TRANSPORTATION LEARNING NETWORK

A partnership with MDT•NDDOT•SDDOT•WYDOT and the Mountain-Plains Consortium Universities

Welcome!

MPC-540 Updating and Implementing the Grade Severity Rating System (GSRS) for Wyoming Mountain Passes

Presented by: Milhan Moomen

Our partners:

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Updating and Implementing the Grade Severity Rating System (GSRS) for Wyoming Mountain Passes

Milhan Moomen, PhD
Khaled Ksaibati, PhD, P.E

WYDOT Sponsor
James A. Evenson, P.E

November 20th , 2019

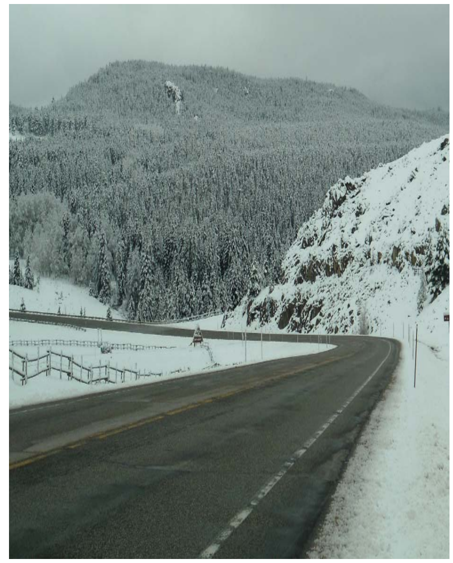
Wyoming Technology Transfer Center
WY T2
LTAP
Local Technical Assistance Program

Outline

- Introduction
- Research Tasks
- Updating the GSRS
- Formulation of WSS signs
- Recommendations
- Future Studies

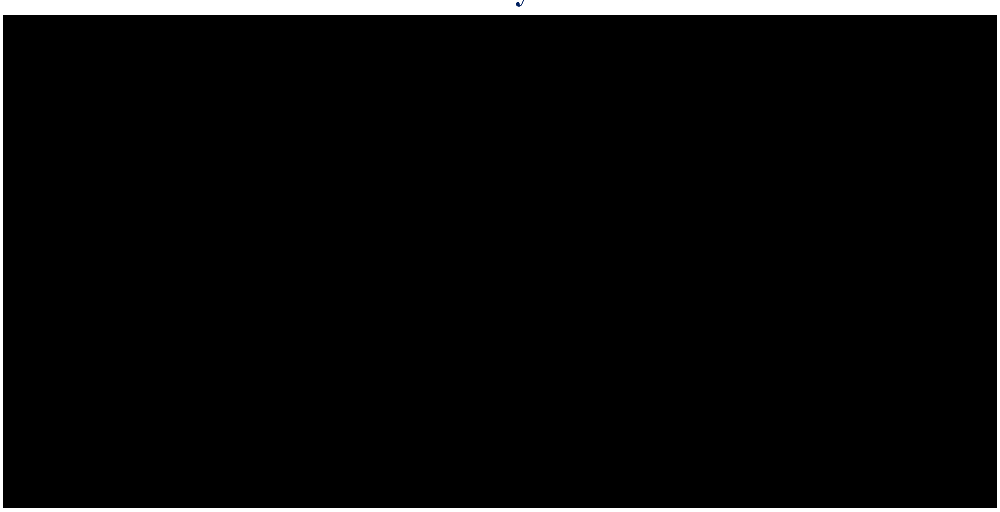
Introduction

- Mountain downgrades are some of the most unforgiving truck environments
- The combination of length and high inclines makes some downgrades hazardous
- Brake systems slow trucks by friction between shoes and drums/discs
- Continuous braking to control descent speed results in elevated temperatures in the brakes
- This increasing temperature can lead brake to brake failure and crashes with devastating consequences.



Introduction

Video of a Runaway Truck Crash



Video: https://www.youtube.com/watch?v=k_UsupHlptw

Introduction

Recent Downhill Truck Crashes

Truck driver in fiery Colorado crash charged with 40 counts, may face decades in prison

Rogel Aguilera was driving recklessly at 85 mph in a 45-mph zone before the deadly crash, a prosecutor said. Aguilera said his brakes failed.

Four people were killed and two others seriously injured in a crash on Interstate 70 near Denver. NBC News

NATIONAL

Colorado Highway Crash: At Least 4 People Killed In Fiery 28-Vehicle Pileup

April 26, 2019 · 9:09 AM ET

BILL CHAPPELL

A chain-reaction crash on I-70 near Denver killed four people and shut down the highway near Colorado Mills Parkway in both directions Thursday.

Hyoung Chang/MediaNews Group/The Denver Post via Getty Images

Source: NBC News

Source: NPR

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Introduction

Recent Downhill Truck Crashes

NEWS

Potatoes and onions sprinkle Teton Pass, driver ok

Source: Buckrail News

TANKER ROLLS OVER IN MOUNTAINOUS AREA OF US HIGHWAY 14A

KEVIN KOILE | September 9, 2014

Photo Courtesy: Wyoming Highway Patrol

Source: K2Radio

LARAMIE BOOMERANG

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Crash

Second semitrailer crash in Woods Landing raises concerns among residents

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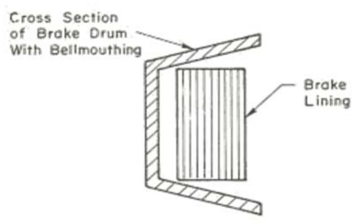
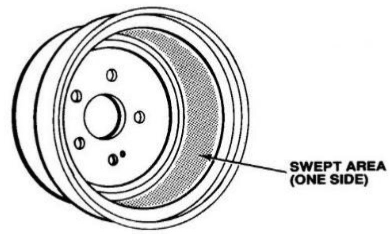
Introduction

The Grade Descent Control Problem

- High temperatures cause brake drums to expand outward and distort in shape
- Drum expansion can exceed the available distance shoe and lining can travel
- Brake fade will occur due to the reduction of braking effectiveness due to an exceeding of the brake system's thermal capacity
- On downgrades, truck speed will increase uncontrollably due to brake fade
- Total loss of control may occur with devastating consequences



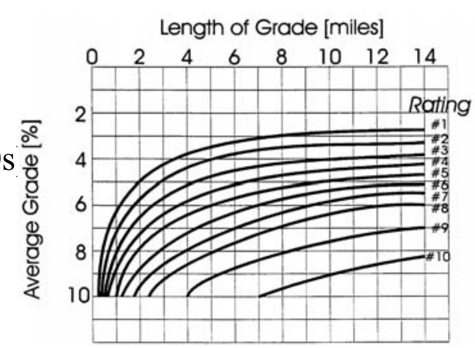


Pictures: Myers et al. 1981

Introduction

Grade Rating Systems

- Grade rating systems give drivers information about hazardous downgrades
- Drivers select descent speeds or modify driving based on information provided by the rating system
- Previous grade rating systems include:
  - Bureau of Public Roads rating system (1950s
  - Hyke's grade rating system (1963)
  - Lill's grade rating system (1975)

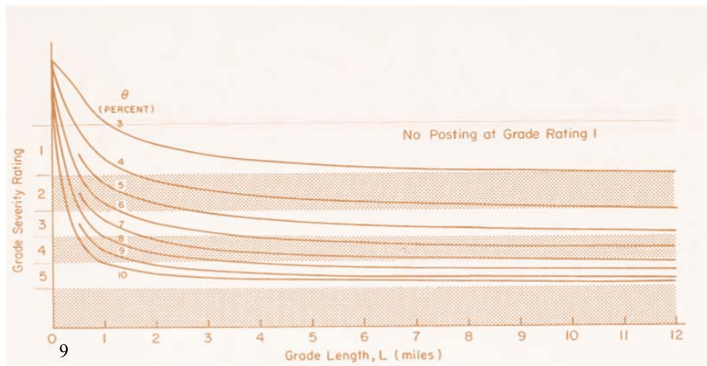


Picture: Myers et al 1981

Introduction

Grade Rating Systems

- Some of the grade rating systems were arbitrary
- Variations with severity categories created confusion among drivers
- The effects of initial brake temperatures, ambient temperatures, brake heat capacity and transfer were not considered in some rating systems
- Drivers were required to use their experience to safely travel over steep downgrades

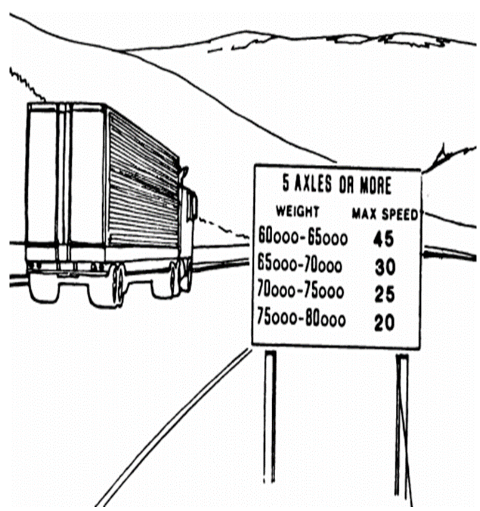


Picture: Myers et al. 1981

Introduction

What is the FHWA GSRS?

- A warning system based on brake temperature
- Developed by the FHWA
- Used to recommend safe advisory speeds to prevent brake fade
- Accomplished through the use of weight specific speed (WSS) signs
- Considers:
  - Truck weight
  - Slope of downgrade
  - Downgrade length
  - Initial temperatures of truck brakes
  - Environmental conditions



Picture: Bowman 1990

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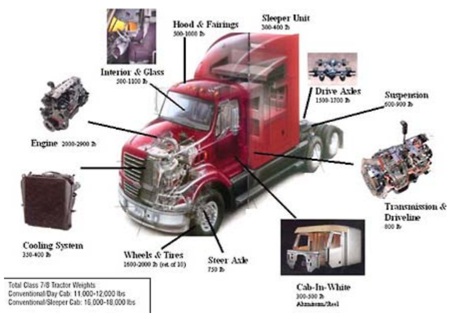
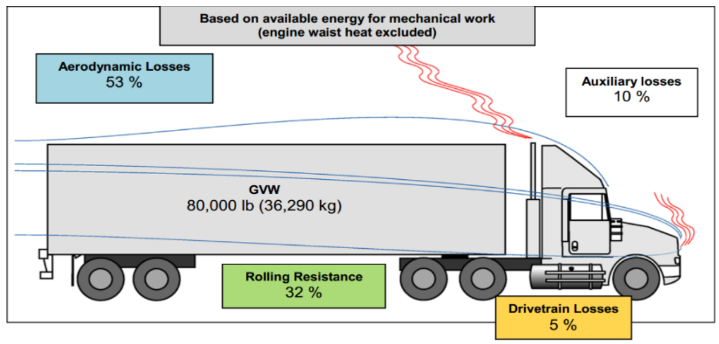
Introduction

The Need to Update the GSRS

- Efforts to conserve fuel and reduce emissions has led to improved truck designs
- The change from bias-ply to radial tires has resulted in lower rolling resistance of trucks



Picture: The National Academy Press



Picture: Woodrooffe 2014

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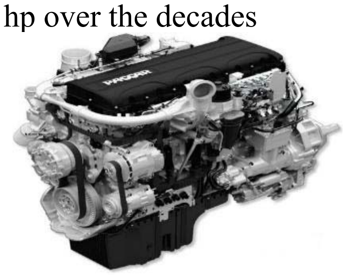
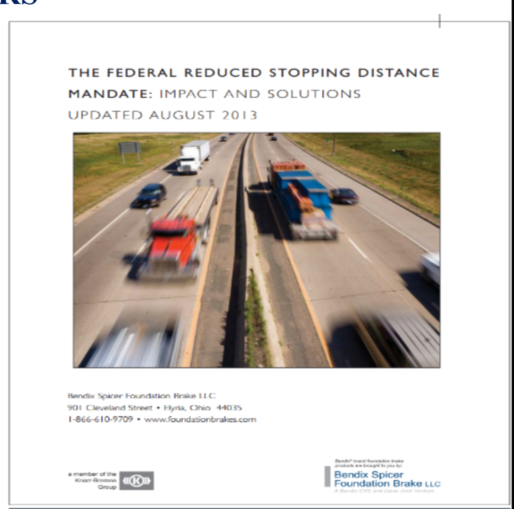
Introduction

The Need to Update the GSRS

- Truck brakes have been enhanced due to the federal reduced stopping distance mandate
- Some trucks have been fitted with disc brakes
- Engine friction reduced to enhance fuel efficiency
- Engine horsepower and braking force increased to between 400 to 550 hp over the decades





Pictures: Bendix

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Objectives

- Update the GSRS to reflect current truck designs, brake and engine characteristics and make recommendations for implementation
- Evaluate mountain passes and their warning systems with regards to downgrade truck crashes

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Research Tasks

- Selecting Representative Truck
- Developing Testing Protocol for Field Testing
- Instrumenting Test Truck
- Undertaking Field Tests
- Updating GSRS Model to Determine Maximum Descent Speed

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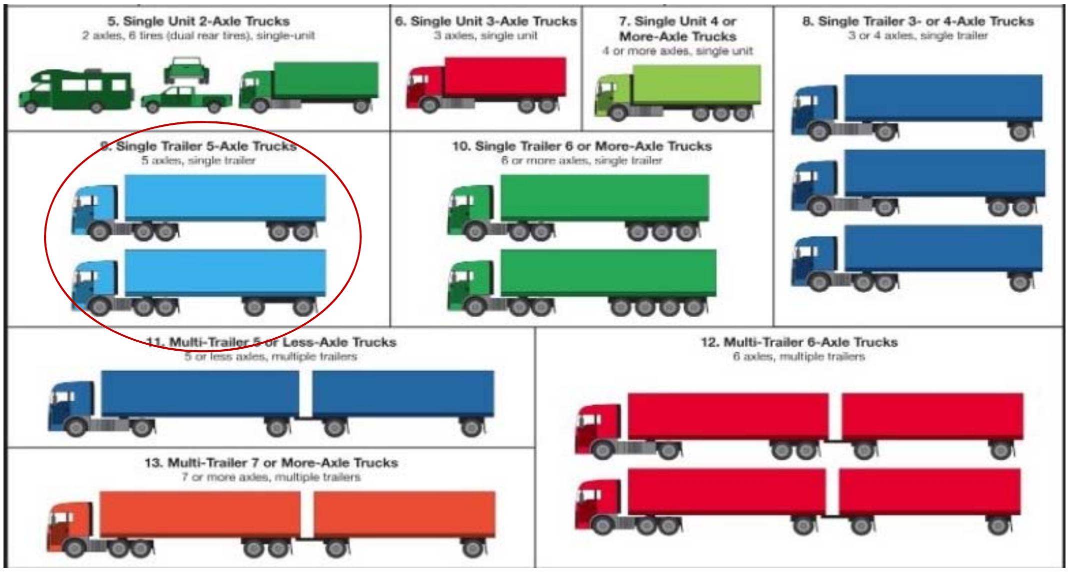
Selecting Representative Truck



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Selecting Representative Truck

Test Truck

Kenworth T680 Series
2016 Model
76 inch Sleeper
13 speed manual transmission

Hyundai Trailer (2007)
Trailer-Van
65000 GVWR
Dual Tires

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Selecting Representative Truck

Test Truck Engine

Cummins ISX15 Engine (2013)
550-Hp
2050 lb-ft torque @ 1200 rpm
1200 rpm – 2000 rpm speed range
Jacobs (Jake) Engine Brake

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Selecting Representative Truck

Tires and Brakes

Michelin (Radial) Tractor Tires
275/80R22.5
Bridgestone Dual Trailer Tires
295/75R22.5

Castlite S-Cam Drum Brakes
(Tractor and Rear)

Bendix Air Disc Front Brakes

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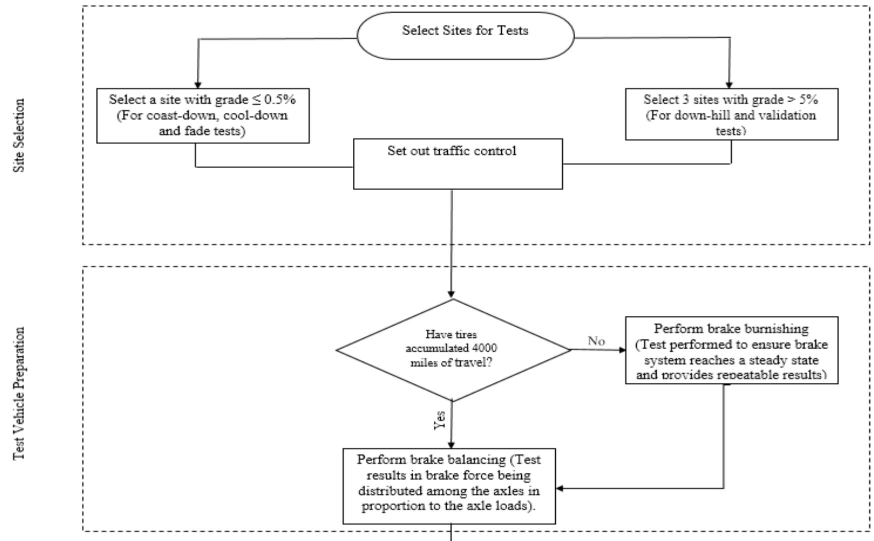
Developing Testing Protocol

GSRS Field Testing Procedure



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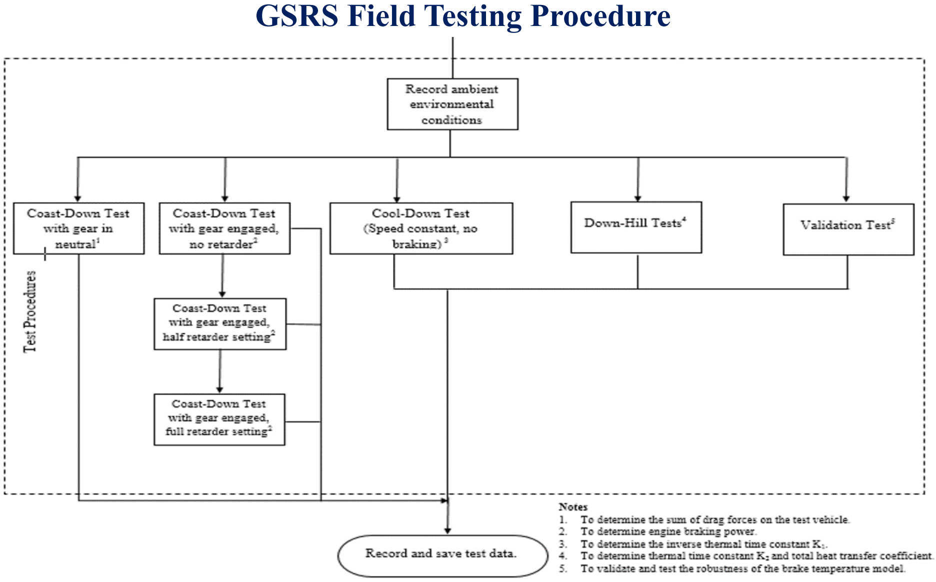
Developing Testing Protocol

GSRS Field Testing Procedure



Notes
1. To determine the sum of drag forces on the test vehicle.
2. To determine engine braking power.
3. To determine the inverse thermal time constant K_1.
4. To determine thermal time constant K_2 and total heat transfer coefficient.
5. To validate and test the robustness of the brake temperature model.

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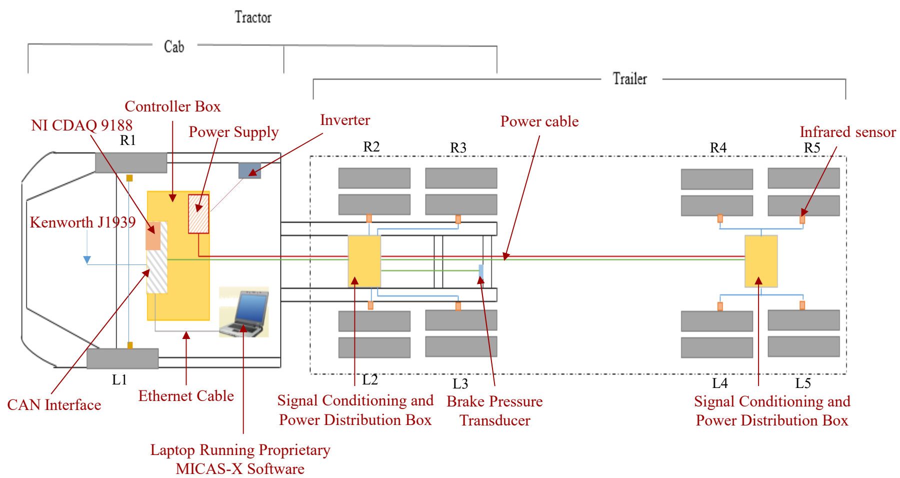
Instrumenting Test Truck



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Instrumenting Test Truck

Measured Parameters

Measured Parameter	Instrument or Sensor
Brake Temperature	Infrared sensor
Vehicle Speed	CAN bus
Deceleration	CAN bus
Vehicle Gross Weight	Weigh Station
Engine Speed	CAN bus
Coordinates	GPS
Brake Application Pressure	Pressure Transducer
Ambient Temperature	Thermocouple
Wind speed and Direction	Weather Station
Atmospheric Pressure	Weather Station
Ambient Humidity	Weather Station
Number of Snubs	CAN bus

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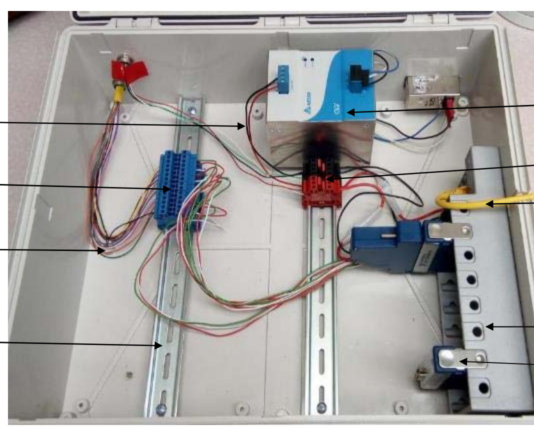
Instrumenting Test Truck

Infrared Sensors

Instrumenting Test Truck

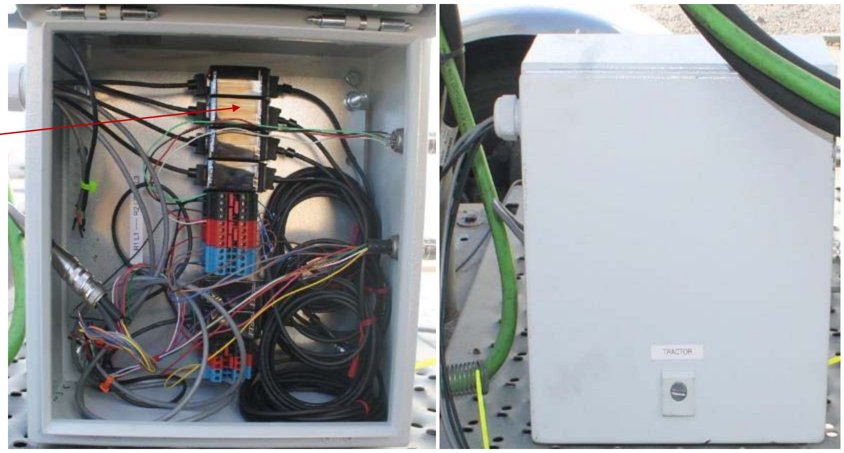
Controller Box - Cab



Instrumenting Test Truck

Signal Conditioning and Power Distribution Box - Tractor

Amplifier



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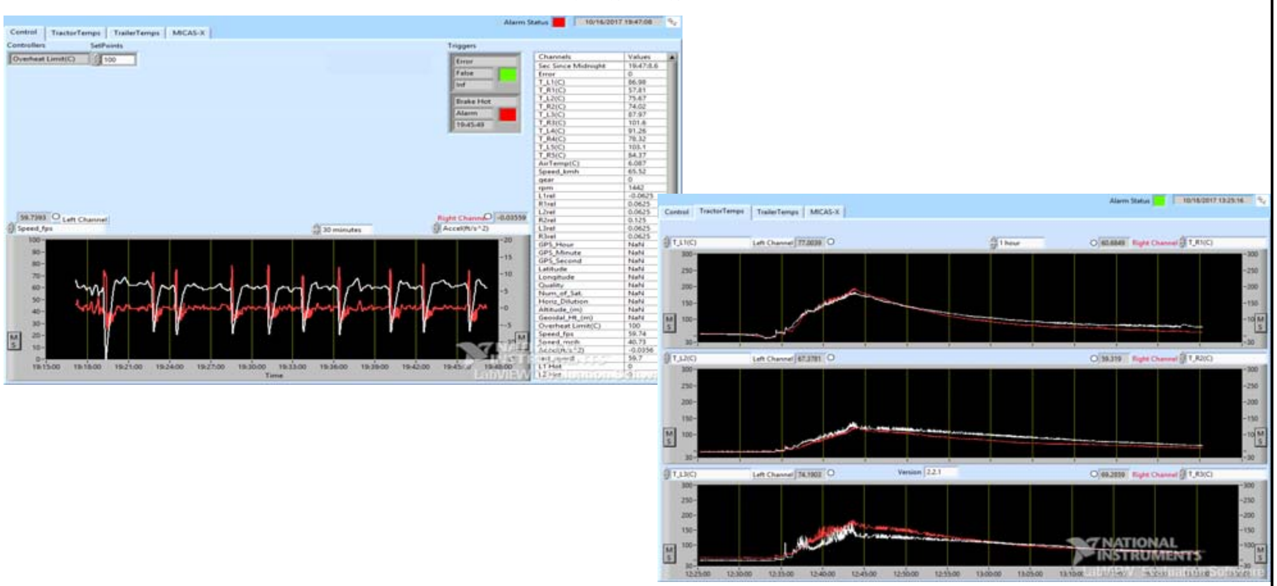
Instrumenting Test Truck

MICAS-X Software



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Instrumenting Test Truck

Load

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Field Tests and Updating the GSRS

- Three main tests performed to update the GSRS model:
  - Coast-down
  - Cool-down
  - Hill descent tests

Parameter	Expression/Value	Units
Horsepower into brakes (HP_B)	$HP_B = (W\theta - F_{drag})\frac{V}{375} - HP_{eng}$	hp
Drag forces (F_{drag})	$F_{drag} = 450 + 17.25V$	lb
Diffusivity (K_1)	$K_1 = 1.23 + 0.0256V$	1/hr
Heat transfer parameter (K_2)	$K_2 = (0.100 + 0.00208V)^{-1}$	°F/hp
Engine brake force (HP_{eng})	$HP_{eng} = 73$	hp
Ambient temperature (T_∞)	$T_\infty = 90$	°F
Initial brake temperature (T_o)	$T_o = 150$	°F

FHWA GSRS Model Parameters (Myers et al. 1980)

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Field Tests and Updating the GSRS

Brake Temperature Equation

$$T(t) = T_o + [T_\infty - T_o + K_2 HP_B][1 - e^{-K_1 t}]$$ Equation **1**

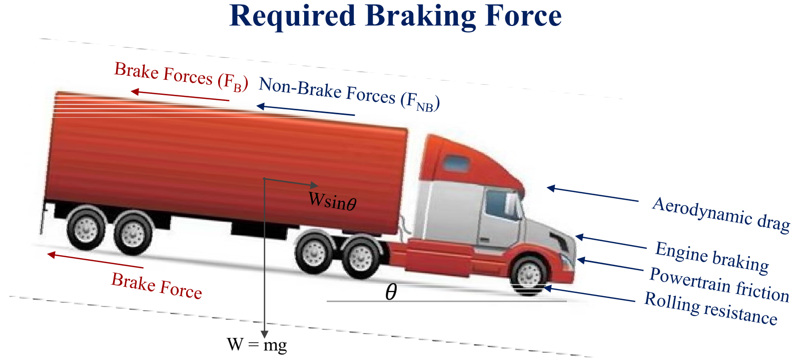
$$T(f) \leq T_{lim}$$

$$T_f = T_o + [T_\infty - T_o + K_2 HP_B]\left[1 - e^{-K_1 \frac{L}{V}}\right] \leq T_{lim}$$ Equation **2**

T_f = Final brake temperature (°F)
T_o= Initial brake temperature (°F)
T_t = Temperature at time t (°F)
T_∞ = Ambient temperature (°F)
T_{lim} = Limiting brake temperature (°F)
L = Downgrade length (miles)
V = Speed (mph)
HP_B = Horsepower into the brakes (hp)
t = Time (hr)
K_1= Diffusivity constant (hr^{-1})
K_2 = Thermal constant parameter (hp/°F)
L = Length of grade (miles)

Field Tests and Updating the GSRS

Required Braking Force



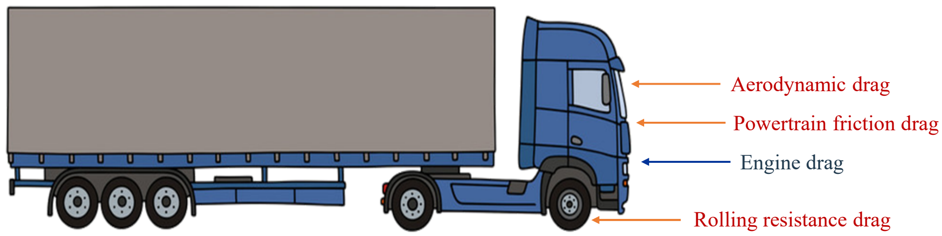
Sum of forces in downgrade direction = $W sin\theta - F_B - F_{NB}$
$= W\theta - F_B - F_{NB}$

This equation can be solved for required brake force during any level of deceleration

Required $F_B = W\theta - F_{NB}$

Determination of Drag Force (F_{drag})

- The objective of this test was to derive an expression for drag force and engine power absorption from field tests and simulation using coast-down tests
- Coast-down tests conducted according to SAE J1263 and EPA standards



- Truck coasts to a stop on level ground
- Two different tests conducted
  - With gear in neutral to measure drag forces
  - With gear and engine brake engaged to measure engine power absorption

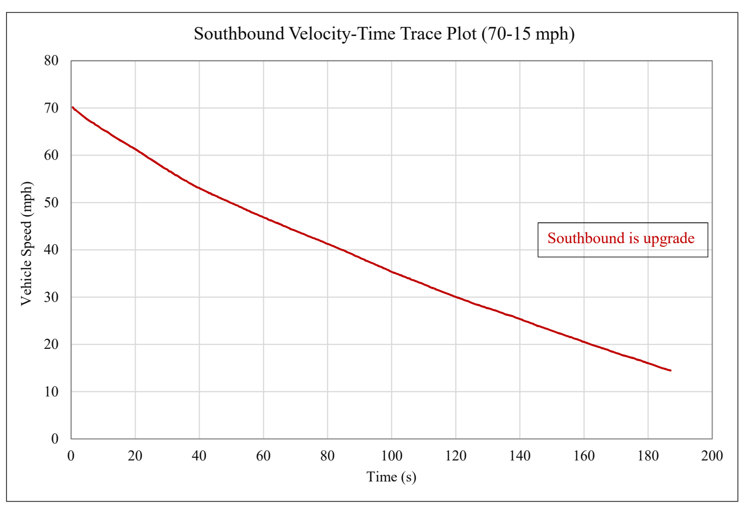
Determination of Drag Force (F_{drag})

- Drag force calculated as:

$$F_i = -M_e a_i$$

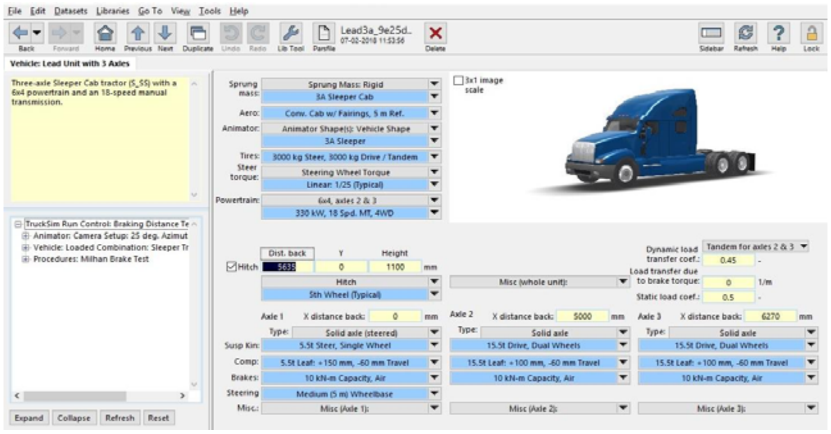
$$F_i \pm M_e g \frac{\Delta h}{\Delta s} = A_m + D v_i^2$$

Me = Effective truck mass (slugs)
a = deceleration (ft/s^2)
g = acceleration due to gravity (ft/s^2)
$\Delta h/\Delta s$ = slope
v = Speed (mph)
A_m, D = Drag coefficients



Field Tests and Updating the GSRS

Determination of Drag Force (F_{drag})



$$F_{corrected} = 357.77 + 0.785 Fsimulation$$

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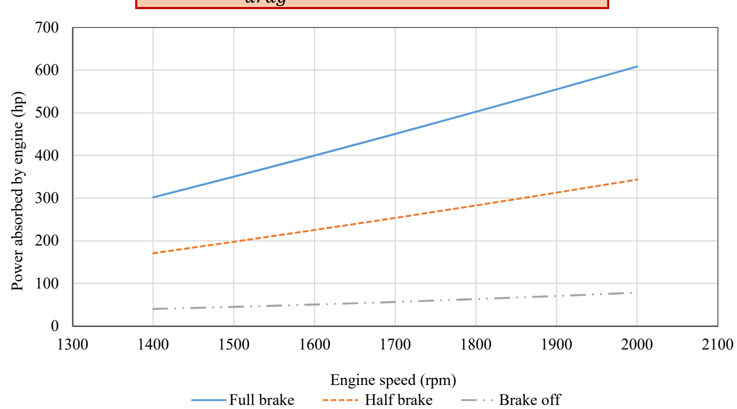
Field Tests and Updating the GSRS

Determination of Drag Force (F_{drag})

$$F_{drag} = 459.35 + 0.132V^2$$



$HP_{eng}(no\ eng.brake) = 63.3\ hp$
$HP_{eng}(full\ eng.brake) = 502.0\ hp$
@1800 rpm

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Estimating Diffusivity Parameter (K_1)

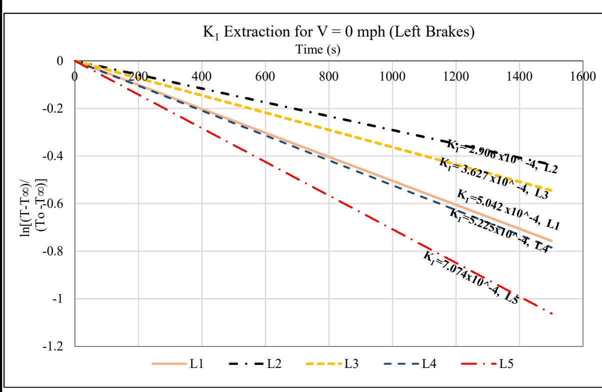
- The diffusivity parameter (K_1) defines the cooling characteristics of brakes
- K_1 derived according to Newton's Law of Cooling
- Newton's Law of Cooling states that:

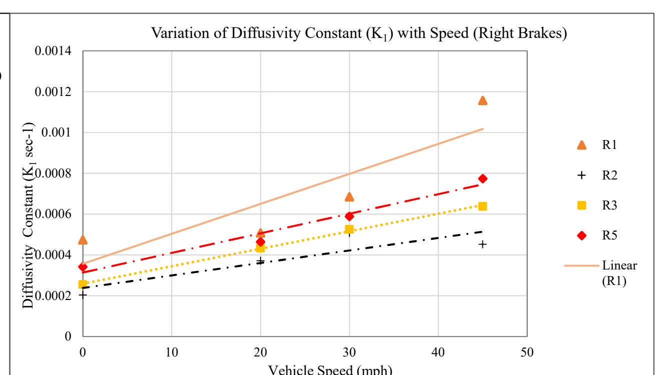
$$In\left(\frac{T - T_{\infty}}{T_o - T_{\infty}}\right) = -K_1 t$$

T = Temperature at current time (°F)
T_{∞} = Ambient temperature (°F)
T_o = Initial temperature (°F)
t = time (s)

Estimating Diffusivity Parameter (K_1)

- The diffusivity parameter (K_1) was derived as a function of speed
  - Brakes heated to an average temperature of 500°F by "dragging"
  - Truck driven at various constant speeds (0 mph, 20 mph,30 mph and 45 mph) until brakes cool to ambient temperature

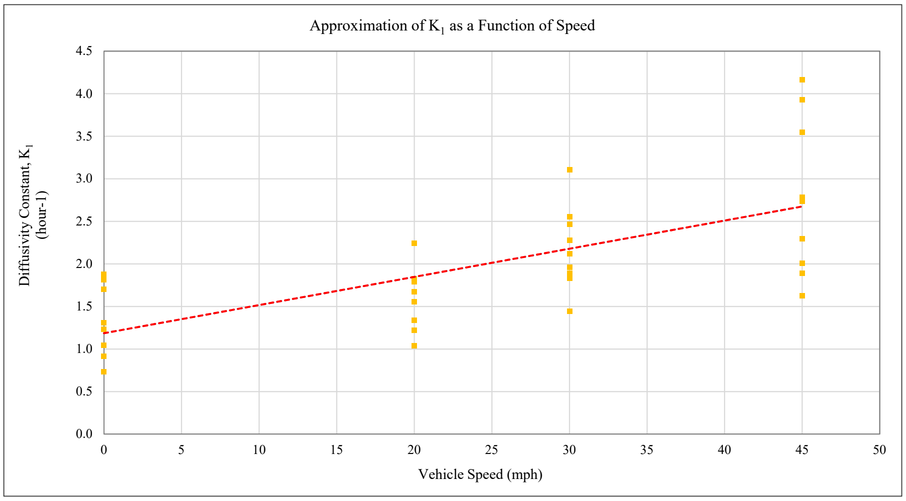




Field Tests and Updating the GSRS

Estimating Diffusivity Parameter (K_1)

$$K_1 = 1.1852 + 0.0331V$$



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Field Tests and Updating the GSRS

Estimation of Heating Parameter (K_2)

- The hill descent test correlates brake temperature with horsepower absorbed during a grade descent
- This correlation is achieved by rearranging the brake temperature equation

$$T^* = \frac{T - T_o}{1 - e^{\frac{-k_1 L}{V}}} + (T_o - T_\infty) = K_2 F_B V$$

- Given that : $F_B V = HP_B$

$$T^* = K_2 HP_B$$

T^* = Thermodynamic variables (°F)
T = Temperature at a specified time
T_∞ = Ambient temperature (°F)
T_o = Initial temperature (°F)
K_1 = Diffusivity constant (hr^{-1})
K_2 = Heating transfer parameter (hp/°F)
F_B = Brake force (lb)
V = Speed (mph)
HP_B = Horsepower into brakes (hp)
t = time (s)

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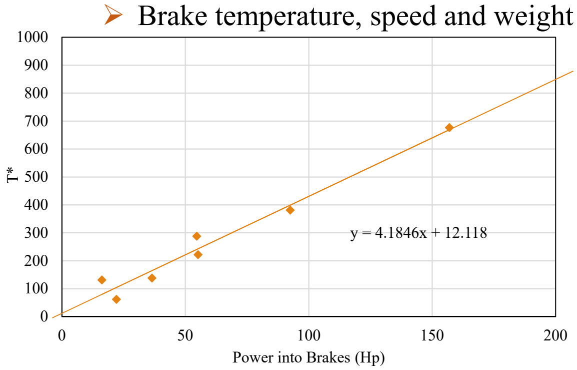
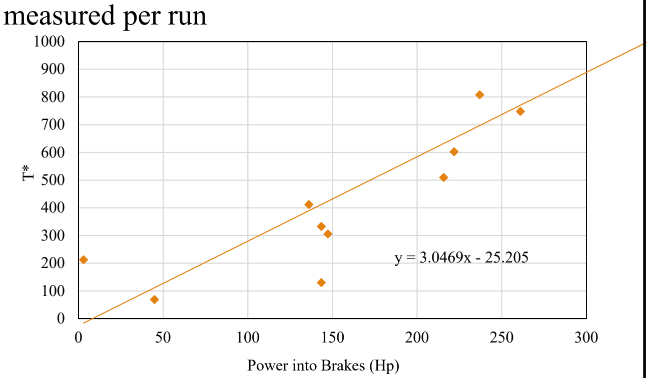
Hill Descent Test

Estimation of Heating Parameter (K_2)

- Heating constant (K_2) expressed as a function of vehicle speed (V) from hill descents
  - Hill descended at constant speed by modulating brake pressure
  - Tests conducted for different speeds (10 mph, 21 mph, 31 mph, 36 mph and 50 mph)
  - Conducted at different retarder and weight settings (80000 lb., 74,000 lb., etc)
  - Brake temperature, speed and weight measured per run



Power into the brakes at 10 mph



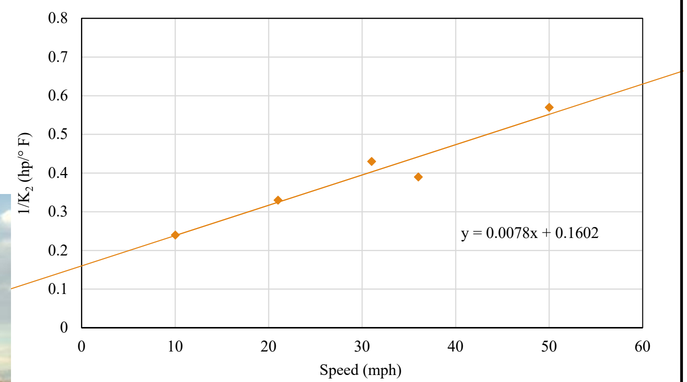
Power into the brakes at 21 mph

Field Tests and Updating the GSRS

Estimation of Heating Parameter (K_2)

- K_2 relates to V by the expression:

$$K_2 = (0.1602 + 0.0078V)^{-1}$$



Variation of heat transfer parameter $\left({}^{1}/_{K_2}\right)$ with speed

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Updating the GSRS

Updated Brake Temperature Model

Parameter	Expression/Value	Units
Horsepower into brakes (HP_B)	$HP_B = (W\theta - F_{drag})\frac{V}{375} - HP_{eng}$	hp
Drag forces (F_{drag})	$F_{drag} = 459.35 + 0.132V^2$	lb
Diffusivity (K_1)	$K_1 = 1.5x(1.1852 + 0.0331V)$	1/hr
Heat transfer parameter (K_2)	$K_2 = \frac{1}{hA_c} = (0.1602 + 0.0078V)^{-1}$	°F/hp
Engine brake force (HP_{eng})	$HP_{eng} = 63.3$	hp
Temperature from emergency stopping (T_E)	$T_E = 3.11\ x\ 10^{-7}WV^2$	°F
Ambient temperature (T_∞)	$T_\infty = 90$	°F
Initial brake temperature (T_o)	$T_o = 150$	°F

- Temperature Plots from expression:

$$L = -\frac{V}{K_1} ln\left[\frac{T_{lim} - 90 - K_2HP_B}{60 - K_2HP_B}\right]$$

- Where: $T_{lim} = T_f + T_E$

T_{lim} = Limiting temperature (°F)
T_f = Temperature from steady descent of grade (°F)
T_E = Temperature rise from emergency stop (°F)

- A limiting temperature of 500°F was used in model.

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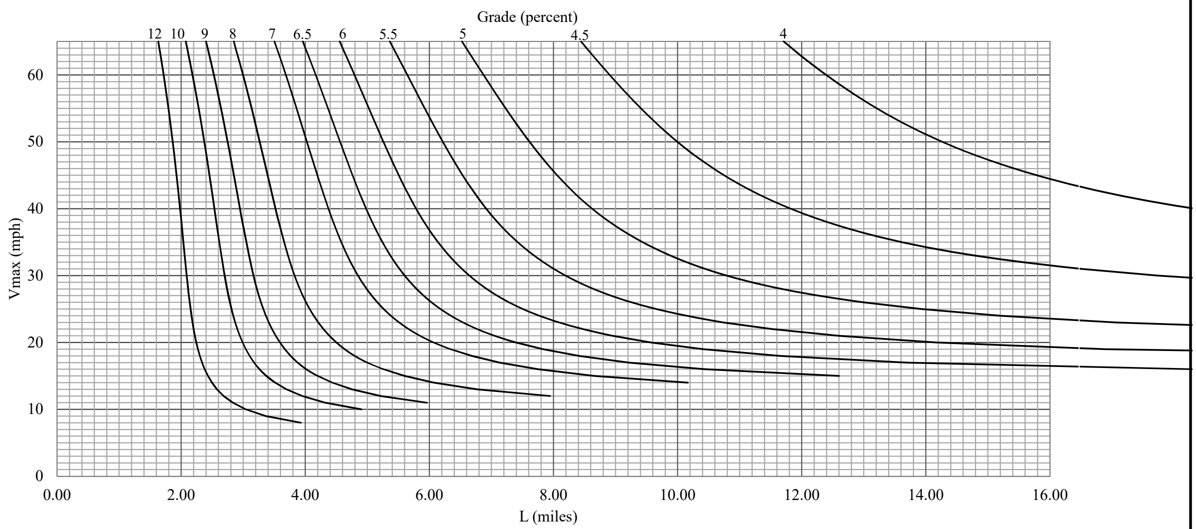
Updating the GSRS

Maximum Safe Descent Speed Plot



Maximum Speed as a function of Grade Length and Steepness for Truck Weight 80,000 lb.

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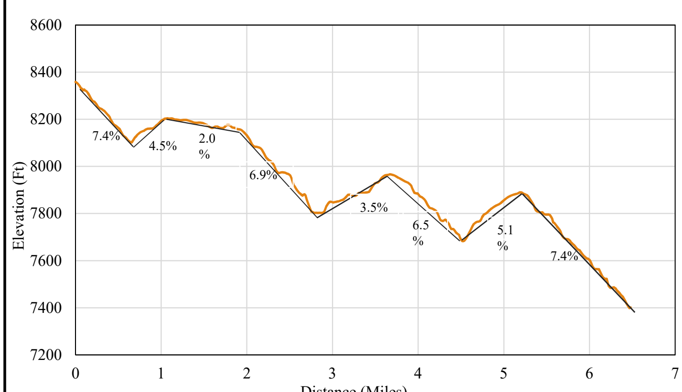
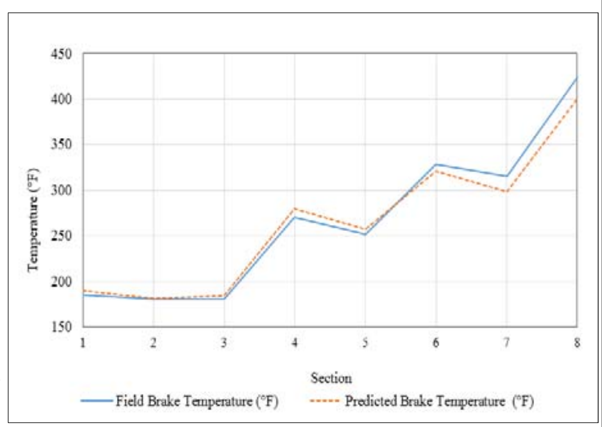
Updating the GSRS

Validation Test





US 16 Eastern face (MP 67.4 - 73.9)

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Safety Effectiveness

Safety Effectiveness of Downgrade Warning Signs

- Analyses undertaken to evaluate safety effectiveness of downgrade warning signs in preventing truck crashes
- Overall and individual sign effectiveness undertaken
- Propensity scores and cross-sectional analyses approaches used
- Overall the probability of a downgrade truck crash occurring on sections without downgrade warning signs was 15% higher in comparison to sections with warning signs
- Truck escape ramp signs, hill signs, directional and speed signs, Chevron signs, trucker warning signs and other miscellaneous downgrade signs were found to be effective in reducing crash frequency

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Safety Effectiveness

Safety Effectiveness of Downgrade Warning Signs

Truck escape ramp sign

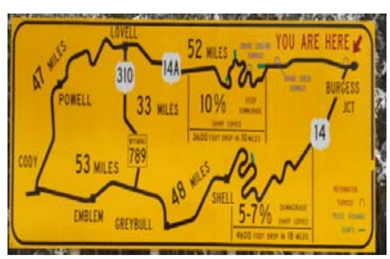
Hill sign with downgrade distance combination

Direction and speed sign combination

Hill sign

Chevron sign

Trucker sign



Miscellaneous downgrade signs

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ITS Technologies

Infrastructure and Vehicle-Based ITS Technologies

Thermal Imaging of Brakes

Picture: www.moderntiredealer.com

Dynamic Truck Curve Warning System

Picture: Smadi et al. 2014

Downhill Truck Warning System

Picture: Sisiopiku, 2000

Automatic Emerg. Braking Sys

Picture: www.moderntiredealer.com

Intelligent Speed Adaptation

Picture: www.belmog.com

On Board Monitoring Systems

Picture: www.autoalliance.org

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ITS Technologies

Connected Vehicle Technologies

Reduced Speed Zone Warning

Picture: www.firehouse.com

Spot Weather Impact Warning

Picture: fleetnewsdaily.com

Oversize Vehicle Warning

Picture: www.sa.gov.au

In-Vehicle Signage

Picture: www.its.dot.gov

Control Loss Warning

Picture: www.ltts.com

Forward Collision Warning

Picture: the frylawfirm.com

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Updating the GSRS

Updating and Implementing the GSRS – Final Reports (WY-1901F)

State of Wyoming
Department of Transportation

FINAL REPORT
WY-1901F (Vol 1)

UPDATING AND IMPLEMENTING THE GRADE SEVERITY RATING SYSTEM (GSRS) FOR WYOMING MOUNTAIN PASSES (VOLUME 1)

By:

Department of Civil & Architectural Engineering
Wyoming Technology Transfer Center
University of Wyoming
1000 E. University Avenue, Dept. 3295
Laramie, Wyoming 82071

December 2018

FINAL REPORT
WY-1901F (Vol 2)

State of Wyoming
Department of Transportation

UPDATING AND IMPLEMENTING THE GRADE SEVERITY RATING SYSTEM (GSRS) FOR WYOMING MOUNTAIN PASSES: EVALUATING THE SAFETY EFFECTIVENESS OF DOWNGRADE WARNING SIGNS (VOLUME 2)

By:

Department of Civil & Architectural Engineering
Wyoming Technology Transfer Center
University of Wyoming
1000 E. University Avenue, Dept. 3295
Laramie, Wyoming 82071

December 2018

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Formulation of WSS Signs

Users' Manual

USERS' MANUAL TO THE UPDATED GRADE SEVERITY RATING SYSTEM

By:

Milhan Moomen

Khaled Ksaibati

Department of Civil & Architectural Engineering
Wyoming Technology Transfer Center
University of Wyoming
1000 E. University Avenue, Dept. 3295
Laramie, Wyoming 82071

February, 2019

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Formulation of WSS Signs

Activities to Derive Maximum Descent Speeds

1. **Identify potential sites in need of WSS signing**
   - Analyze truck crash data, traffic data, geometric data, and police reports to identify hazardous locations that will benefit from WSS signs.

2. **Perform field inspection of sites identified**
   - Verify the percent, length of downgrades, truck braking length and traffic control of candidate sites.

3. **Determine grade severity**
   - Estimate maximum safe descent speeds for different weight categories using the grade percent and truck braking length

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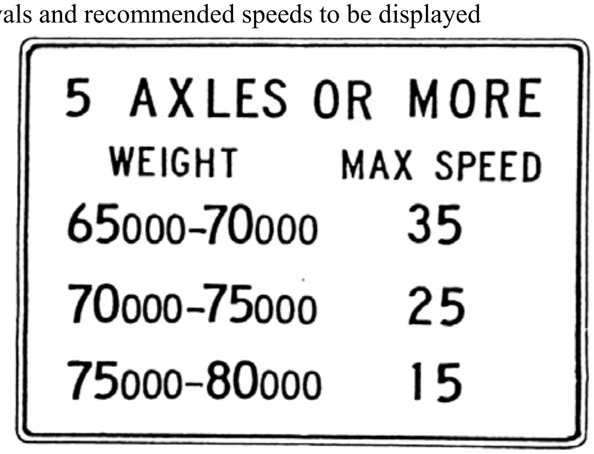
Formulation of WSS Signs

Activities to Derive Maximum Descent Speeds

4. **Determine WSS signing needs**
   - Determine the appropriate weight intervals and recommended speeds to be displayed on the WSS sign.

5. **Install WSS signs**
   - Construct and install WSS signs



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Formulation of WSS Signs

WSS Signs from GSRS

Formulating WSS Signs

1. Determine the grade percent (θ) and truck braking length (L) in miles, maximum load limit and maximum speed limit on the downgrade.
2. Using the plots of V_{max} versus L for various values of θ, determine the heaviest weight, W_L , that is an integral multiple of 5000 lb, and for which V_{max} is greater than or equal to the speed limit.
3. Compute the number of 5,000 lb weight interval (N) between W_L and the weight at the maximum speed limit, W_M from:

$$N = \frac{W_M - W_L}{5{,}000}$$

4. If N is less than or equal to 5, the column of weights will begin with W_L and increase in 5,000 lb increments to the load limit, W_M.
5. If N is greater than 5, the column of weights for placement on the WSS sign will begin with the lower weight, (W_L) and increase in 10,000 lb to the load limit, W_M.
6. The speed associated with each weight interval for the WSS sign (defined by the two adjacent weights in the weight column) will be the safe downgrade speed for the heaviest weight of the interval. The maximum speeds are then placed in columns for each weight category.

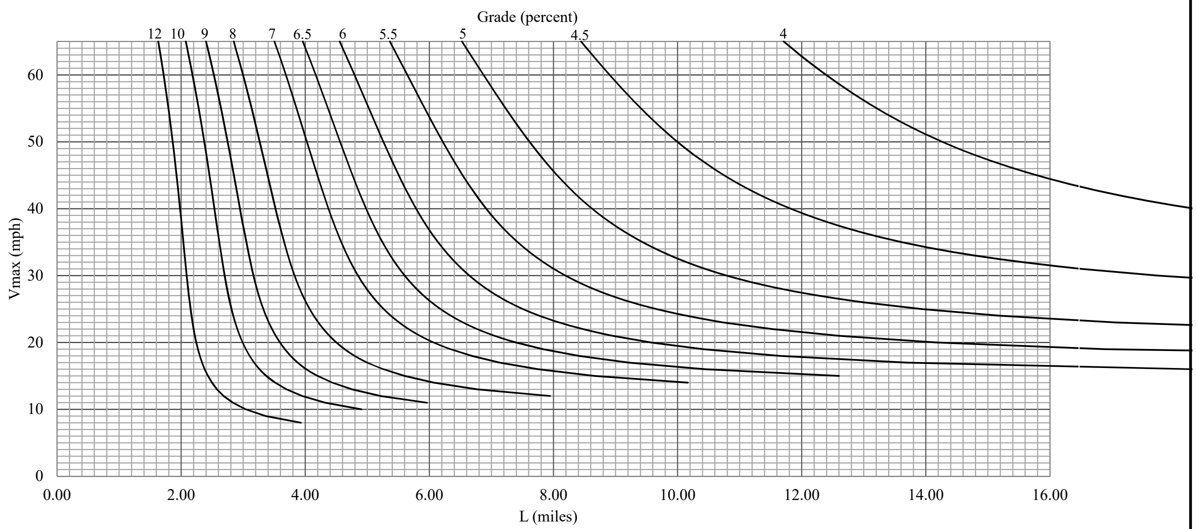
Formulation of WSS Signs

WSS Signs from GSRS – Case Study

- Case Study (Using the Updated GSRS model:
  - Downgrade incline = 7.0%
  - Braking length = 6.5 miles
  - Maximum weight = 80,000 lb.
  - Speed Limit = 55 mph
- The first step is to determine the number of intervals N which should be placed on the WSS sign
- Using the plots of V_{max} versus L plot for different values of θ, the highest integral multiple of 5000 lb for which V_{max} is greater than 55 mph is 60,000 lb.

Updating the GSRS

Maximum Safe Descent Speed Plot



Maximum Speed as a function of Grade Length and Steepness for Truck Weight 80,000 lb.

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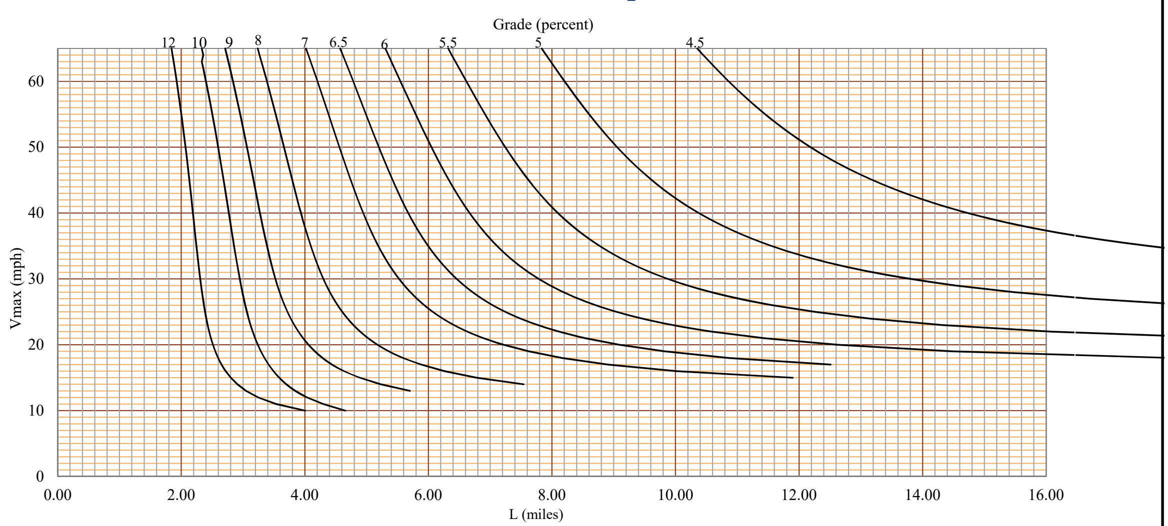
Formulation of WSS Signs

Maximum Safe Descent Speed Plot



Maximum Speed as a function of Grade Length and Steepness for Truck Weight 75,000 lb

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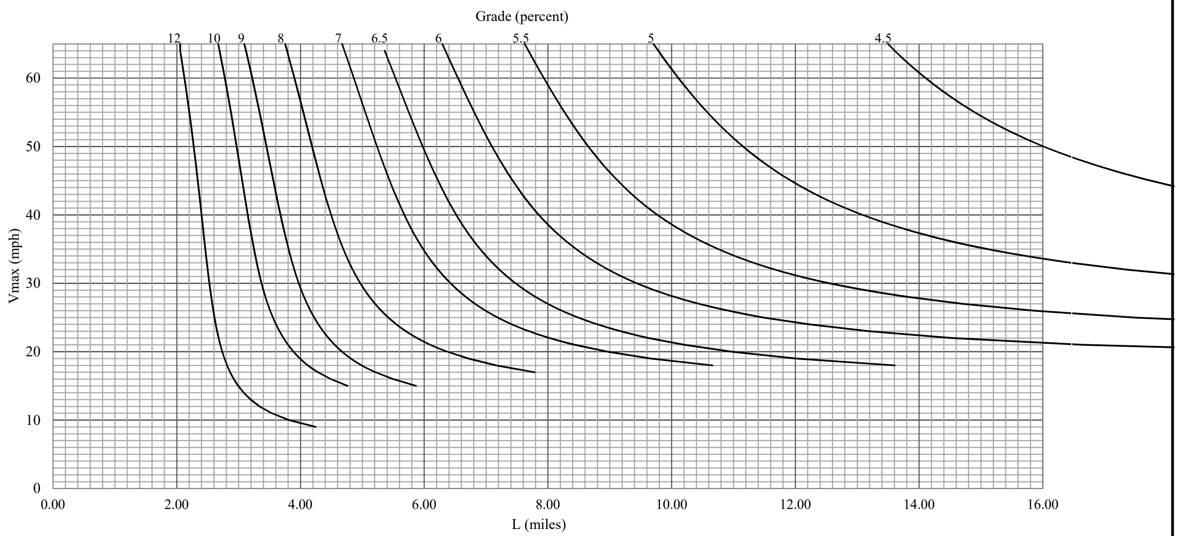
Formulation of WSS Signs

Maximum Safe Descent Speed Plot



Maximum Speed as a function of Grade Length and Steepness for Truck Weight 70,000 lb.

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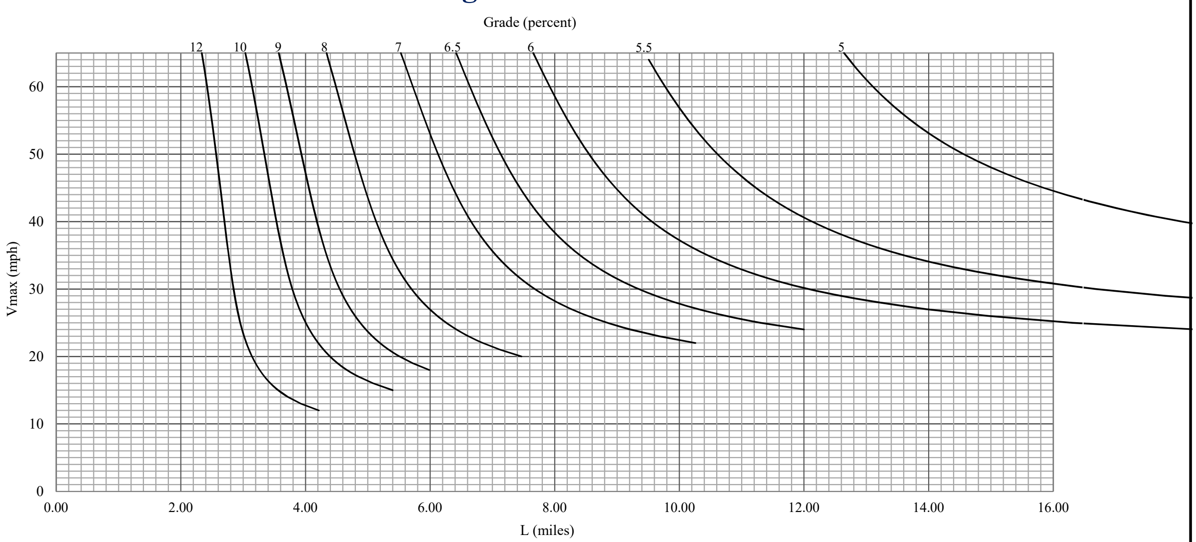
Formulation of WSS Signs

WSS Signs from GSRS



Maximum Speed as a function of Grade Length and Steepness for Truck Weight 65,000 lb.

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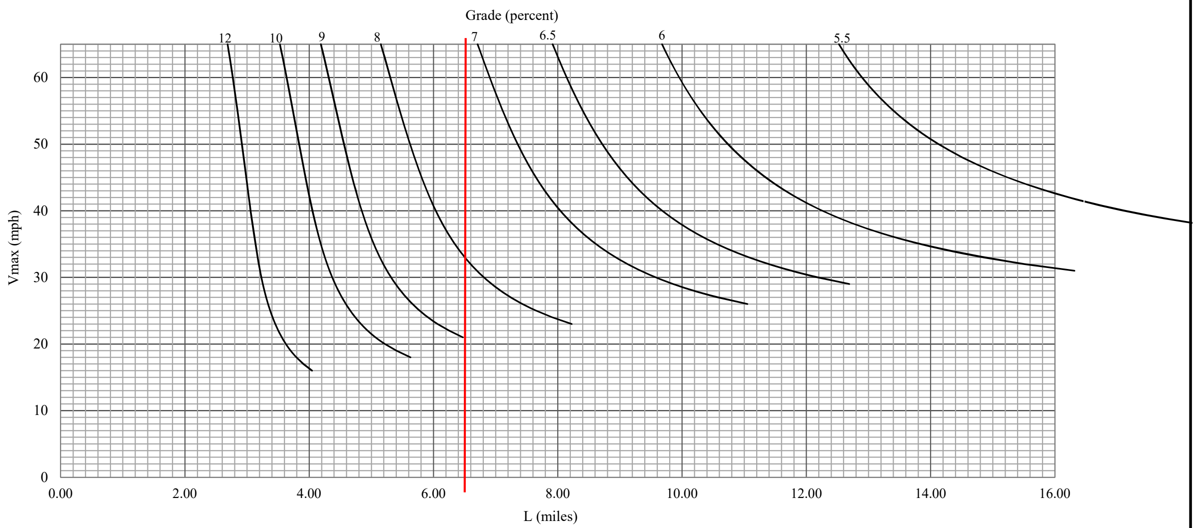
Formulation of WSS Signs

WSS Signs from GSRS



Maximum Speed as a function of Grade Length and Steepness for Truck Weight 60,000 lb.

Formulation of WSS Signs

WSS Signs from GSRS

- The number of weight categories on the WSS signs will be:

$$N = \frac{80{,}000-60{,}000}{5{,}000} = 4$$

- $N = 4$. N <5, so the column of weights will begin with 60,000 lb and increase in 5,000 lb increments to 80,000 lb.
- From the V_{max} versus L plots, the maximum truck weights and corresponding speeds are :

Maximum Truck Weight (lb)	Maximum Safe Speed (mph)
80,000	18
75,000	22
70,000	29
65,000	42
60,000	55

Advisory Maximum Descent Speeds

Weight Increments (lb)	Maximum Safe Speed (mph)
61,000 - 65,000	40
66,000 - 70,000	30
71,000 - 75,000	25
76,000 - 80,000	20

Recommendations

- Installation of WSS signs from the updated and validated GSRS model will enhance truck safety on Wyoming mountain passes. Maximum safe speeds displayed on the WSS signs cannot be currently enforced and are to be considered only as advisory speeds.
- Drivers should be educated on the use of the GSRS and WSS signs. The education should also focus on improving mountain driving for inexperienced drivers and those unfamiliar with mountain passes.
- The trucking industry should be encouraged to adopt and install disc brakes, especially for fleets which frequently travel over mountain passes. Disc brakes are much more resistant to brake fade and their adoption will reduce the incidence of runaway crashes on mountain passes.
- Brake systems have to be regularly checked and maintained. Attention should be paid to reducing brake imbalance on truck fleets.

Recommendations

- Trucks equipped with retarders should be set to their maximum setting on downgrades. The trucks should then descend the downgrade at the highest speed displayed on the WSS sign.
- The test truck used to update the GSRS model was fitted with disc brakes on the steer axles. However, the current penetration of disc brakes in the American market is about 20% and is continuously growing. The GSRS will become fully implementable once the proportion of trucks fitted with disc becomes substantial.
- Before-after studies should be conducted after implementation of the GSRS/WSS signs to assess their safety effectiveness. The empirical bayes method may be adopted if suitable data is available.

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Future Studies

- More tests should be conducted to validate the GSRS model especially for higher truck loads and axles.
- The use of the GSRS will be simplified if a software is developed to estimate maximum descent speeds from the model. This will also enable engineers to easily calculate safe speeds for multi-grade hills.
- The presence of curves on downgrades should be incorporated into the procedure for estimating maximum descent speeds. This may be included in the software
- Before-after studies should be conducted after implementation of the GSRS/WSS signs to assess their safety effectiveness.

Acknowledgements

ADMIRAL TRANSPORT CORP.

TSC

WYOMING TRANSPORTATION DEPARTMENT

MPC
MOUNTAIN-PLAINS CONSORTIUM

Questions??

Updating and Implementing the Grade Severity Rating System for Wyoming Mountain Passes

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Formulation of Weight Specific Speed Signs (Case Studies)

Table 1 Overview of the GSRS Procedure and Activities (Bowman, 1989)

Step Definition	Purpose	Output
1. Identify Potential Sites in Need of WSS Signing Activity 1 - Identify the locations of all severe downgrades. Activity 2 - Collect and analyze truck crash and volume data. Activity 3 - Determine the magnitude of the truck runaway problem.	To develop a list of all possible project sites and to determine which of these possible sites are probable candidates for further analysis. Data used to accomplish this purpose include geometric, police, maintenance and accident data.	A list of downgrade locations that would benefit from the installation of WSS signs.
2. Perform Field Inspection of Sites Identified Activity 1 - Verify percent and length of downgrade. Activity 2 - Perform site familiarization and observational studies. Activity 3 - Determine truck braking length.	To obtain a familiarity of geometric conditions, presence of traffic control devices and potential hazards. The last activity of the field review consists of performing necessary field measurements to obtain the percent and physical length of grade.	Knowledge of the geometric and traffic control conditions of the site. Measurement of the percent and physical length of grade and a determination of the truck braking length.
3. Determine Grade Severity Activity 1 - GSRS/WSS considerations. Activity 2 - Determine grade severity.	To determine the maximum safe downgrade speeds for different weight categories using the percent and truck braking length.	A list of maximum safe downgrade speeds for different categories of truck weight.
4. Determine WSS Signing Needs	To determine the number of weight intervals and associated maximum safe downgrade speeds.	A determination of the weight intervals and recommended safe downgrade speeds to be placed on the WSS sign.
5. Install WSS Signs	To present concerns that should be followed when constructing and installing WSS signs.	WSS sign design and placement criteria.

Determining Maximum Safe Speed for Different Weight Categories

The following procedure is used to determine the WSS weights and safe speeds for any grade (Bowman, 1989; Johnson et al., 1982):

1. Determine the percent of grade (θ), the truck braking length (L) in miles, maximum load and speed limits on the downgrade.

2. Using the plots of V_{max} versus L for various values of θ, determine the heaviest weight, W_L , that is an integral multiple of 5000 lb, and for which V_{max} is greater than or equal to the speed limit.

3. Compute the number of 5,000 lb weight intervals (N) between W_L and the weight at the maximum speed limit, W_M from:

$$N = \frac{W_M - W_L}{5,000}$$

4. If N is less than or equal to 5, the column of weights will begin with W_L and increase in 5,000 lb increments to the load limit, W_M.

5. If N is greater than 5, the column of weights for placement on the WSS sign will begin with the lower weight, (W_L) and increase in 10,000 lb increments to the load limit, W_M.

6. The speed associated with each weight interval for the WSS sign (defined by the two adjacent weights in the weight column) will be the safe downgrade speed for the heaviest weight of the interval. The maximum speeds are then placed in columns for each weight category

Three case studies are used to demonstrate the formulation of WSS signs. This is presented below. The case studies presented here are for single downgrades.

Case Study 1

The downgrade used for this case study is a section of the Loveland Pass in the Colorado Rockies on the Continental Divide. The Loveland pass is located on U.S. Highway 6 close to the town of Dillon in Colorado. The load limit on the roadway is 80,000 lb. The downgrade percent for the section is 6% with an 8.4-mile truck braking length. The speed limit for the section is 45 mph.

Downgrade Characteristics

Percent downgrade (%): 6

Braking length (L) (miles): 8.4

Maximum load limit (W_M) (lb): 80,000

Maximum speed limit (mph): 45 mph

- From the V_{max} versus L plot for 80,000 lb (Figure 3), a line is traced from the 8.4 mile line on the x-axis to the 6% curve. The point where the line and curve intersect is then traced to the y-axis where V_{max} is read.

- This exercise is continued for different weights until the weight for which V_{max} is greater than or equal to 45 mph is found. For this case study, the highest integral multiple of 5000 lb for which V_{max} is greater than or equal to 45 mph is 65,000 lb (Figure 6).

- The number of weight categories N is calculated as:

$$N = \frac{80{,}000 - 65{,}000}{5{,}000} = 3$$

- Since N = 3, the column of weights will begin with 65,000 lb and increase in 5,000 lb increments to 80,000 lb.

- From the V_{max} versus L plots, the maximum truck weights and corresponding speeds are (Table 2):

Table 2. Truck Weights and Estimated Safe Speeds (Case Study 1)

Maximum Truck Weight (Pounds)	Maximum Safe Speed (mph)
80,000	22
75,000	27
70,000	35
65,000	45

- The weight intervals and corresponding maximum safe speeds determined as appropriate for the WSS sign are (Table 3):

Table 3. Weight Categories and Approximate Safe Speeds (Case Study 1)

Maximum Truck Weight (Pounds)	Maximum Safe Speed (mph)
66,000 – 70,000	35
71,000 – 75,000	30
76,000 – 80,000	20

Case Study 2

The downgrade section used for this case study forms part of US highway 14 in northern Wyoming close to Dayton. This is a long downgrade stretch with an average slope of 6% and 12 miles long, with a speed limit of 40 mph. For demonstration purposes, it is assumed the maximum weight limit on this highway is 90,000 lb.

- From the V_{max} versus L plot 90,000 lb (Figure 1), a line is traced from the 12 mile line on the x-axis to the 6% curve. The point where the line and curve intersect is then traced to the y-axis where V_{max} is read.

- This exercise is first done for the maximum weight of 90,000 lb continued for different weights until the weight for which V_{max} is greater than or equal to 40 mph is found. For this case study, the highest integral multiple of 5000 lb for which V_{max} is greater than or equal to 40 mph is 60,000 lb (Figure 7).

- The number of weight categories N is calculated as:

$$N = \frac{90{,}000 - 60{,}000}{5{,}000} = 6$$

- Since N > 5, the column of weights will begin with 60,000 lb and increase in 10,000 lb increments to 90,000 lb.

- From the V_{max} versus L plots, the maximum truck weights and corresponding speeds are (Table 4):

Table 4. Truck Weights and Estimated Safe Speeds (Case Study 3)

Maximum Truck Weight (Pounds)	Maximum Safe Speed (mph)
90,000	14
80,000	18
70,000	24
60,000	40

- The weight intervals and corresponding maximum safe speeds determined as appropriate for the WSS sign are (Table 5):

Table 5. Weight Categories and Approximate Safe Speeds (Case Study 3)

Maximum Truck Weight (Pounds)	Maximum Safe Speed (mph)
60,000 – 70,000	25
71,000 – 80,000	20
81,000 – 90,000	15

Case Study 3

The downgrade segment used for this case study is located on the Vail Pass on Interstate 70. The load limit on the roadway is 80,000 lb. The downgrade is 7% with 7 miles of truck braking length. The speed limit for the section has been set at 65 mph.

- From the V_{max} versus L plot for 80,000 lb (Figure 3), a line is traced from the 7 mile line on the x-axis to the 7% curve. The point where the line and curve intersect is then traced to the y-axis where V_{max} is read.

- This exercise is continued for different weights until the weight for which V_{max} is greater than or equal to 65 mph is found. For this case study, the highest integral multiple of 5000 lb for which V_{max} is greater than or equal to 65 mph is 55,000 lb (Figure 8).

- The number of weight categories N is calculated as:

$$N = \frac{80{,}000 - 55{,}000}{5{,}000} = 5$$

- Since N = 5, the column of weights will begin with 55,000 lb and increase in 5,000 lb increments to 80,000 lb.

- From the V_{max} versus L plots, the maximum truck weights and corresponding speeds are (Table 6):

Table 6. Truck Weights and Estimated Safe Speeds (Case Study 3)

Maximum Truck Weight (Pounds)	Maximum Safe Speed (mph)
80,000	17
75,000	21
70,000	26
65,000	36
60,000	58
55,000	65

- The weight intervals and corresponding maximum safe speeds determined as appropriate for the WSS sign are (Table 7):

Table 7. Weight Categories and Approximate Safe Speeds (Case Study 3)

Maximum Truck Weight (Pounds)	Maximum Safe Speed (mph)
55,000 – 60,000	60
61,000 – 65,000	35
66,000 – 70,000	25
71,000 – 75,000	20
76,000 – 80,000	15

MAXIMUM SAFE SPEED PLOTS

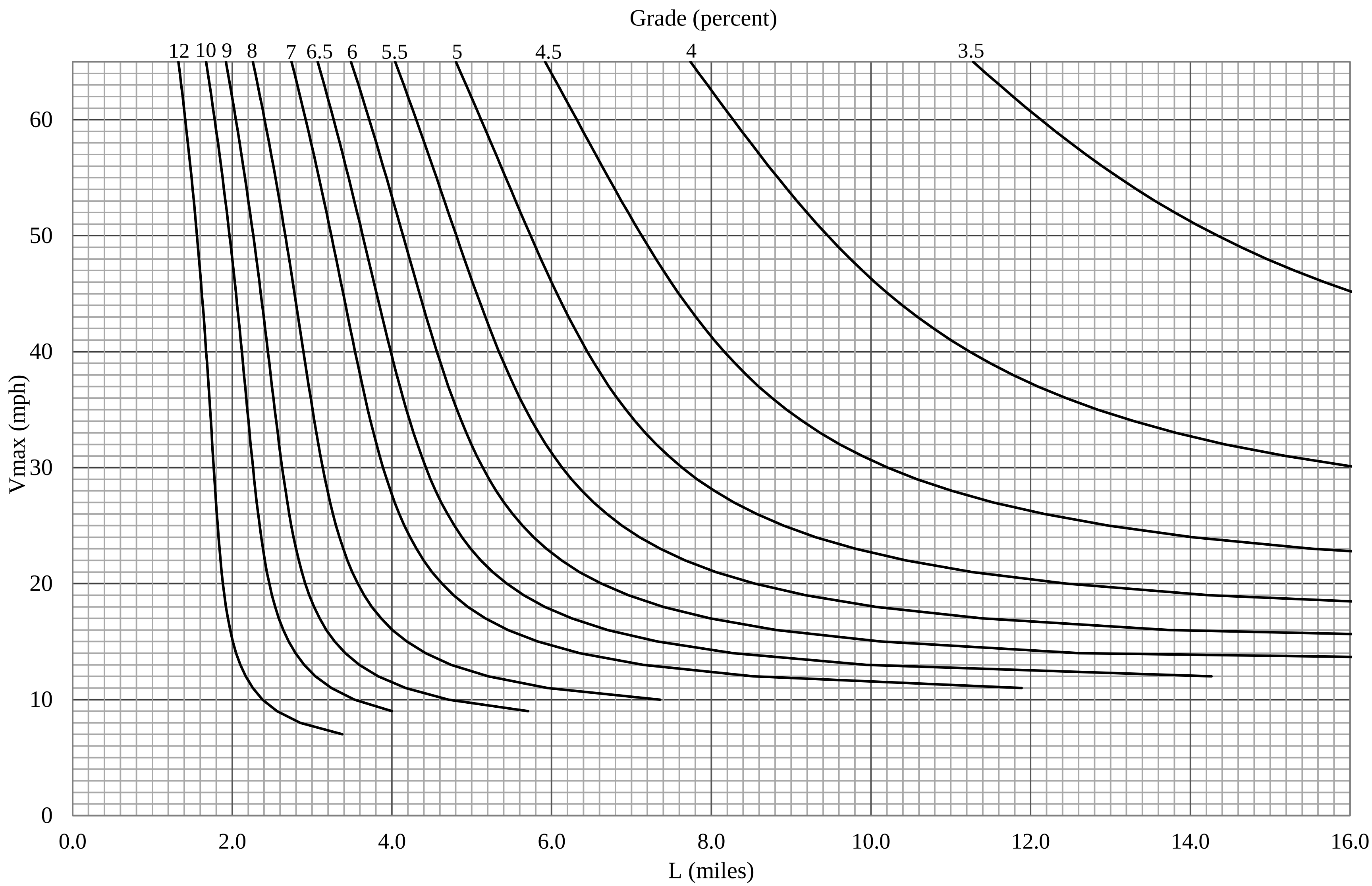

Figure 1. Graph. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 90,000 lb

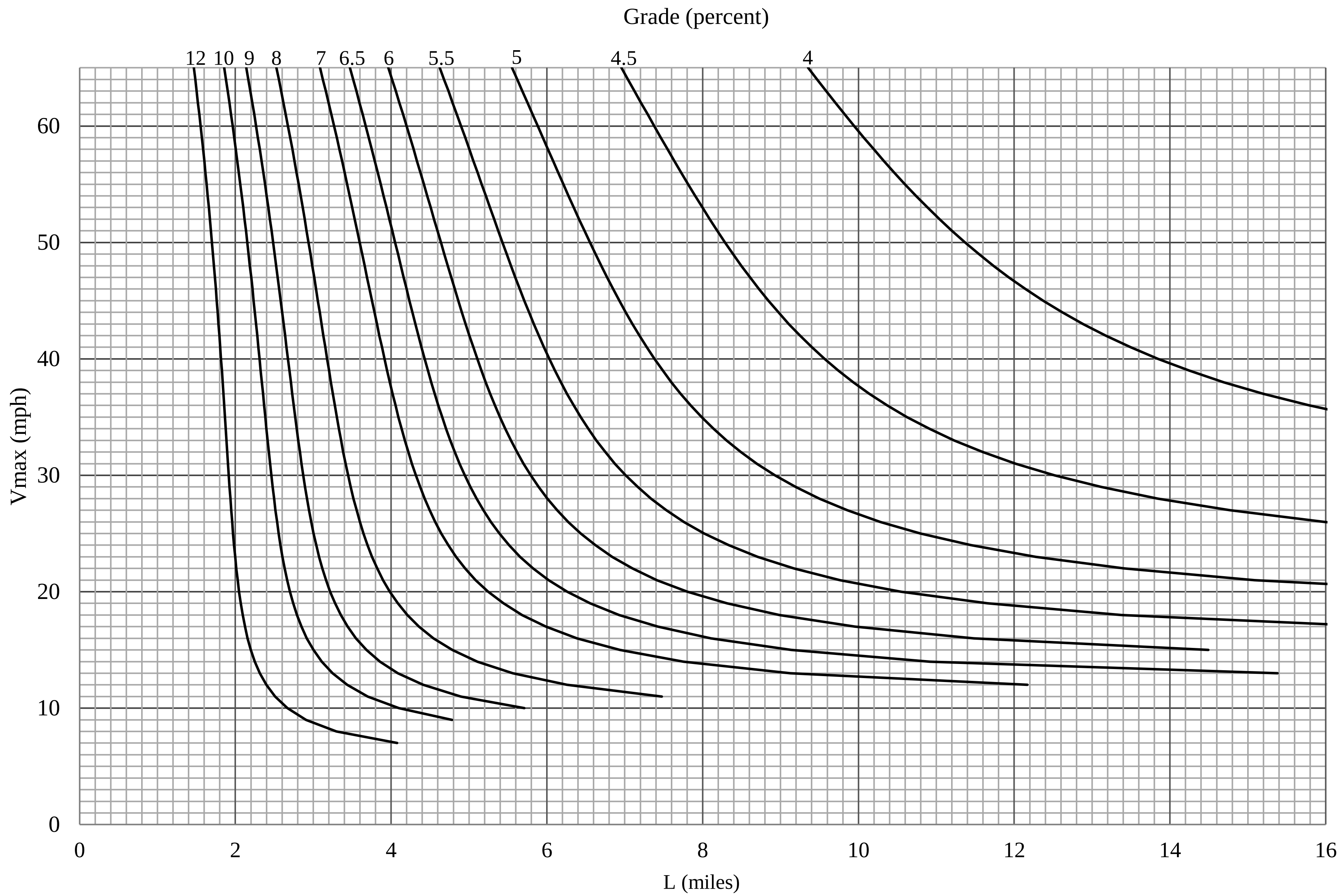

Figure 2. Graph. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 85,000 lb

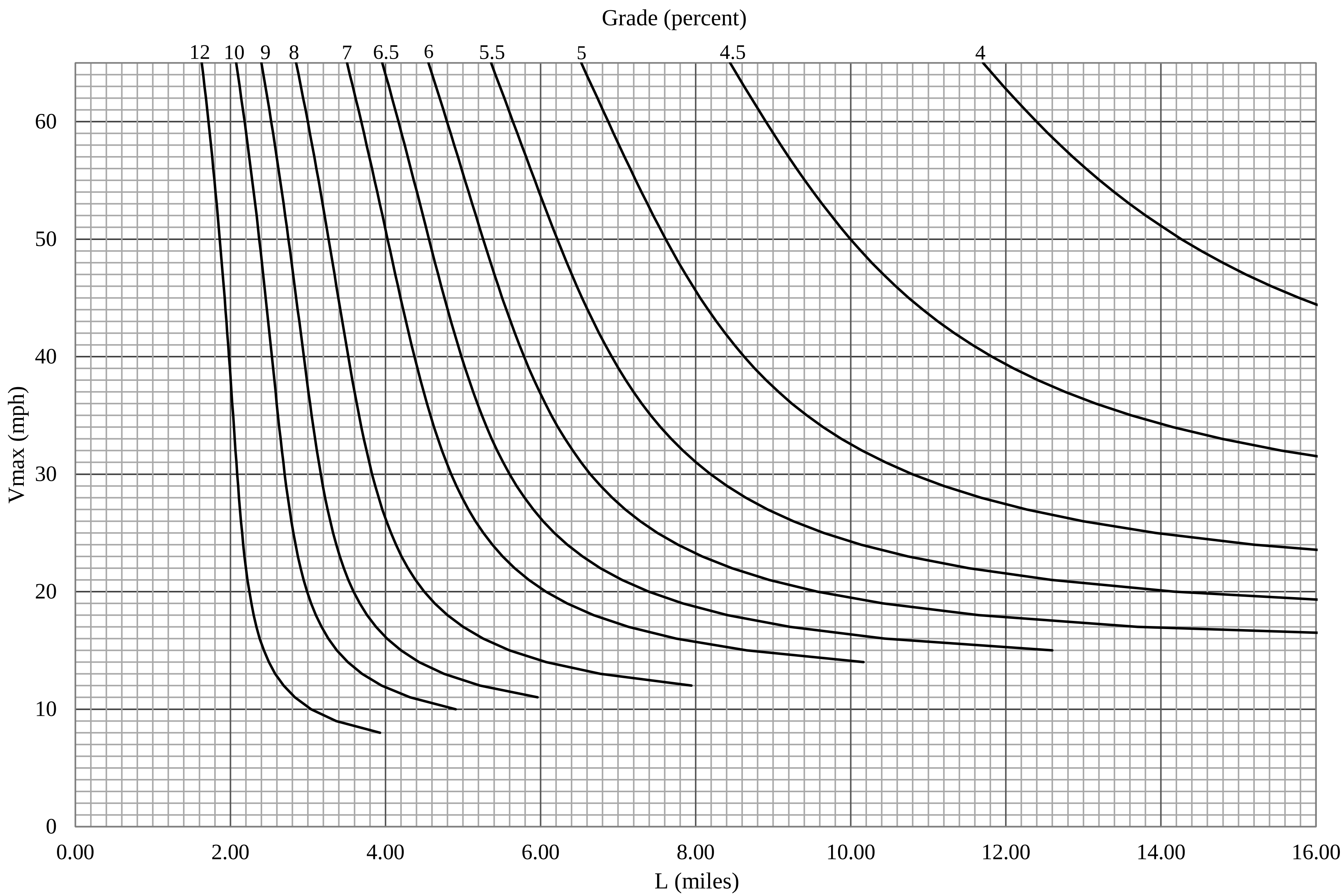

Figure 3. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 80,000 lb

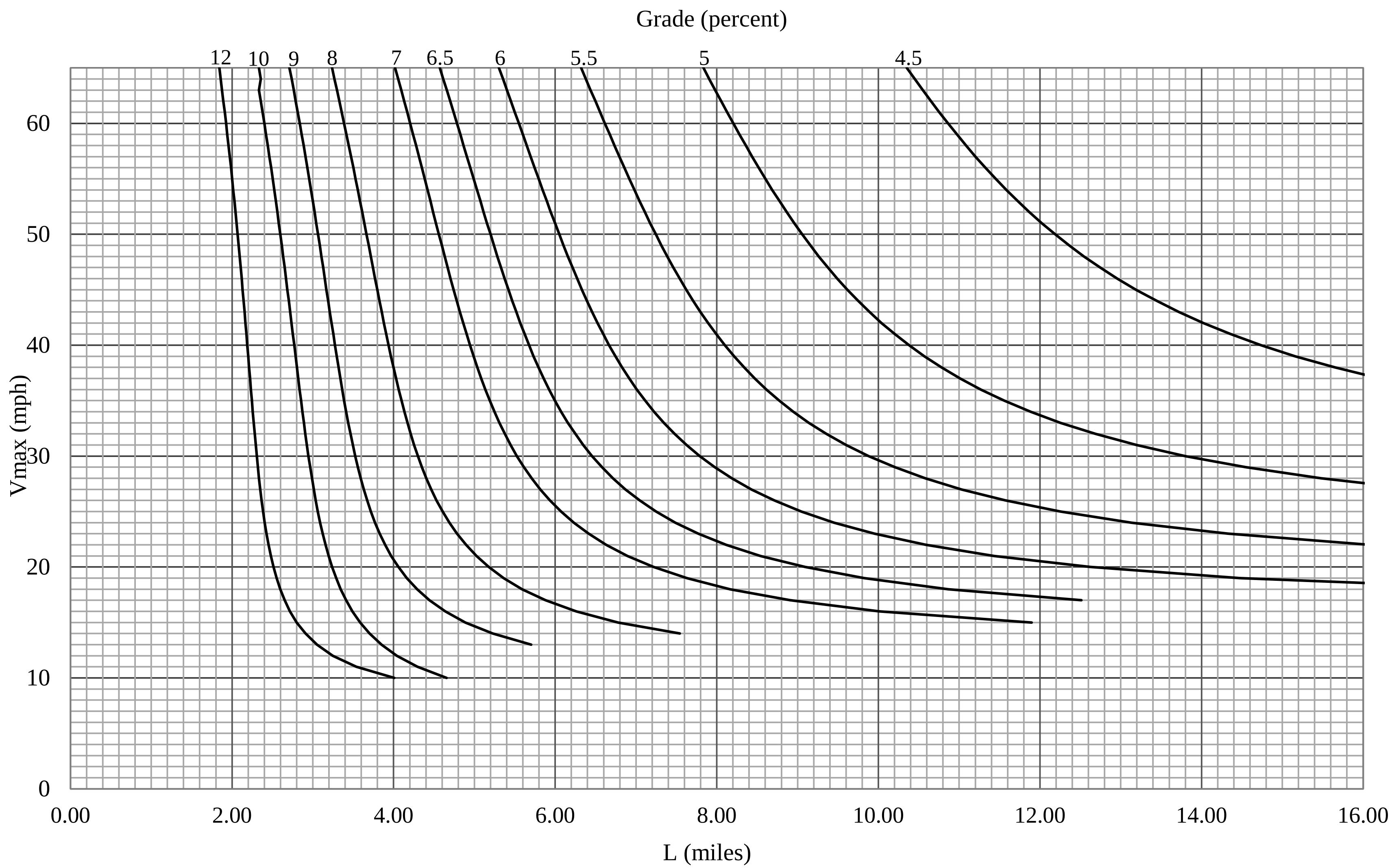

Figure 4. Graph. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 75,000 lb

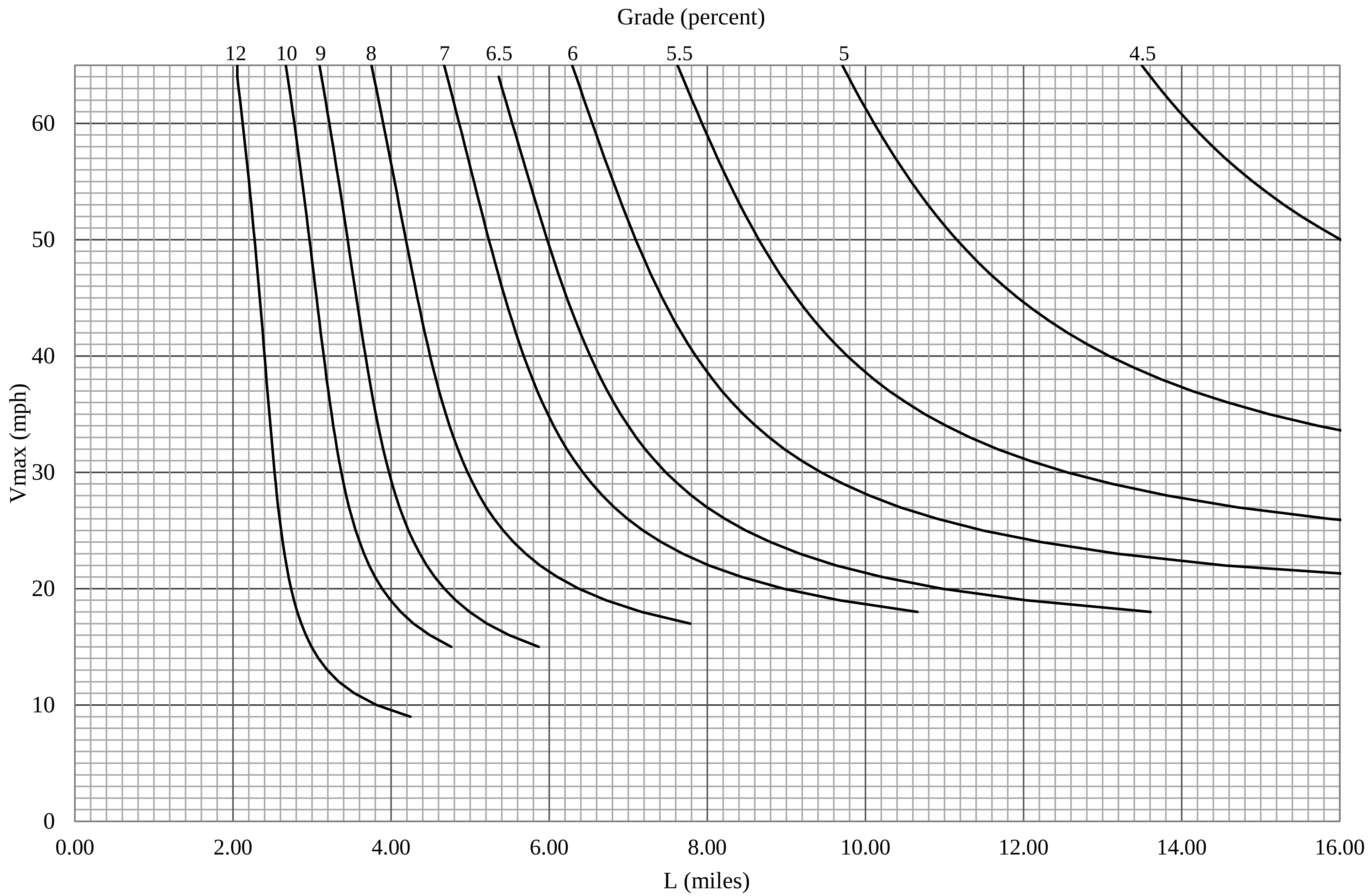

Figure 5. Graph. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 70,000 lb

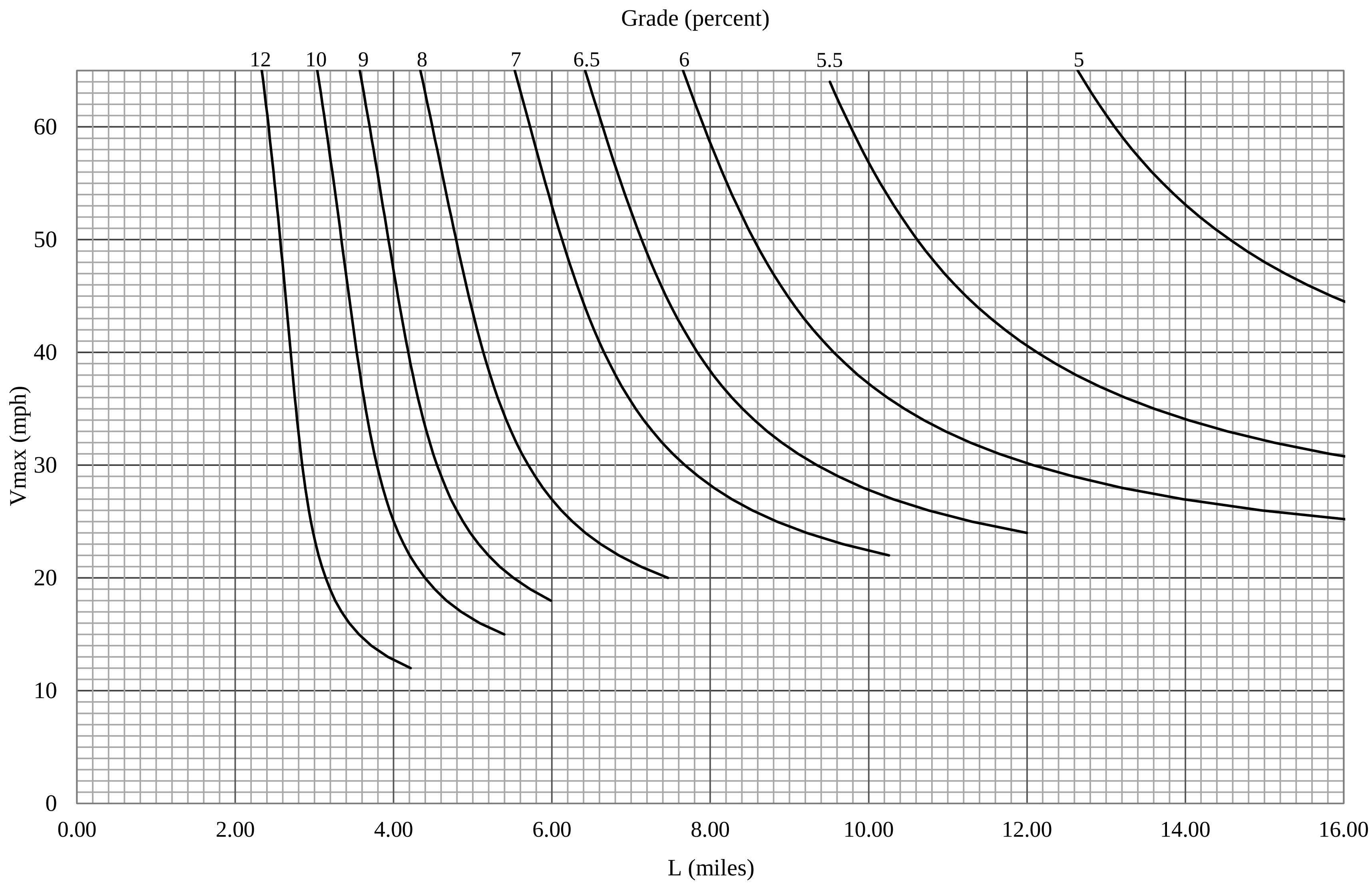

Figure 6. Graph. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 65,000 lb

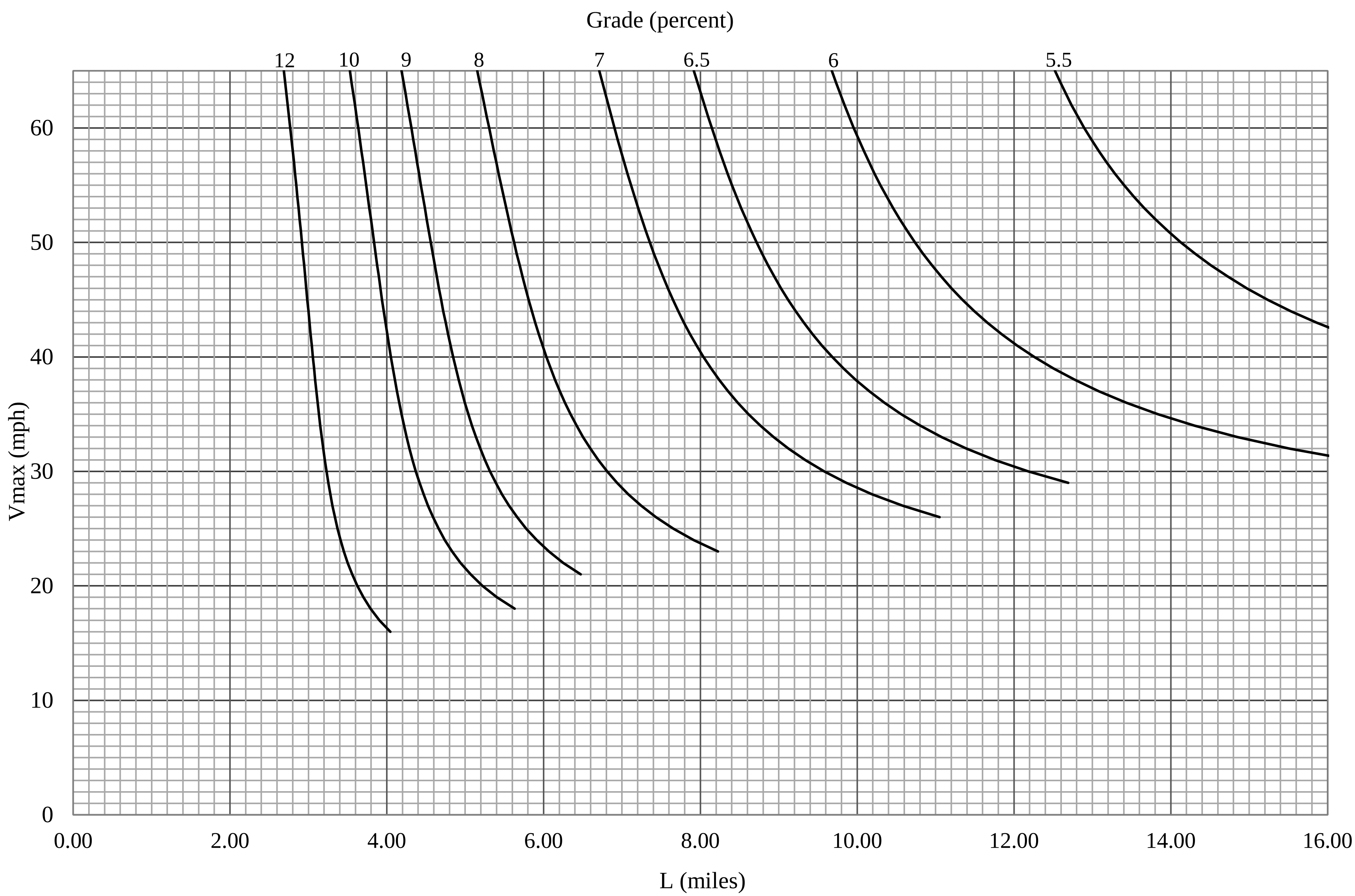

Figure 7. Graph. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 60,000 lb

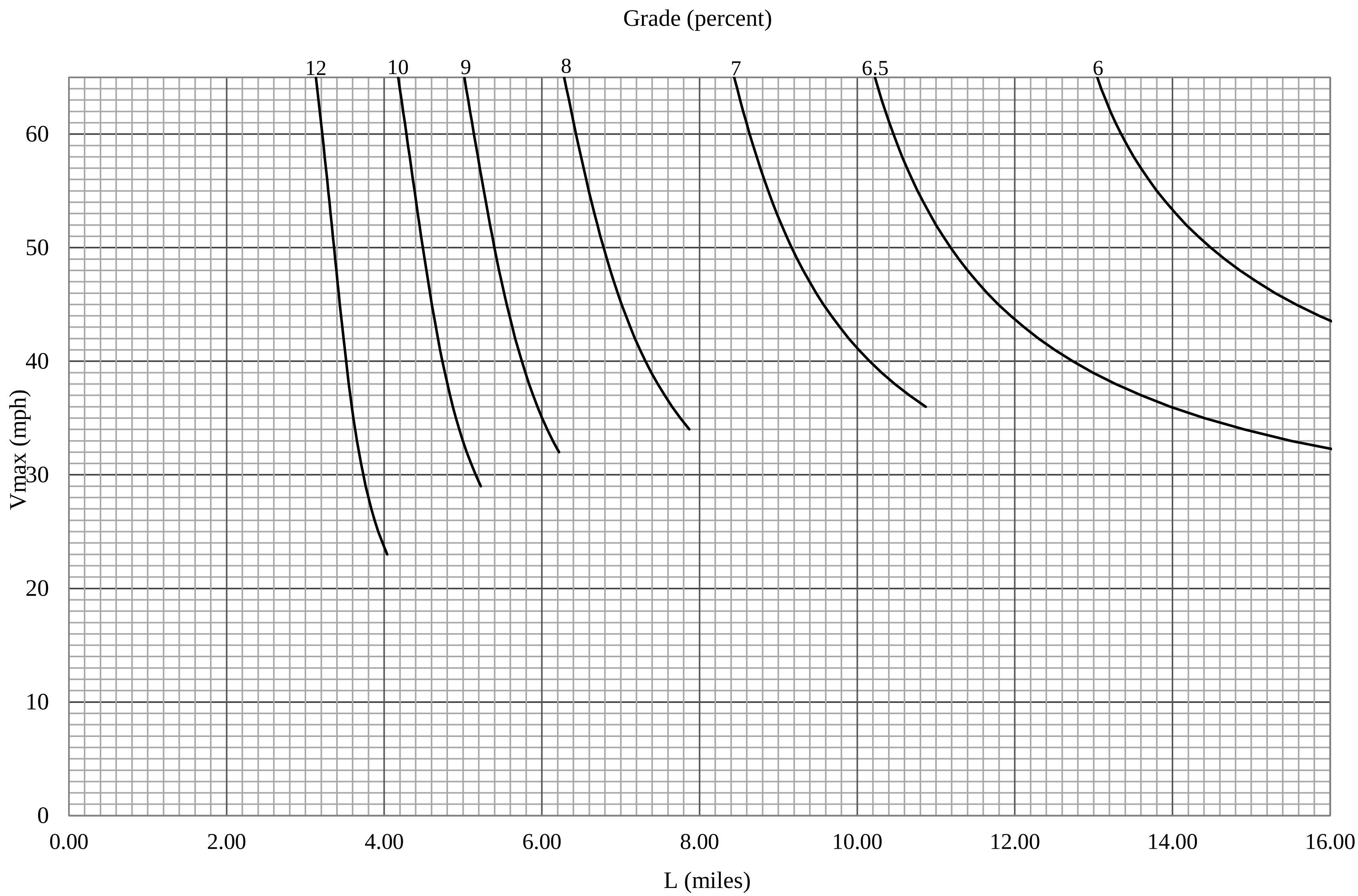

Figure 8. Graph. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 55,000 lb

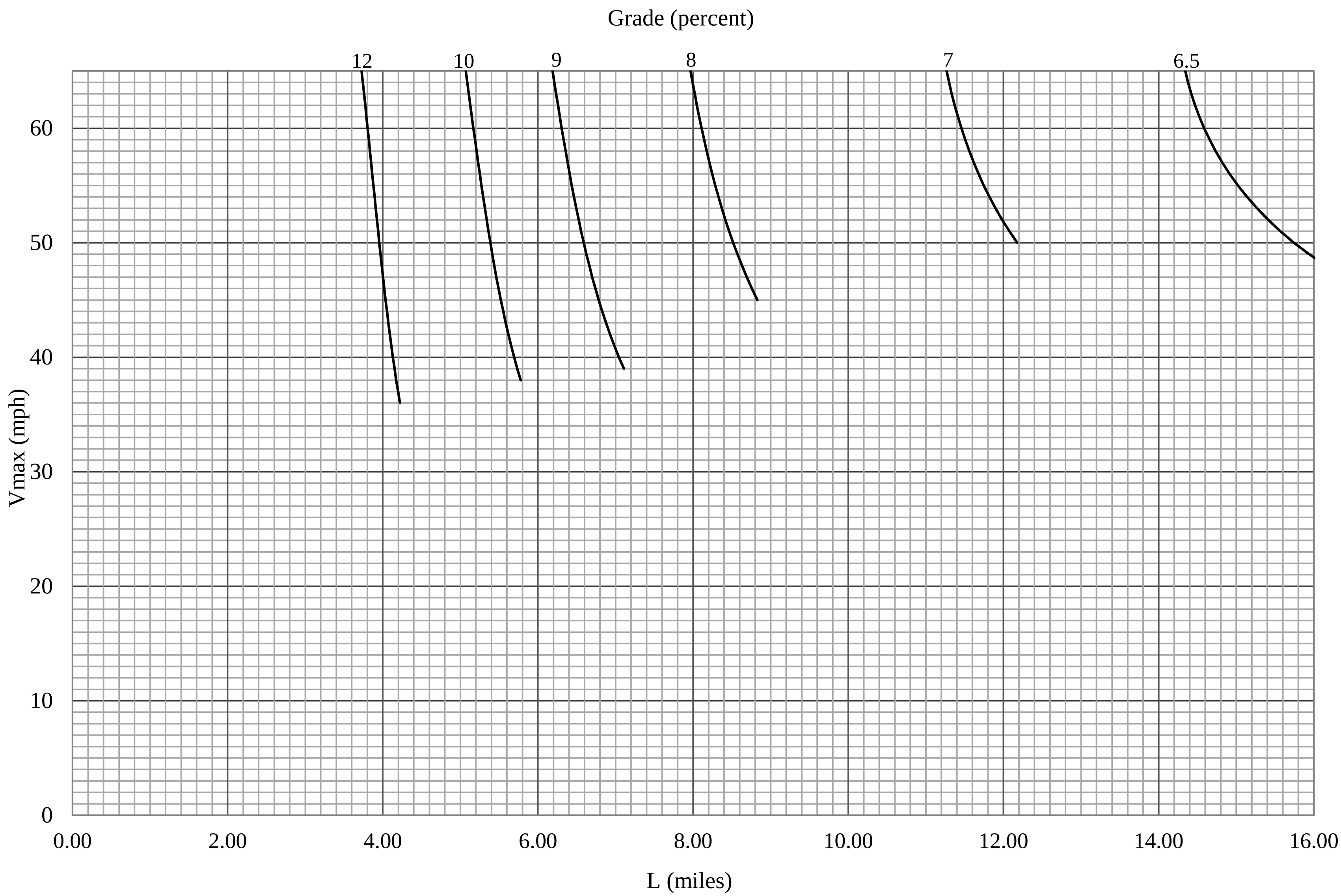

Figure 9. Graph. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 50,000 lb

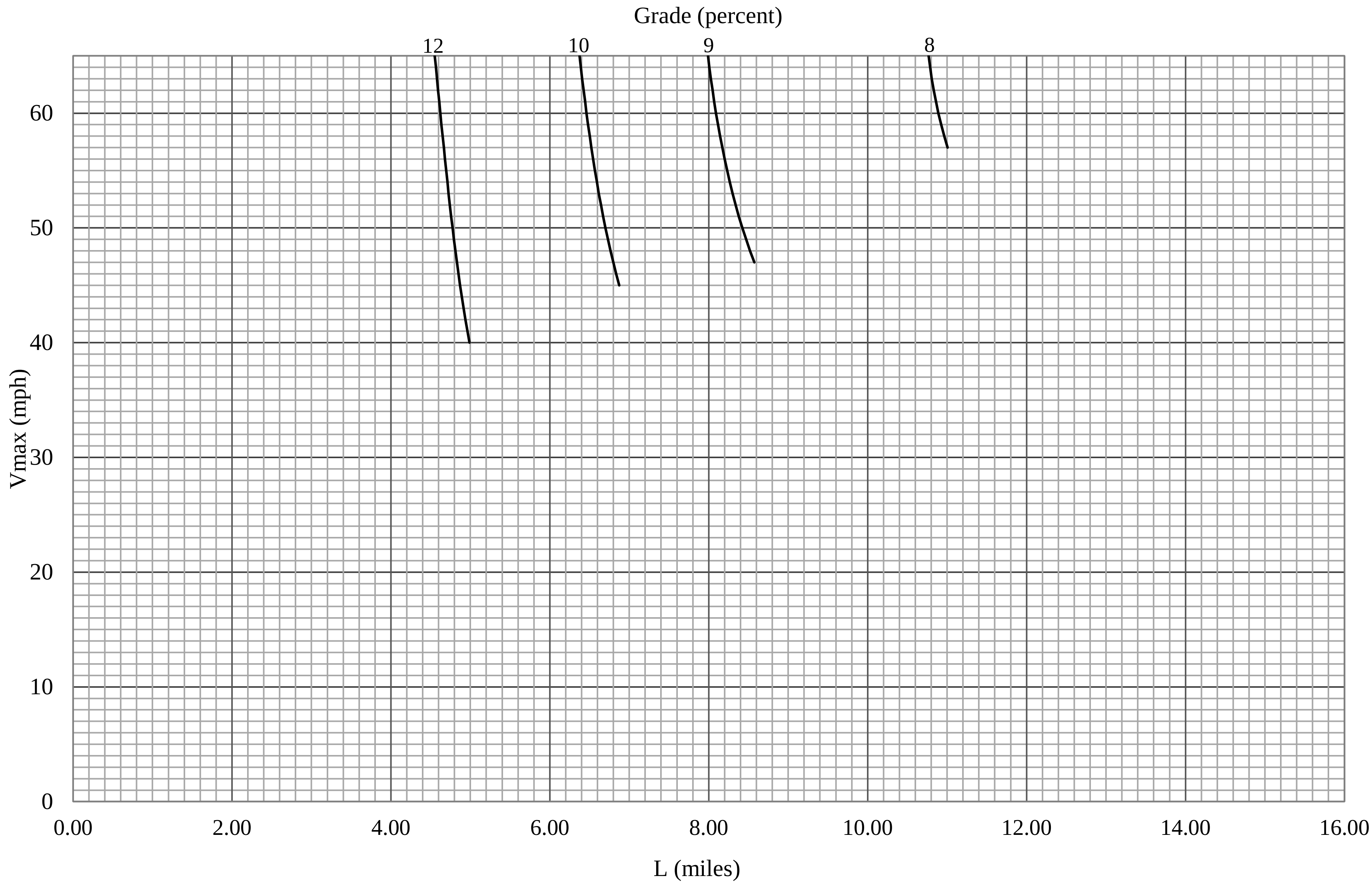

Figure 10. Graph. Maximum Safe Speed as a Function of Grade Length and Steepness for Truck Weight 45,000 lb

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