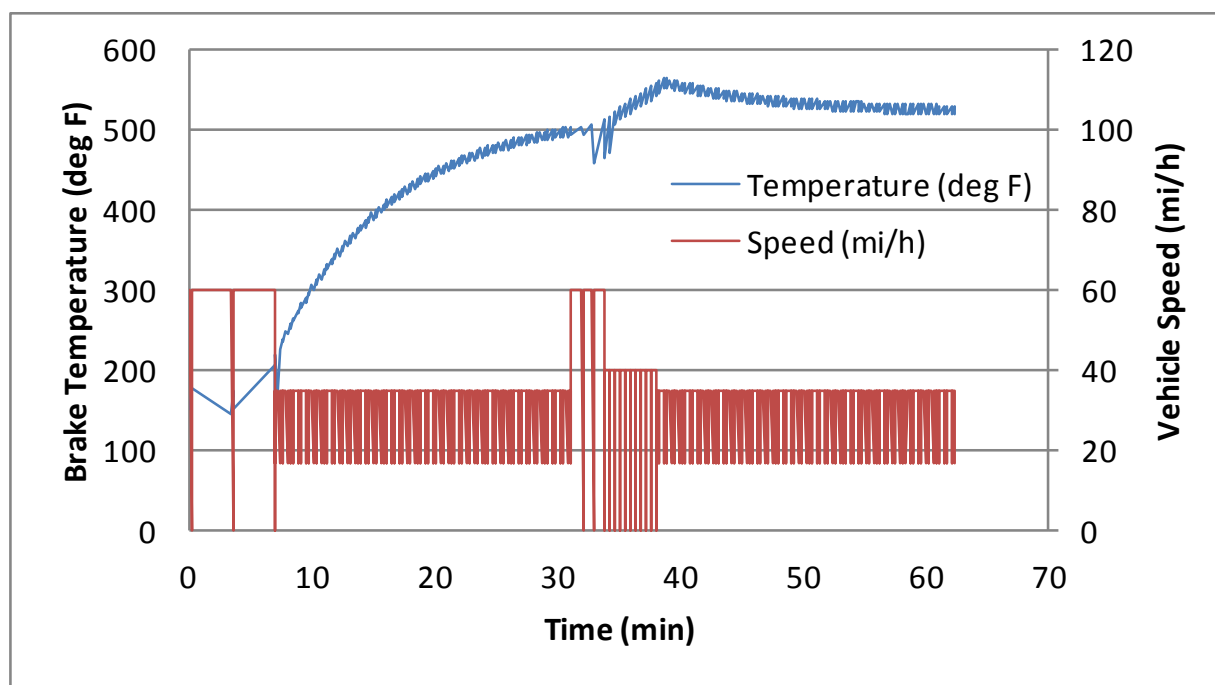


Figure 4: SAE J1247 Road Test Brake Temperature and Speed

JSAE Japanese Automobile Standards Organization (JASO) Standard C438 is a road test procedure intended to simulate a mountain descent for braking performance. There are four variants on this procedure depending upon vehicle type. Vehicle types are broken into a total of ten categories based upon type (passenger cars, busses, and trucks), maximum speed, and GVW. The procedure has no upper limit on GVW. For this study, the appropriate category and procedure were selected based upon a 26,000 lb truck. This procedure was the least aggressive of all those evaluated in that the maximum estimated brake temperature produces was only 286 deg F. This is primarily due to its relatively low maximum braking speed and long cooling periods between stops.

Figure 5 illustrates the test procedure drive cycle of vehicle stops and cooling periods represented by plotting the simulated vehicle speed versus time in red. The resultant temperature time history is displayed in blue. Following a brake burnish, the procedure begins with three cold effectiveness stops. At this point the brakes are cooled to 140 deg F and so the estimated temperature calculation does not begin until this step in the road test procedure since the final temperature is a function of the initial temperature. With the brakes at this temperature, sixty brake stops are conducted from 31 mi/h (50 km/h) at 9.8 ft/s^2 (3 m/s^2) with cooling intervals of 40 s. At this point, three hot effectiveness stops are conducted from 31 mi/h at 9.8 ft/s^2 (3.0 m/s^2) with 40 s cooling intervals at 31 mi/h between stops. After the hot effectiveness stops the vehicle is driven at 31 mi/h for 180 s and a recovery procedure commences with ten stops from 31 mi/h with 180 s cooling intervals between them. Following this recovery, sixty brake stops are conducted in the same manner as was done previously. The highest temperatures would occur sometime up to this point as a cool down soak is immediately conducted following the brake snubs.

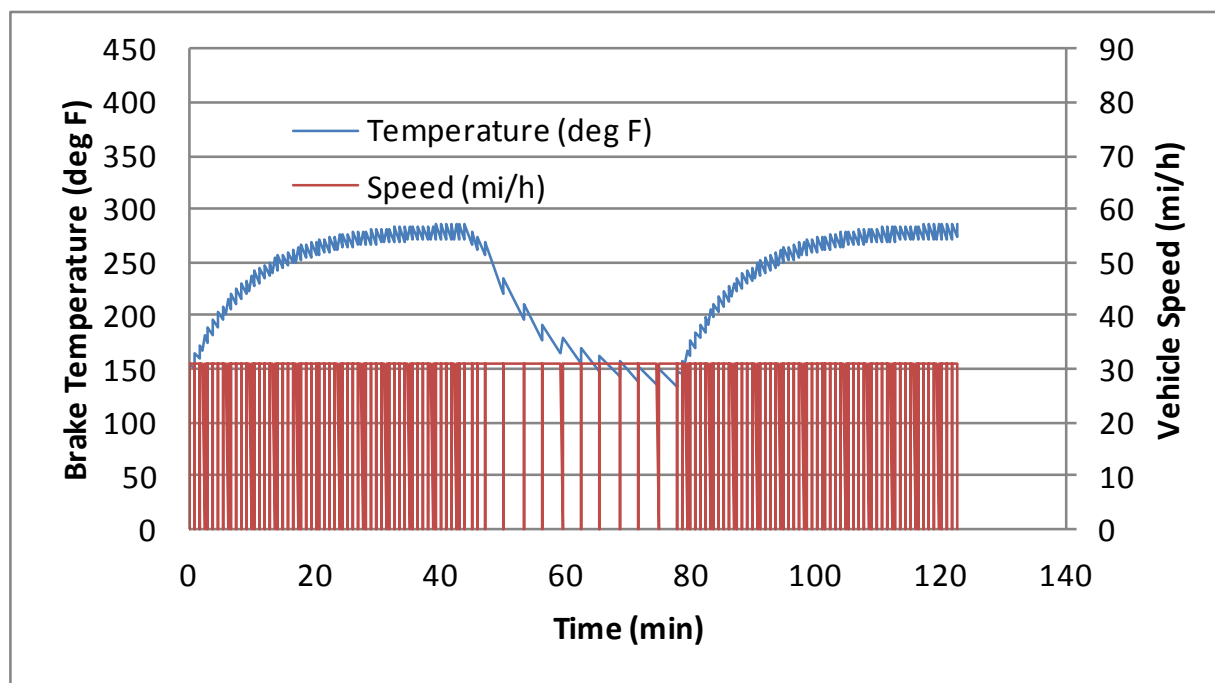


Figure 5: JASO C438 Road Test Brake Temperature and Speed

The U.S. Army Test and Evaluation Command (ATEC) Test Operations Procedure (TOP) 2-2-608 includes a variety of braking performance evaluation tests to cover wheeled vehicles of any weight. It includes three mountain highway braking test procedures, the Brake Fade Test, the High Temperature Endurance Test, and the Brake Durability and Wear Test that are conducted in the Jennerstown, Pennsylvania area. Figure 6 roughly plots the elevation versus distance traveled for this area from the TOP. The Brake Fade Test is conducted over a section of Laurel Mountain's east face that has an average grade of 7.5%. The High Temperature Endurance Test includes Jennerstown area mountain ascents and descents that test the durability of the brake system. The section of the High Temperature Endurance Test that would produce the highest brake temperatures is the eastward descent from Bald Knob that has an average grade of 6.2% over 3.0 miles (4.8 km) that includes forty-five decelerations from 30 mi/h (48 km/h) to 25 mi/h (40 km/h) with 0.6 miles of cool down after the first fifteen decelerations around the intermediate (Grandview) Peak.

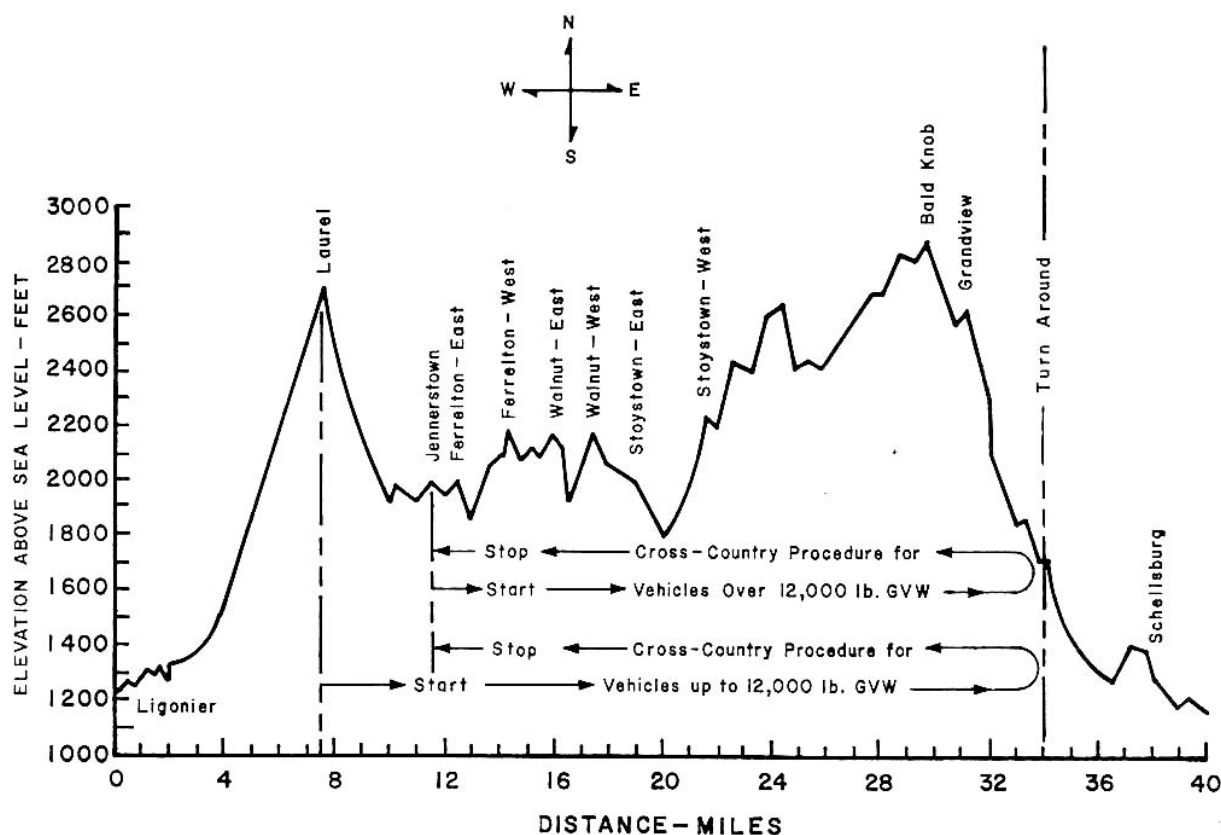


Figure 6: Mountain Brake Test Course, Jennerstown, Pennsylvania US Route 30

The Brake Fade and High Temperature Endurance Tests have variants based upon three weight classes, Light Truck with GVWs up to 12,000 lb (5,440 kg), Medium Truck with GVWs from 12,000 to 45,000 lb (20,400 kg), and Heavy Truck with GVWs greater than 45,000 lb. The Medium Truck procedures were simulated for this study and produced estimated maximum

brake temperatures of 365 deg F in the Brake Fade Test and 371 deg F in the High Temperature Endurance Test.

Figure 7 illustrates the Brake Fade Test procedure drive cycle of vehicle decelerations and cooling periods represented by plotting the simulated vehicle speed versus time in red. The resultant temperature time history is displayed in blue. Following a brake burnish, the procedure begins with three cold effectiveness stops. The initial brake temperature is not specified, but was chosen to be 150 deg F to be consistent with most of the other procedures evaluated. With the brakes at this temperature, thirty brake decelerations are conducted from 30 to 25 mi/h (48 to 40 km/h) at 7.9 ft/s^2 (2.4 m/s^2) followed by one full stop from 40 mi/h (64 km/h) at 14.4 ft/s^2 (4.4 m/s^2). The acceleration between brake applies to resume the 30 mi/h braking speed was determined based upon completing the entire procedure within the 2 mile (3.20 km) length of the Laurel Mountain Grade. The acceleration between brake applies worked out to 1.05 ft/s^2 (0.319 m/s^2), which resulted in cooling intervals of about 7 s.

Note that in the simulation the mountain grade effect is added to the braking decelerations when calculating the braking horsepower required and the resultant rate of brake temperature increase. For a 7.5% grade this works out to 0.075 g or 2.4 ft/s^2 (0.74 m/s^2). Note also that the test driver reads a u-tube manometer to determine his deceleration rate during the Fade Test. The u-tube is adjusted to compensate for the grade of the road, but not for the vehicle's dynamic pitch when braking. For the simulation, a 3 deg/g vehicle pitch gradient was assumed which effectively reduced the 7.9 ft/s^2 deceleration by 1.7 ft/s^2 (0.51 m/s^2).

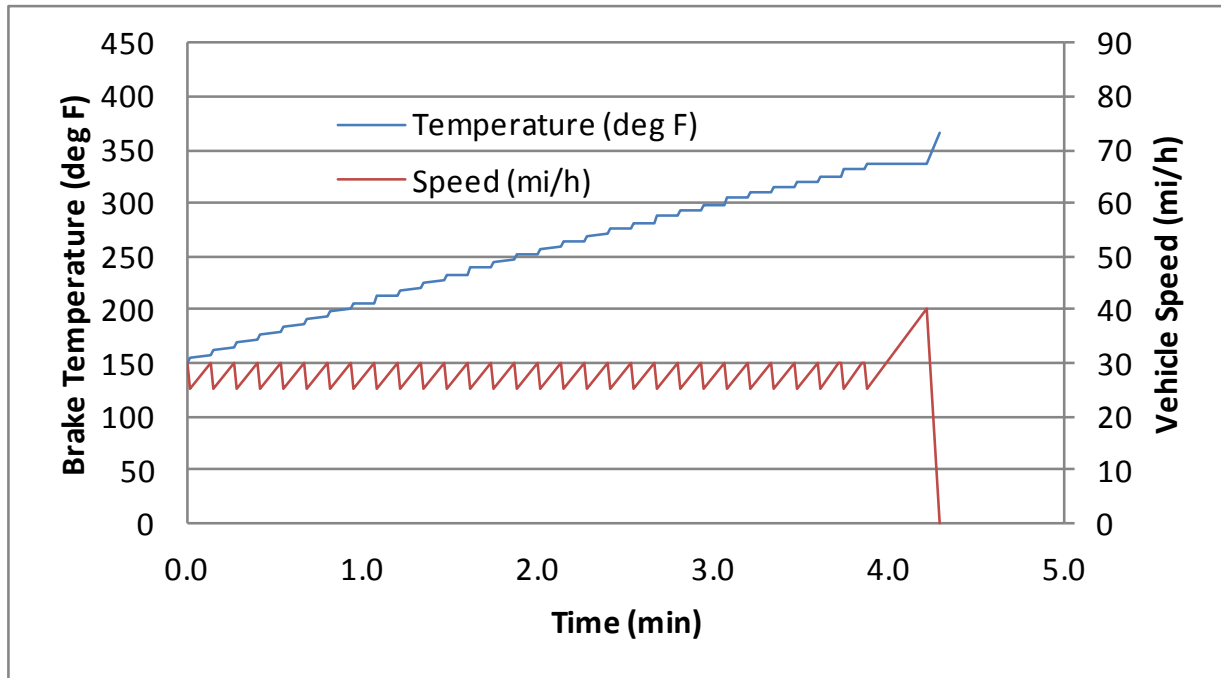


Figure 7: TOP 2-2-608 Brake Fade Road Test Brake Temperature and Speed

Figure 8 illustrates the portion of the High Temperature Endurance Test that would produce the highest brake temperatures. This is the section of the course from Bald Knob to the turnaround shown in Figure 6. The initial brake temperature can vary in this point in the road test, but was chosen to be 150 deg F for the simulation to be consistent with most of the other procedures evaluated. With the brakes at this temperature, fifteen decelerations are conducted from 30 to 25 mi/h (48 to 40 km/h) followed by a 74 s cooling interval and then another thirty decelerations from 30 to 25 mi/h. This cooling interval is based upon what was observed in actual test data and occurs at the approach to the Grandview peak shown in Figure 6. The deceleration and acceleration rate was determined based upon getting the simulated procedure completed within the 2.98 mile (4.80 km) length of the descent. The acceleration/deceleration value works out to 2.09 ft/s^2 (0.637 m/s^2), which is similar to the calculated RMS value of 2.5 ft/s^2 (0.77 m/s^2) from a sample of ATC test data.

To calculate the braking horsepower required and the resultant rate of brake temperature increase, the Bald Knob descent grade effect is added to the braking decelerations. For a 6.2% grade this works out to 0.062 g or 2.00 ft/s^2 (0.608 m/s^2) resulting in a total effective deceleration level of 4.09 ft/s^2 (1.25 m/s^2).

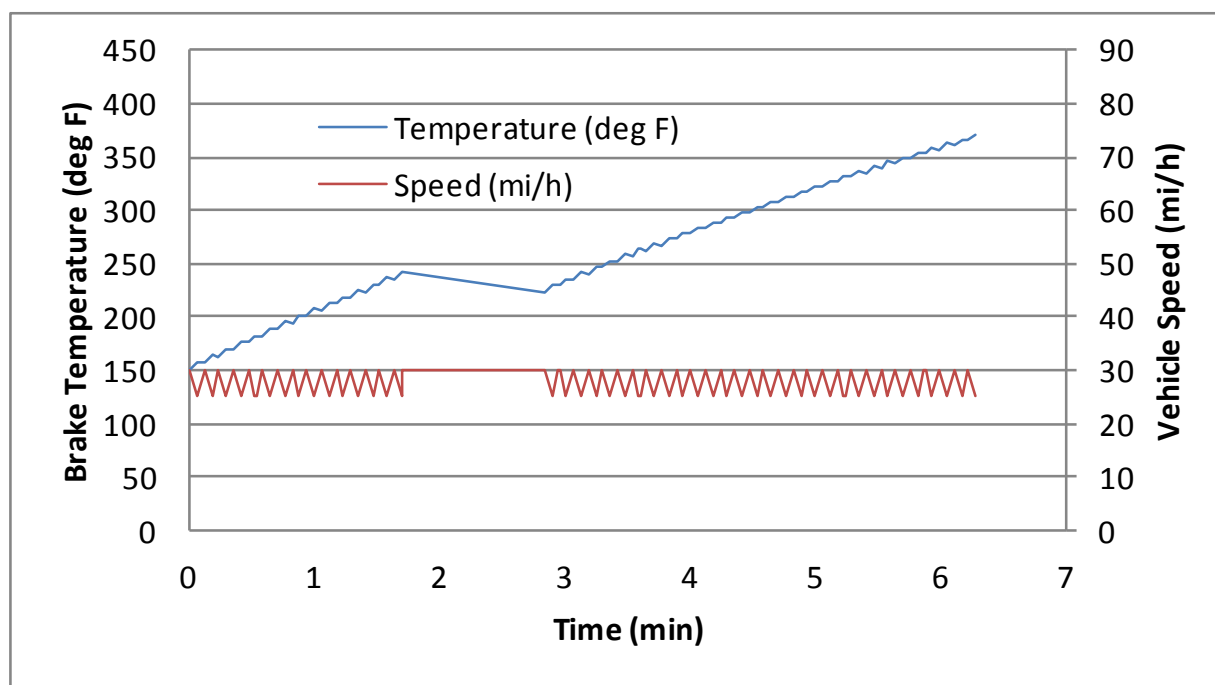


Figure 8: TOP 2-2-608 High Temperature Endurance Road Test Brake Temperature and Speed

The U.S. Department of Defense Army Tank Purchase Description 2354A (ATPD-2354A) includes dynamometer test procedures intended to simulate the TOP 2-2-608 Brake Fade Test (Laurel Mountain Fade Snubs and Hot Stop) and High Temperature Endurance Test (Laurel Mountain Cross Country Cycle). ATPD-2354A provides variants for the Laurel Mountain Fade Snubs/Hot Stop and Laurel Mountain Cross Country Cycle for the same Light Truck, Medium

Truck, and Heavy Truck weight classifications as TOP 2-2-608. As with the TOP 2-2-608 simulation, the Medium Truck procedure variants were used in the simulation. The estimated maximum brake temperatures are 257 deg F for the Laurel Mountain Fade Snubs/Hot Stop and 261 deg F for the Laurel Mountain Cross Country.

Figure 9 illustrates the test procedure drive cycle for the Laurel Mountain Fade/Hot Stop. The initial brake temperature is specified to be ≤ 150 deg F and was chosen to be 150 deg F to be consistent with most of the other procedures evaluated. With the brakes at this temperature, thirty brake decelerations are conducted from 30 to 25 mi/h (48 to 40 km/h) at 8 ft/s^2 (2.44 m/s^2) followed by one full stop from 40 mi/h (64 km/h) at 14.4 ft/s^2 (4.39 m/s^2). The cooling period between brake applies is specified to be 14 s. For this laboratory test, the cooling air speed is specified to be less than 3 mi/h (4.8 km/h) and was chosen to be 1 mi/h (1.6 km/h) for the simulation. However, the cooling air speed in this range has little effect on the brake temperature.

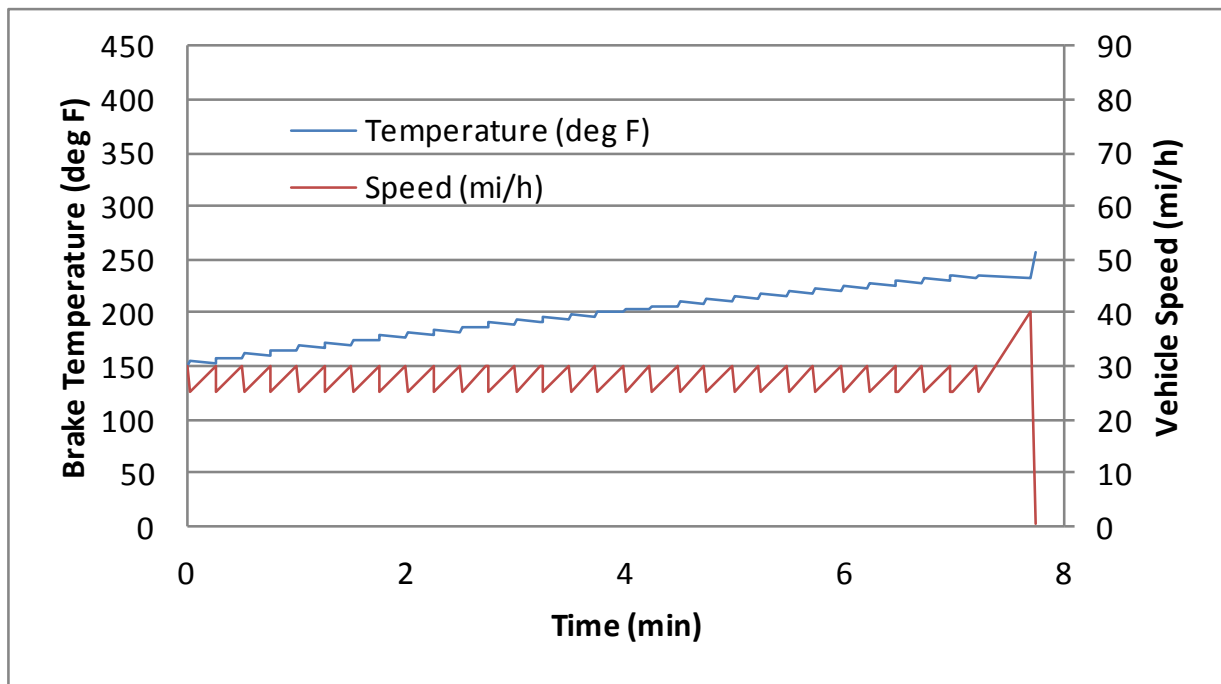


Figure 9: ATPD-2354A Laurel Mountain Lab Test Brake Temperature and Speed

The resultant calculated maximum brake temperature estimate of 257 deg F is significantly lower than the 365 deg F produced by the simulation of the Brake Fade Test TOP that this ATPD procedure is intended to emulate. There are two main reasons for this. First the cooling period for the Brake Fade Test schedule is shorter. Although both the TOP and ATPD specify thirty decelerations and a final stop, the TOP schedule test length is 167 s, while the ATPD version is 466 s long. The second reason is difference in the braking power requirements. The ATPD deceleration rate is 8 ft/s^2 (2.44 m/s^2) for the first thirty decelerations, but there is no grade contribution. By comparison the effective deceleration resisted by braking power for the TOP 2-

2-608 Brake Fade simulation is 9.87 ft/s^2 (3 m/s^2). The deceleration for the TOP, after accounting for the vehicle pitch effect discussed previously, is 7.46 ft/s^2 (2.27 m/s^2) and the effect of the 7.5% grade is 2.41 ft/s^2 (0.74 m/s^2). The final full stop decelerations in the schedules are 14.4 ft/s^2 (4.39 m/s^2) for ATPD-2354A and (effectively) 16.1 ft/s^2 (4.91 m/s^2) for the TOP.

Figure 10 illustrates the test procedure drive cycle for the ATPD-2354A Laurel Mountain Cross Country Cycle. The driving cycle is complex with a series of varied number and magnitude of decelerations, and speed differentials that pretty closely match what is specified in the TOP 2-2-608 High Temperature Endurance Test. According to the ATPD-2354A schedule, the test would require about 2 hr to complete. The most notable difference between the TOP and ATPD is that deceleration rates are not specified in the TOP. The test operator is only instructed as to the number of brake snubs, start and end speed, and the location on the circuit (see Figure 6) where the snubs are to occur.

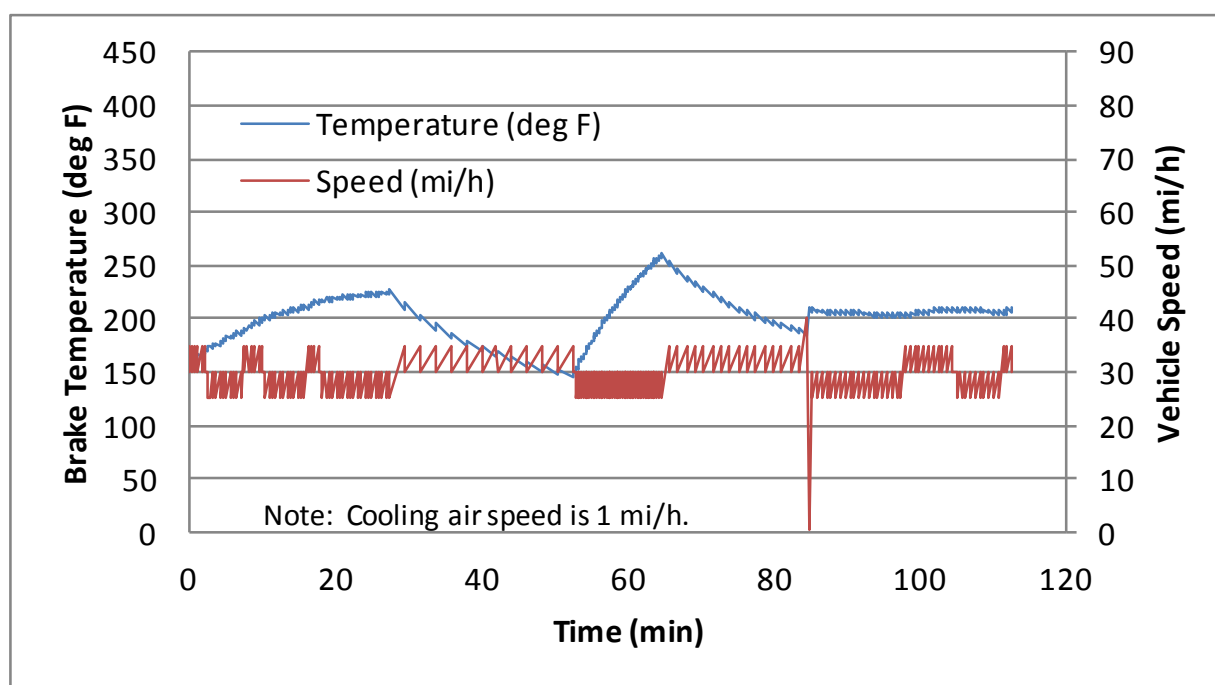


Figure 10: ATPD-2354A Cross Country Lab Test Brake Temperature and Speed

The highest temperatures occur during after the forty-five decelerations from 30 mi/h to 25 mi/h during the 53 min to 65 min part of the test. This is the section that mimics the descent from Bald Knob (see Figure 6) that was also simulated for the TOP (see Figure 8). Coincidentally, the brake temperature at which this segment of the ATPD-2354A schedule begins is 150 deg F, just as was used in the High Temperature Endurance Test TOP simulation. The peak temperature achieved is 261 deg with the ATPD-2354A schedule as compared to 371 deg F for the TOP simulation. The ATPD deceleration rate in this section is 8 ft/s^2 (2.44 m/s^2) while the TOP simulation rate was 4.09 ft/s^2 (1.25 m/s^2). However, the TOP simulation includes the effect

of the 6.2% grade that requires the brakes to resist an additional 2.00 ft/s^2 (0.608 m/s^2). The effective deceleration thus becomes 6.09 ft/s^2 (1.86 m/s^2).

In and of itself, the higher deceleration rate of the ATPD would require more braking horsepower and higher brake temperatures. However, as with the Brake Fade TOP and Laurel Mountain Descent ATPD comparison, there are several reasons this isn't the case. First, while the TOP simulation of the Bald Knob descent indicates the procedure requires 6.4 min, the equivalent section of the ATPD-2354A schedule requires 11.7 min to complete, due to the longer cooling periods between ATPD brake snubs. If the ATPD's cooling cycles are reduced from

15 s to the 3.5 s observed between the TOP brake snubs, the final brake temperature increases by 60 deg F to 321 deg F, which is still lower than the 371 deg F of the TOP simulation.

It would make sense to wonder why with a higher effective deceleration rate in combination with equivalent cooling time the ATPD-2354A simulation results in lower brake temperatures than the TOP simulation. To further help understand the difference between the ATPD and TOP schedules on brake temperature, the effect of a 6.2% grade was added to the brake power calculation of the ATPD as had been included in the TOP simulation. That brings the effective deceleration to 10.0 ft/s^2 (3.05 m/s^2). This results in the ATPD final brake temperature being 367 deg F, still less than that of the TOP simulation.

With now a significantly higher effective deceleration rate and cooling cycles equivalent to that of the TOP simulation, one would expect the revision to the ATPD-2354A schedule to result in a final brake temperature at least as high as the TOP simulation value of 371 deg F. However, with the addition of the 6.2% grade effect to the braking power requirement, reducing the actual vehicle deceleration paradoxically increases the brake temperature. This is because reducing the deceleration results in longer periods of time and longer total distance and thus more total energy input from the brakes resisting the 6.2% grade. Reducing the deceleration level to the 2.09 ft/s^2 (0.637 m/s^2) used in the TOP simulation, while retaining the previously added 6.2% grade effect on braking power and 3.5 s cooling time, increases the final brake temperature to 456 deg F.

The last of the test procedures examined was the SAE Recommended Practice J2684 lab test intended to emulate FMVSS 105 for GVWR greater than 10,000 lb (4,540 kg). This is not a mountain brake test procedure, however was included for comparison. Comparing the schedules for J2684 and FMVSS 105 show the Recommended Practice accurately emulates the FMVSS test. The primary brake fade event, the "2nd Fade" event of the Recommended Practice and of FMVSS 105 section 14.13, are identical. As shown in Figure 1, twenty brake snubs from 40 mi/h (64 km/h) to 20 mi/h (32 km/h) are conducted with an initial brake temperature of 140 deg F and decorations of 0.31 g. FMVSS 105 specifies an initial brake temperature of 130 deg F to 150 deg F. For initial brake temperatures of 140 deg and 150 deg F, the final brake temperatures are 376 deg F and 380 deg F, respectively.

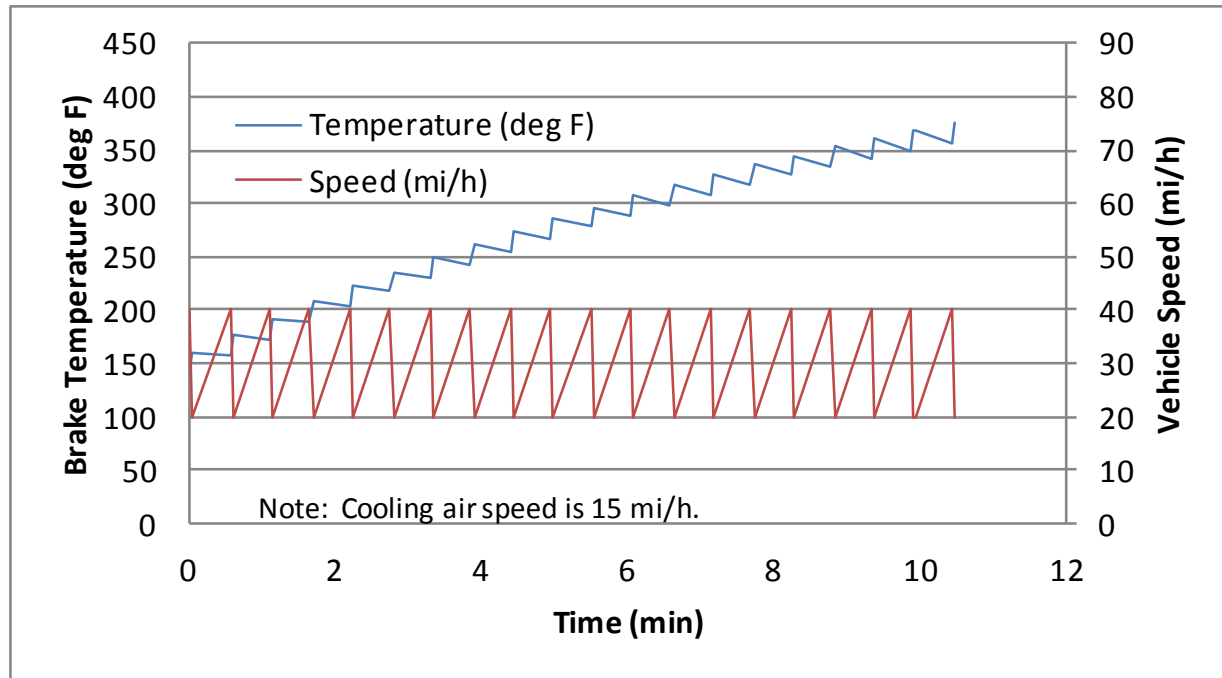


Figure 11: SAE J2684 FMVSS 105 Lab Test Brake Temperature and Speed

4.5 Study Part 4: Drive Cycle Optimization for Laurel Mountain and Union Pass

This part of the study discusses optimizing the brake apply schedule on a mountain descent to generate maximum brake temperatures. Although optimizing a mountain descent brake schedule to generate maximum brake temperatures has little face validity for a test, it is a good academic exercise for understanding some of the control factors that cause extreme brake temperatures.

The TOP 2-2-608 Road Test; Brake Fade Test is conducted on Laurel Mountain near Jennerstown, Pennsylvania. As discussed earlier, the procedure consists of thirty decelerations from 30 to 25 mi/h (48 to 40 km/h) and one full stop from 40 mi/h (64 km/h) over the 2 mile (3.2 km) length of the 7.5% grade. The simulation showed that the test would require about 4 minutes to run and estimates a maximum brake temperature of 365 deg F for the vehicle characteristics modeled. Recall also that the optimum constant speed of 45.6 mi/h (73.4 km/h) on this grade produced an estimated maximum brake temperature of 370 deg F.

Excel Solver was used to determine whether there was an optimum number of brake applies, deceleration magnitude and speed that generated a maximum brake temperature. The limits placed on the optimization were a rate of change of vehicle speed with time between 0.001 g and 0.3 g inclusive, acceleration between brake applies between 0.001 g and 0.1 g inclusive, maximum speed of 65 mi/h (105 km/h) (US Route 30 speed limit), and a total grade length of 2 miles. The maximum acceleration and deceleration limits were deliberately chosen to be

moderate for easier and more consistent real-world execution if a physical study were performed.

Note that increasing the number of brake applies requires a smaller speed change to meet the total distance criterion. Brake applies of 1, 6, 7, 8, 10, 20, 40, and 80 were examined. For the particular vehicle characteristics modeled and the 7.5% grade of 2 mi length, the optimum number of decelerations was seven. Figure 12 illustrates this optimum schedule that has an estimated maximum brake temperature of 575 deg F resulting from 0.3 g decelerations from 65 to 20.8 mi/h (105 to 33.5 km/h).

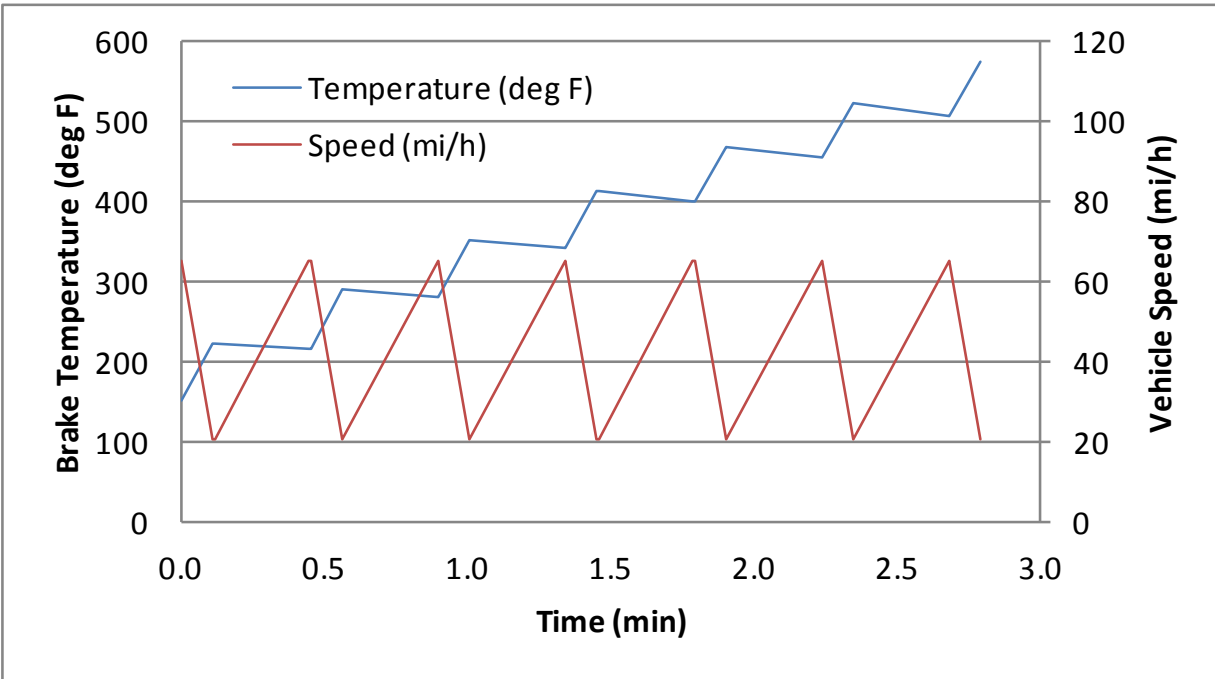


Figure 12: Laurel Mountain Brake Apply Schedule for Maximum Brake Temperature (Scenario Dependent)

Figure 13 shows comparable simulation results for eighty brake applies over the 2 mi Laurel Mountain descent. In order to achieve eighty brake applies, the decelerations were only from 65 to 62.7 mi/h (105 to 101 km/h), again at 0.3 g. Estimated maximum brake temperature is less at 540 deg F.

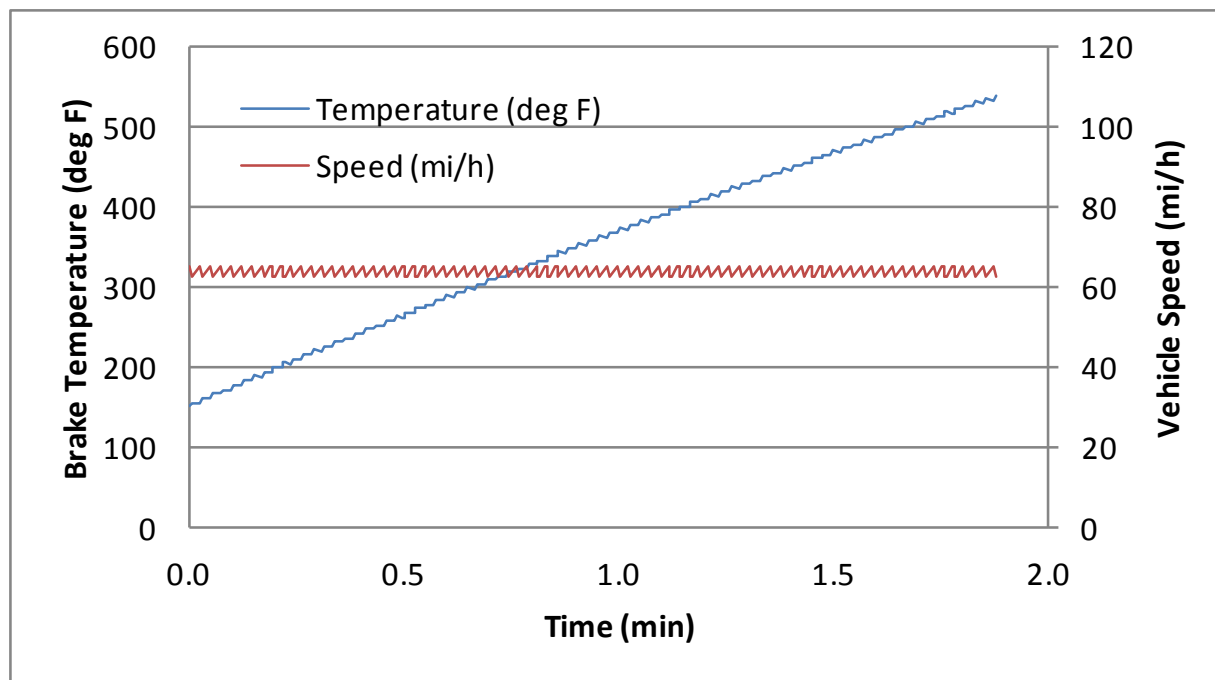


Figure 13: Laurel Mountain Estimated Brake Temperature with Eighty Brake Applies (Scenario Dependent)

The optimum accelerations and decelerations for each of the brake apply conditions were always at the maximum permissible values of 0.3 g and 0.1 g respectively until the number of applies was fewer than seven. At that point the optimum deceleration began to decrease in order to utilize the full 2 mile grade length. Table 5 compares the optimum values for speed and deceleration/acceleration for the various number of brake applies over the Laurel Mountain descent. Previously it was shown that driving at a constant speed of 65 mi/h down the 2 mile grade produced an estimated brake temperature of 370 deg F.

Number of Brake Applies	1	6	7	8	10	20	40	80
Deceleration (g)	0.013	0.232	0.300	0.300	0.300	0.300	0.300	0.300
Acceleration between Applies (g)	N/A	0.100	0.100	0.100	0.100	0.100	0.100	0.100
Maximum Speed (mi/h)	65.0	65.0	65.0	65.0	65.0	65.0	65.0	65.0
Minimum Speed (mi/h)	14.2	7.7	20.8	30.9	40.8	54.7	60.2	62.7
Maximum Temp (deg F)	424	560	575	572	566	551	544	540

Table 5: Optimum Characteristics for Maximizing Laurel Mountain Descent Brake Temperature (Scenario Dependent)

A similar optimization effort was conducted for AZ-68 between Bullhead City and Kingman, Arizona near Davis Dam that goes through Union Pass. This stretch of highway has a speed limit of 70 mi/h (113 km/h) and a fairly constant grade of 5% over 11 miles (18 km). The

optimum accelerations and decelerations for each of the brake apply conditions were always at the simulation's maximum permissible values of 0.3 g and 0.1 g respectively until the number of applies was fewer than about forty. At that point the optimum deceleration began to decrease in order to utilize the full 11 mile grade length. Table 6 compares the optimum values for speed and deceleration/acceleration for the various number of brake applies over the Laurel Mountain descent. For this long mountain descent, the estimated brake temperature increases with the number of brake applies and reaches 1328 deg F at one thousand applies. Previously it was shown that driving at a constant speed of 70 mi/h down the 11 mile grade produced an estimated brake temperature of 483 deg F. Optimizing the brake apply schedule almost triples this value. Again, this is not a realistic scenario and would not be recommended as a test procedure.

Number of Brake Applies	20	40	60	80	1000
Deceleration (g)	0.110	0.300	0.300	0.300	0.300
Acceleration between Applies (g)	0.100	0.100	0.100	0.100	0.100
Maximum Speed (mi/h)	70.0	70.0	70.0	70.0	70.0
Minimum Speed (mi/h)	15.4	39.8	52.0	57.1	69.1
Maximum Temp (deg F)	996	1294	1314	1320	1328

Table 6: Optimum Characteristics for Maximizing Union Pass Descent Brake Temperature
(Scenario Dependent)

Figures 13 and 14 illustrate the buildup in temperature for optimum brake apply schedule with eighty and one thousand brake applies respectively.

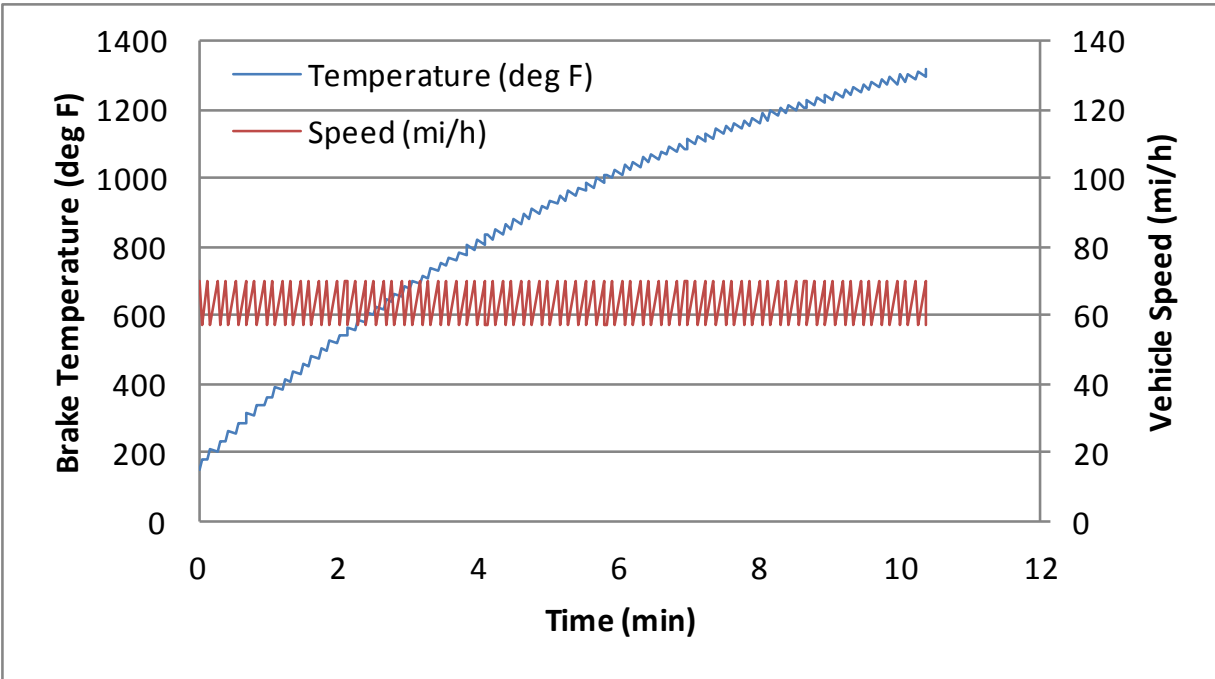


Figure 13: Union Pass Estimated Brake Temperature with Eighty Brake Applies (Scenario Dependent)

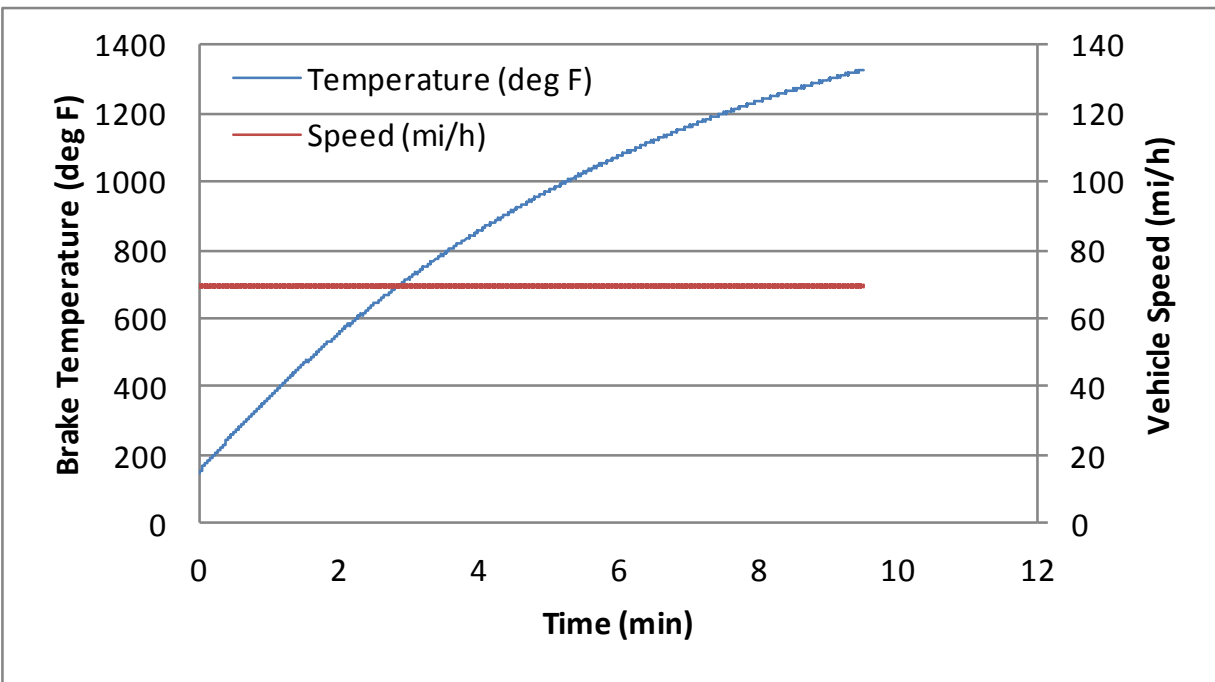


Figure 14: Union Pass Estimated Brake Temperature with One Thousand Brake Applies (Scenario Dependent)

An impromptu look at the effect of grade magnitude and length indicated that, for the vehicle represented in this simulation, descents longer than about 7 miles (11 km) continue to see higher brake temperatures as the number of brake applies increases. Shorter grades will have an optimum number of brake applies within the specified distance to reach maximum brake temperature beyond which temperatures decrease. There is some trend toward steeper descents requiring fewer brake applies over the specified distance to optimize the schedule for high brake temperatures. Again, this assumes that the decelerations and accelerations are performed in succession and the maximum and minimum speed optimized such that the distance constraint is achieved. A more structured study of the relationship between grade magnitude, length, number of brake applies, and perhaps vehicle characteristics would be necessary to provide clear and useful results.

It is important to note that frequent pulsing of the brakes to control speed within a narrow range was found by University of Michigan Transportation Research Institute (UMTRI) to have benefits in providing more even distribution of brake temperatures.[11] UMTRI conducted a study to determine the optimum mountain braking strategy to reduce the range of brake temperatures among the brakes of a tractor-semitrailer combination weighing nearly 80,000 lb. They measured individual brake temperatures while descending a 6% to 7% grade over 5 miles (8 km). Their recommended braking strategy was to repeat the cycle of releasing and applying the brakes to control speed about a desired value. The brake was released until the vehicle reached a speed 3 mi/h (4.8 km/h) above the desired speed. At this point a moderately aggressive brake application was made to reduce the speed to 3 mi/h below the desired speed.

These periodic brake applications rather than continuous light brake dragging were found to provide a more even temperature distribution among all the brakes on the vehicle. Examination of the brake drums also showed less even coloration with continuous light brake dragging that is evidence of uneven heat distribution that could lead to drum failure. Brake temperature averaged across all the brakes was similar for either strategy. These conclusions resulted in a recommendation by UMTRI for Commercial Driver's License manuals that for convenience are included in the Appendix. This verbiage should be considered for the operator's manuals of all tactical wheeled vehicles with modifications to add emphasis that prolonged brake dragging must be avoided in practice.

UMTRI's conclusion that pulsing the brakes results in similar maximum brake temperatures to those from a continuous light brake drag would appear to contradict the findings from this study. However, in this study additional energy is applied to accelerate the vehicle between brake applications, which would increase the total work done by the brakes during the descent and therefore their maximum temperature.

5.0 Conclusions

- 1) Highway mountain descents of grades longer than 8 miles (13 km) and grades exceeding 5% are not uncommon in the U.S. east and west mountain ranges and would likely produce real world brake temperatures higher, some much higher, than those seen in Government and automotive engineering society brake fade road and lab test procedures.
- 2) There are a number of mountain highway candidates that would appear to present safe environments for evaluation of brake fade. These are summarized in the Results and Discussion section 4.3.
- 3) There is an optimum constant speed for a mountain descent that will generate the highest temperature for a particular vehicle. This speed is dependent upon the grade magnitude and length, and the relationship between the vehicle weight, its resistive drag with speed, and the brake cooling with speed. For the roads and vehicle characteristics examined this speed was typically between 45 mi/h (72 km/h) and 55 mi/h (89 km/h) where speed limit did not enforce a lower value.
- 4) In general, a mountain descent brake schedule that consists of repeated brake applies with acceleration to resume the initial speed results in higher brake temperatures. Depending upon the grade magnitude and length there may be an optimum number of brake applies to generate the highest brake temperature. Long descents combined with low grade magnitudes will tend to generate a higher brake temperature with increasing number of brake applies.
- 5) Conclusion 4 can be extended to anticipate that real world mountain descent scenarios, where braking for curves is a frequent occurrence followed by accelerations to the initial speed, could exacerbate brake fade. These braking events would need to be closely spaced while allowing for a return to high speed in order to be effective in generating brake temperatures that are higher than those from an optimized constant speed down the same grade.

6.0 Recommendations

6.1 Mountain Braking Road Test Development

A mountain braking road test scenario ideally should not include artificially inserted brake applies to increase brake temperature as this reduces real world validity. Worst case realistic scenarios for high brake temperatures may likely be steep grades of sufficient length that can be traversed at a constant speed. It is conceivable that brake applications due to curves or other impediments could be spaced such that brake temperature is increased, but seems unlikely. More likely the real world frequency of braking for turns during a descent would decrease brake temperature as a result of decreasing average speed.

To determine whether a real world mountain descent scenario with and without braking events generates higher brake temperatures, more sophisticated simulations could be conducted (16)

or vehicle evaluations could be conducted on the roads recommended in Results and Discussion section 4.3. These roads have a variety of grades, lengths, and tight turn content.

In order to achieve a good method of evaluating various mountain highway venues for brake temperatures, an IPT consisting representatives from TARDEC Analytics, TARDEC Physical Simulation and Test, Program Executive Office (PEO) Combat Support & Combat Service Support (CS & CSS) to include PD-LTV, and the Army Test and Evaluation Center (ATEC) should be convened.

Issues to be considered by the IPT to provide consistent and definitive mountain highway braking venue evaluation results should include:

- Vehicle type(s) and model(s)
- Vehicle ballast, occupant, fuel level condition
- Tire and brake pad/shoe wear states and allowable range
- Vehicle performance assessment before/after each venue evaluation
 - Coastdown (SAE J1247 section 6 and figure 14)
 - Brake Effectiveness (SAE J1247 sections 5.4/5.6 and figures 4/6)
- Brake temperature at start of evaluation
- Number of event repeats
- Limits on speed control (straight and in turns)
- Deceleration rate approaching turns
- Transmission gear
- Number of test drivers
- Number of nominal vehicle speeds
- Data to be recorded

6.2 Mountain Braking Lab Test Development

A logical and desired conclusion for a mountain braking test would be to conduct the procedure in a laboratory where the environment and inputs are tightly controlled to provide more consistent results than a road test. Once a road test has been defined as proposed in section 6.1 including the mountain braking venue, a similar IPT should be convened to develop a laboratory test. Considerations need to be given as to whether or not such a test should be conducted on a full vehicle, a brake subsystem, or both. For laboratory test development, the mountain road braking test should be conducted on tactical wheeled vehicles of various types, weight class, brake system, and other variations as determined by the IPT. Lab test development should include a study of correlation to road test results of these vehicles.

6.3 Tactical Vehicle Operator's Manual Mountain Braking Verbiage

As discussed in the Results and Discussion section 4.5 of this report, it is recommended that the operator guidelines developed by UMTRI for CDL manuals should be revised as appropriate for inclusion in all tactical wheeled vehicle operator's manuals to educate drivers on how to mitigate mountain descent brake fade. The verbiage recommended by UMTRI is included in the Appendix. Reference to light dragging of the brakes on grades as being acceptable would need to be removed and emphasis added to promote brake snubbing.

7.0 References

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Appendix

UMTRI Recommendation for Commercial Driving License Manuals

The right way to go down long grades is to use a low gear and go slow. Use close to rated engine speed to maximize drag. If you go slowly enough, the brakes will be able to get rid of enough heat so they will work as they should. The driver's most important consideration is to pick a control speed that is not too fast for the weight of the vehicle, the length of the grade, and the steepness of the grade.

Drivers who are unfamiliar with routes in mountainous regions need to select a low speed to be safe. Ideally, the driver should be familiar with the route and should be prepared by knowing the appropriate speed of descent for the vehicle as loaded. However, if the driver is not familiar with which grades are long ones, the driver needs to proceed with caution-perhaps at a low speed of no more than 20 mph on long grades.

If at all possible, the driver should plan ahead and obtain information on any severe grades. Often severe grades are well marked ahead of time by highway signs, and the driver of a heavily-laden vehicle needs to heed these warnings because overheated brakes will result from travelling too fast for the severity of the mountain and the condition of the vehicle and its braking system.

To control speed going down a mountain, some people favor using a light, steady pressure to drag the brakes while others favor a series of snubs, each sufficient to slow the vehicle by approximately 6 mph in about 3 sec. The snubbing strategy uses pressures over 20 psi for heavy trucks while the light drag may involve pressures under 10 psi. Tests have shown that either method will result in approximately the same average brake temperature at the bottom of the mountain as long as the same average speed is maintained. However, the snubbing method, due to the higher pressure involved, will aid in making each brake do its fair share of the work. Hence, the snubbing method will result in more uniform temperatures from brake to brake and thereby aid in preventing brakes from overheating.

Furthermore, light, steady pressure at highway speeds on short grades of roughly one mi in length can lead to problems with "hot spotting" and drum cracking and fragmenting if the brake linings are new.

In summary, the most important considerations are to go slow enough and use the right gear. Remember that compared to a strategy based upon a light pressure dragging, the snubbing strategy will aid in making each brake do its fair share of the work and reduce the tendency for hot-spotting and drum-cracking of new or recently relined brakes.