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

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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.

Video of a Runaway Truck Crash

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

Recent Downhill Truck Crashes

Source: NBC News

Source: NPR

Source: Buckrail News

Source: K2Radio
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

![Grade Rating System Chart](image1)

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

![FHWA GSRS Diagram](image2)

Picture: Bowman 1990
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

- 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
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

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
Selecting Representative Truck

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

Test Truck

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

**Tires and Brakes**
Michelin (Radial) Tractor Tires
275/80R22.5
Bridgestone Dual Trailer Tires
295/75R22.5
Bendix Air Disc Front Brakes
Castlite S-Cam Drum Brakes
(Tractor and Rear)
GSRS Field Testing Procedure

Developing Testing Protocol

Site Selection

- Select Sites for Tests
  - Select a site with grade ≤ 0.5% (For count-down, cool-down, and fue tests)
  - Select 3 sites with grade > 5% (For down-hill and validation tests)
- Set out traffic control

Test Validation Preparation

- More than accumulated 4000 miles of travel?
  - Yes
  - No
- Perform brake balancing (Test results in brake force being distributed among the axles in proportion to the axle load)
- Perform brake balancing (Test performed to ensure brake system reaches a steady state and provides reasonable result)

Test Procedure

- Coast-Down Test with gear in neutral
- Coast-Down Test with gear engaged, no selector
- Coast-Down Test with gear engaged, half-selector setting
- Coast-Down Test with gear engaged, full-selector setting

- Coast-Down Test (Speed constant, no brakes)
- Coast-Down Test (Speed constant, no brakes)
- Down-Hill Tests
- Validation Test

Record ambient environmental conditions

Notes:
1. To determine the cause of long forces on the test vehicle
2. To determine if brake test is steady state
3. To determine the area of brake test to match
4. To determine the brake test to match
5. To determine the test conditions of the brake-sequence model
### Measured Parameters

<table>
<thead>
<tr>
<th>Measured Parameter</th>
<th>Instrument or Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brake Temperature</td>
<td>Infrared sensor</td>
</tr>
<tr>
<td>Vehicle Speed</td>
<td>CAN bus</td>
</tr>
<tr>
<td>Deceleration</td>
<td>CAN bus</td>
</tr>
<tr>
<td>Vehicle Gross Weight</td>
<td>Weigh Station</td>
</tr>
<tr>
<td>Engine Speed</td>
<td>CAN bus</td>
</tr>
<tr>
<td>Coordinates</td>
<td>GPS</td>
</tr>
<tr>
<td>Brake Application Pressure</td>
<td>Pressure Transducer</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>Thermocouple</td>
</tr>
<tr>
<td>Wind speed and Direction</td>
<td>Weather Station</td>
</tr>
<tr>
<td>Atmospheric Pressure</td>
<td>Weather Station</td>
</tr>
<tr>
<td>Ambient Humidity</td>
<td>Weather Station</td>
</tr>
<tr>
<td>Number of Snubs</td>
<td>CAN bus</td>
</tr>
</tbody>
</table>
Infrared Sensors

Controller Box - Cab

- Power Cable
- Signal Terminal Block
- Signal Cables
- Din Rail
- Power Supply Unit
- Power Terminal Block
- Ethernet Cable
- NI CDAQ 9188
- CAN Module (NI 9862)
Signal Conditioning and Power Distribution Box - Tractor

Amplifier

MICAS-X Software
Field Tests and Updating the GSRS

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expression/Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horsepower into brakes ($HP_B$)</td>
<td>$HP_B = (W + F_{drag}) \frac{V}{375} - HP_{eng}$</td>
<td>hp</td>
</tr>
<tr>
<td>Drag forces ($F_{drag}$)</td>
<td>$F_{drag} = 450 + 17.25V$</td>
<td>lb</td>
</tr>
<tr>
<td>Diffusivity ($K_1$)</td>
<td>$K_1 = 1.23 + 0.0256V$</td>
<td>1/hr</td>
</tr>
<tr>
<td>Heat transfer parameter ($K_2$)</td>
<td>$K_2 = (0.10 + 0.00208V)^{-1}$</td>
<td>°F/hp</td>
</tr>
<tr>
<td>Engine brake force ($HP_{eng}$)</td>
<td>$HP_{eng} = 73$</td>
<td>hp</td>
</tr>
<tr>
<td>Ambient temperature ($T_o$)</td>
<td>$T_o = 90$</td>
<td>°F</td>
</tr>
<tr>
<td>Initial brake temperature ($T_b$)</td>
<td>$T_b = 150$</td>
<td>°F</td>
</tr>
</tbody>
</table>

FHWA GSRS Model Parameters (Myers et al. 1980)
Brake Temperature Equation

\[
T(t) = T_o + \left[ T_\infty - T_o + K_2 H_P B \right] \left[ 1 - e^{-K_1 t} \right]
\]

\[ T(f) \leq T_{lim} \]

\[
T_f = T_o + \left[ T_\infty - T_o + K_2 H_P B \right] \left[ 1 - e^{-K_1 \frac{L}{V}} \right] \leq T_{lim}
\]

- \( T_f \) = Final brake temperature (°F)
- \( T_o \) = Initial brake temperature (°F)
- \( T_t \) = Temperature at time \( t \) (°F)
- \( T_\infty \) = Ambient temperature (°F)
- \( T_{lim} \) = Limiting brake temperature (°F)
- \( L \) = Downgrade length (miles)
- \( V \) = Speed (mph)
- \( H_P B \) = 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)

Required Braking Force

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

\[
= W \theta - F_B - F_{NB}
\]

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

\[
\text{Required } F_B = W \theta - F_{NB}
\]
Field Tests and Updating the GSRS

**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

\[ F_t = -M_e a_t \]

\[ F_t \pm M_e g \frac{\Delta h}{\Delta s} = A_m + D v_i^2 \]

*Me = Effective truck mass (slugs)*
*a = deceleration (ft/s²)*
*g = acceleration due to gravity (ft/s²)*
\(\Delta h/\Delta s\) = slope
*v = Speed (mph)*
*A_m, D = Drag coefficients*
**Determination of Drag Force (F_{drag})**

\[ F_{corrected} = 357.77 + 0.785F_{simulation} \]

**Field Tests and Updating the GSRS**

\[ F_{drag} = 459.35 + 0.132V^2 \]

\[ HP_{eng(full \, brake)} = 63.3 \, \text{hp} \]

\[ HP_{eng(full \, brake)} = 502.0 \, \text{hp} \quad @1800 \, \text{rpm} \]
Field Tests and Updating the GSRS

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:

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

- $T$ = Temperature at current time (°F)
- $T_\infty$ = Ambient temperature (°F)
- $T_o$ = Initial temperature (°F)
- $t$ = time (s)

- 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.

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Field Tests and Updating the GSRS

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.

---

$K_1$ Extraction for $V = 0$ mph (Left Brakes)

- Linear (L1)
- Non-Linear (L2, L3, L4, L5)

Variation of Diffusivity Constant ($K_1$) with Speed (Right Brakes)

- R1
- R2
- R3
- R4
- R5
- Linear (R1)
Estimating Diffusivity Parameter \((K_1)\)

\[ K_1 = 1.1852 + 0.0331V \]

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

\[ T^* = \frac{T - T_o}{-K_1} + (T_o - T_\infty) = K_2 F_B V \]

Given that:

\[ F_B V = H P_B \]

\[ T^* = K_2 H P_B \]

- \(T^*\) = Thermodynamic variables (°F)
- \(T\) = Temperature at a specified time
- \(T_\infty\) = 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)
- \(H P_B\) = Horsepower into brakes (hp)
- \(t\) = time (s)
Field Tests and Updating the GSRS

**Hill Descent Test**

- 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

---

**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

\[
y = 4.1846x + 12.118
\]

\[
y = 3.0469x - 25.205
\]
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 ($1/K_2$) with speed](image)

Updated Brake Temperature Model

<table>
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<td>hp</td>
</tr>
<tr>
<td>Drag forces ($F_{drag}$)</td>
<td>$F_{drag} = 459.35 + 0.132V^2$</td>
<td>lb</td>
</tr>
<tr>
<td>Diffusivity ($K_1$)</td>
<td>$K_1 = 15x(1.1852 + 0.0331V)$</td>
<td>1/hr</td>
</tr>
<tr>
<td>Heat transfer parameter ($K_2$)</td>
<td>$K_2 = \frac{1}{K_2} = (0.1602 + 0.0078V)^{-1}$</td>
<td>°F/hp</td>
</tr>
<tr>
<td>Engine brake force ($HP_{eng}$)</td>
<td>$HP_{eng} = 63.3$</td>
<td>hp</td>
</tr>
<tr>
<td>Temperature from emergency stopping ($T_e$)</td>
<td>$T_e = 3.11 \times 10^{-7}WV^2$</td>
<td>°F</td>
</tr>
<tr>
<td>Ambient temperature ($T_a$)</td>
<td>$T_a = 90$</td>
<td>°F</td>
</tr>
<tr>
<td>Initial brake temperature ($T_i$)</td>
<td>$T_i = 150$</td>
<td>°F</td>
</tr>
</tbody>
</table>

- Temperature Plots from expression:

$$L = -\frac{V}{K_1} \ln \left[ \frac{T_{lim} - 90 - K_2HP_b}{60 - K_2HP_b} \right]$$

- Where:

$$T_{lim} = T_f + T_e$$

- A limiting temperature of 500°F was used in model.
Maximum Safe Descent Speed Plot

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

Validation Test

US 16 Eastern face (MP 67.4 - 73.9)
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
ITS Technologies

**Infrastructure and Vehicle-Based ITS Technologies**

- Thermal Imaging of Brakes
  - Picture: www.modern tire dealer.com
- Dynamic Truck Curve Warning System
  - Picture: Smaidi et al. 2014
- Downhill Truck Warning System
  - Picture: Sissipiku, 2000
- Automatic Emerg. Braking Sys
  - Picture: www.modern tire dealer.com
- Intelligent Speed Adaptation
  - Picture: www.belmog.com
- On Board Monitoring Systems
  - Picture: www.autoalliance.org

**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.itsm.com
- Forward Collision Warning
  - Picture: the frylawfirm.com
Updating the GSRS

Formulation of WSS Signs

Users’ Manual
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

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

<table>
<thead>
<tr>
<th>5 AXLES OR MORE</th>
<th>WEIGHT</th>
<th>MAX SPEED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>65000-70000</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>70000-75000</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>75000-80000</td>
<td>15</td>
</tr>
</tbody>
</table>
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:

$$N = \frac{W_M - W_L}{5000}$$

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

Formulation of WSS Signs

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

Formulation of WSS Signs

WSS Signs from GSRS

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

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 \( V_{\text{max}} \) versus \( L \) plots, the maximum truck weights and corresponding speeds are:

<table>
<thead>
<tr>
<th>Maximum Truck Weight (lb)</th>
<th>Maximum Safe Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80,000</td>
<td>18</td>
</tr>
<tr>
<td>75,000</td>
<td>22</td>
</tr>
<tr>
<td>70,000</td>
<td>29</td>
</tr>
<tr>
<td>65,000</td>
<td>42</td>
</tr>
<tr>
<td>60,000</td>
<td>55</td>
</tr>
</tbody>
</table>

Advisory Maximum Descent Speeds

<table>
<thead>
<tr>
<th>Weight Increments (lb)</th>
<th>Maximum Safe Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>61,000 - 65,000</td>
<td>40</td>
</tr>
<tr>
<td>66,000 - 70,000</td>
<td>30</td>
</tr>
<tr>
<td>71,000 - 75,000</td>
<td>25</td>
</tr>
<tr>
<td>76,000 - 80,000</td>
<td>20</td>
</tr>
</tbody>
</table>
**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.

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**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.
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
Questions??

Updating and Implementing the Grade Severity Rating System for Wyoming Mountain Passes
Formulation of Weight Specific Speed Signs (Case Studies)

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

<table>
<thead>
<tr>
<th>Step Definition</th>
<th>Purpose</th>
<th>Output</th>
</tr>
</thead>
</table>
| 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>
<thead>
<tr>
<th>Maximum Truck Weight (Pounds)</th>
<th>Maximum Safe Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80,000</td>
<td>22</td>
</tr>
<tr>
<td>75,000</td>
<td>27</td>
</tr>
<tr>
<td>70,000</td>
<td>35</td>
</tr>
<tr>
<td>65,000</td>
<td>45</td>
</tr>
</tbody>
</table>
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)**

<table>
<thead>
<tr>
<th>Maximum Truck Weight (Pounds)</th>
<th>Maximum Safe Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>66,000 – 70,000</td>
<td>35</td>
</tr>
<tr>
<td>71,000 – 75,000</td>
<td>30</td>
</tr>
<tr>
<td>76,000 – 80,000</td>
<td>20</td>
</tr>
</tbody>
</table>

**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)**

<table>
<thead>
<tr>
<th>Maximum Truck Weight (Pounds)</th>
<th>Maximum Safe Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90,000</td>
<td>14</td>
</tr>
<tr>
<td>80,000</td>
<td>18</td>
</tr>
<tr>
<td>70,000</td>
<td>24</td>
</tr>
<tr>
<td>60,000</td>
<td>40</td>
</tr>
</tbody>
</table>
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)**

<table>
<thead>
<tr>
<th>Maximum Truck Weight (Pounds)</th>
<th>Maximum Safe Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60,000 – 70,000</td>
<td>25</td>
</tr>
<tr>
<td>71,000 – 80,000</td>
<td>20</td>
</tr>
<tr>
<td>81,000 – 90,000</td>
<td>15</td>
</tr>
</tbody>
</table>

**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 $V_{\text{max}}$ 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 $V_{\text{max}}$ is read.

- This exercise is continued for different weights until the weight for which $V_{\text{max}}$ is greater than or equal to 65 mph is found. For this case study, the highest integral multiple of 5000 lb for which $V_{\text{max}}$ 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 $V_{\text{max}}$ versus L plots, the maximum truck weights and corresponding speeds are (Table 6):

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

<table>
<thead>
<tr>
<th>Maximum Truck Weight (Pounds)</th>
<th>Maximum Safe Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80,000</td>
<td>17</td>
</tr>
<tr>
<td>75,000</td>
<td>21</td>
</tr>
<tr>
<td>70,000</td>
<td>26</td>
</tr>
<tr>
<td>65,000</td>
<td>36</td>
</tr>
<tr>
<td>60,000</td>
<td>58</td>
</tr>
<tr>
<td>55,000</td>
<td>65</td>
</tr>
</tbody>
</table>
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)**

<table>
<thead>
<tr>
<th>Maximum Truck Weight (Pounds)</th>
<th>Maximum Safe Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55,000 – 60,000</td>
<td>60</td>
</tr>
<tr>
<td>61,000 – 65,000</td>
<td>35</td>
</tr>
<tr>
<td>66,000 – 70,000</td>
<td>25</td>
</tr>
<tr>
<td>71,000 – 75,000</td>
<td>20</td>
</tr>
<tr>
<td>76,000 – 80,000</td>
<td>15</td>
</tr>
</tbody>
</table>
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
Thank you for participating!

You will be automatically directed to a short survey, please take a moment to provide your feedback.

Thank you to our partners:

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