Automating the Implementation of the Updated Grade Severity Rating System (GSRS) for Wyoming Mountain Passes

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1 Introduction

Truck crashes on steep downgrades caused by excessive brake heating is an ongoing concern for the Wyoming Department of Transportation (WYDOT). Crashes resulting from brake failure on downgrades exact devastating tolls on lives and property. To counter such crashes, WYDOT initiated a research project in 2016 to update a previous Grade Severity Rating System (GSRS) model originally developed in 1981. This was necessary due to the previous GSRS model being considered insufficiently representative of current truck characteristics which have undergone significant changes over the decades. As a result, descent speeds estimated by the 1981 GSRS have been deemed conservative. Consequently, there was a risk that truck drivers would ignore recommended maximum safe speeds from the system, thereby worsening mountain pass safety.

To update the GSRS model parameters, a truck was fully instrumented and taken through several field tests. Software simulation was used to augment the testing due environmental and time constraints encountered during the tests. A validation test was also conducted to assess the robustness of the updated model by comparing field brake temperatures to the predicted temperatures. The results showed that the predicted temperatures were close to the field temperatures, indicating that the updated GSRS model was accurate. The updated GSRS model took into account changes in truck characteristics including new streamlined designs, reduced frontal areas, changes in tire types, and engine characteristics.

The next stage in the ongoing efforts to enhance Wyoming mountain passes safety is to make the updated GSRS model fully implementable by developing a process that simplifies its implementation. Also, the presence of sharp horizontal curves on steep downgrades that characterize Wyoming's mountain passes have to be factored into the procedures for formulating WSS signs. These are the objectives to be fulfilled by this proposed study.

2 Study Objectives

This study is aimed at achieving three objectives. The first objective is to validate the GSRS model for trucks that have only drum brakes installed. The GSRS model was updated with a truck fitted with disc brakes on the steer axles. However, disc brakes represent about 20 percent of the brake market. Therefore, the model has to be validated for trucks fitted with only drum brakes. This objective will be achieved by conducting some field tests with a fully loaded truck. Truck instrumentation is not required for these field tests.

The second objective is to make the updated Grade Severity Rating System (GSRS) fully implementable by incorporating horizontal curves into the formulation of weight specific speed (WSS) signs. This is because downgrades characterized by the presence of sharp horizontal curves increase the risk of a truck crash after a brake failure has occurred.

The final objective is to develop a program that simplifies the implementation of the GSRS and formulation of WSS signs. The program will have a graphical user interface (GUI) that takes inputs of the physical characteristics of a downgrade, truck weight, and initial brake temperature, and gives maximum speeds for different weight categories as output. The program will also be able to estimate and display maximum descent speeds for two scenarios; single and multigrade hills.

3 Background

Steep grades on mountain passes present considerable challenges for trucks. The combination of heavy loads, steep inclines, and long downgrade lengths increases the risk of brake failure due to brake heating. On downgrades, trucks generate large amounts of potential energy that have to be absorbed by service brakes. This potential energy is absorbed by the brake system in the form of heat which increases braking temperature. As more heat is absorbed, a decrease in braking efficiency referred to as “brake fade” occurs. If the brake system temperature continues to rise, the condition progresses from brake fade to brake failure, leading to an out-of-control or “runaway” truck (Bowman & Coleman, 1990). A truck runaway is described as a truck whose speed, headway, or directional problems are aggravated by a downgrade to the extent that the chances for a crash are substantially increased (Johnson, Di-Marco, & Allen, 1982). Due to the high speed and loss of directional control, runaway truck crashes are usually destructive.

Some highways in Wyoming traverse over mountain passes that feature steep downgrades. Prominent mountain passes in the State include US 14, US 16, Teton Pass, South Pass, and US 14 Alternative. These mountain passes carry significant truck loads and can be very dangerous for heavy trucks. Some mountain passes are so hazardous that lower weight limits are imposed during some periods of the year while others are closed to traffic altogether. For instance, US 14 Alternative located within the Big Horn Mountains features sharply winding hair-pin curves, blind corners and steep grades that may be up to 10% for some sections. The highway is closed during the winter months due to its hazardous nature and only available for use in late May or early June. Runaway truck crashes occurring on Wyoming’s mountain passes have been attributed to driver unfamiliarity with the highways, lack of experience, and poor driver guidance.

4 Literature Review

4.1 FHWA GSRS

The use of WSS signs from the GSRS developed by the Federal Highway Administration (FHWA) has been found to be an effective remedy in reducing the incidence of runaway truck crashes (Bowman & Coleman, 1990). The GSRS is a mathematical model that predicts brake temperature during a grade descent. The model accounts for the physical characteristics of the grade and truck features in computing the brake system temperature. Factors included in the model are grade length and steepness, gross truck weight, speed, non-brake resistive forces, and heat dissipation characteristics of the brake (Bowman & Coleman, 1990). Other factors considered were initial brake temperature, engine speed, and brake heating characteristics. The brake temperature equation and model parameters for the GSRS is shown in Table 1 (Myers, Irving, & Walter, 1981).

Table 1 :FHWA GSRS Model Parameters (Myers et al., 1981)

Parameter	Expression	Units
Brake temperature equation	$T_f = T_o + [T_\infty - T_o + K_2 HP_B]\left[1 - e^{K_1 L/V}\right]$	°F
Horsepower into the brakes (HP_B)	$HP_B = \left(W\theta - F_{drag}\right)\frac{V}{375} - HP_{eng}$	hp
Diffusivity constant (K_1)	$K_1 = 1.23 + 0.0256V$	1/hr
Heat transfer parameter (K_2)	$K_2 = (0.100 + 0.00208V)^{-1}$	°F/hp
Drag forces (F_{drag})	$F_{drag} = 450 + 17.25V$	lb
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

At the time of its development, the GSRS model was determined to predict brake temperatures accurately to a few degrees of measured field temperatures (Johnson et al., 1982). The model assumed a five-axle truck and that engine speed was maintained near the allowable maximum for the engine (i.e. the appropriate gear was used) (Myers et al., 1981).

The GSRS mathematical model was used to solve the 'inverse problem'. That is, it was used to compute corresponding speeds for a given final brake temperature (on a given downgrade, at a given weight etc.). This implies that if a maximum safe final brake system temperature is defined that prevents brake fade, then the maximum safe speed may be determined for a particular downgrade. Thus, a WSS sign giving recommendations of a recommended maximum speed (to be held constant for the entire downgrade) for several weights could be formulated.

Johnson et al., 1982 noted that it was important also for sufficient braking to be available at any point along the downgrade to allow for emergency stopping. They argued that it was possible for a truck to have enough braking capacity to maintain a steady descent, but lack sufficient capacity to slow down in time to avoid a hazard on the downgrade. The sum of the heat energy arising due to the extra burden of emergency braking added to the heat from the constant descent may result in brake fade and failure when the braking need is most critical. The GSRS model was therefore modified to account for the temperature rise that would occur due to an emergency stop (Johnson et al., 1982).

4.2 The Need to Update the GSRS

The concept and development of the GSRS marked a leap from previous grade rating systems because it provided concise guidance to drivers on how to descend grades directly, rather than providing information that still requires evaluation under different conditions. At the time of its development, the GSRS adequately reflected truck designs and configurations. However, over the decades, truck configurations have changed drastically.

A re-evaluation of the GSRS was undertaken in 1989 in the light of changing truck designs that determined that some modifications of the GSRS model was required to account for the fuel conservation measures introduced for trucks almost a decade after the GSRS model was developed (Bowman & Coleman, 1989). The influence of these measures on truck designs have included the lowering of the aerodynamic drag of trucks through airfoils and streamlining, adoption of radial tires and a reduction in engine friction. Also, trailer tails, airtabs, trailer skirts among other aerodynamic devices have been incorporated in recent truck designs. These measures have reduced the non-braking forces available to retard truck motion, thereby placing a greater work load on brake systems. The adoption of radial tires over bias ply tires has led to lower internal friction helping to minimize rolling resistance. Radial tires haven also been found to improve fuel savings by 6% compared to bias ply tires (Goodyear Commercial Tire Systems, 2008).

Changes in engine characteristics have also been responsible for a reduction in engine friction which provided further retardation. In 1974, a standard 290-hp engine absorbed approximately 113-hp, including the effects of driveline efficiency and accessory power while a 1980 model 300-hp engine absorbed approximately 75-hp (Bowman & Coleman, 1989). Calculations from data supplied by a typical truck manufacturer suggests a 450-hp engine manufactured in 2016 will absorb approximately, 60-hp of engine friction (Kenworth, 2018).

The re-evaluation of the GSRS indicated that typical grades had to be increased by 0.34% over the actual grade in calculations to determine maximum safe speeds from the GSRS (Bowman & Coleman, 1989). For example, for a grade of 8.0%, the corrected grade for calculations will be 8.34%. This modification was done three decades ago and there have been more advances in the features of modern trucks.

Another study conducted in 1999 to evaluate the effectiveness of the Dynamic Downhill Truck Speed Warning System recommended changes to be made to advisory speeds obtained using the FHWA GSRS algorithm (Janson, 1999). The study found that there was a risk of maximum speeds being too low with the danger of drivers ignoring the recommended speeds as being unrealistic. This is a relevant justification for updating the FHWA GSRS model, given that current truck braking systems have been enhanced in response to the reduced stopping distance requirement of the Federal Motor Vehicle Safety Standard (FMVSS) rule 121. This rule requires that the stopping distance of tractors traveling at 60 mph be reduced from 355 feet to 25 feet, a 30% reduction. The 30% reduction in stopping distance for the vast majority of commercial vehicles is envisaged to increase the safety of trucks (NHTSA, 2009). In response to the stopping distance requirements of FMVSS 121, most fleets have modified their tractor brakes. Steer axle brakes are now fitted with $16\frac{1}{2}$ x5 inches brake drums while drive-axles have stayed as $16\frac{1}{2}$ x7 inches (Berg, 2014). Other manufacturers have installed disc brakes on their steer axles. The implication is that the FHWA GSRS model is recommending maximum speeds for trucks that may be conservative and can lead to lower compliance by drivers.

4.3 Field Tests to Update the GSRS

Taking these changes into consideration, a study was initiated by WYDOT in 2016 to update the GSRS to adapt to current truck designs. Full-scale truck tests were conducted in the fall of 2017 to obtain the necessary data to update the mathematical brake temperature model on which the GSRS is based. The tests were conducted taking into account factors such as economy, simplicity, time constraints, accuracy requirements and compliance with current published standards.

A typical five-axle truck semi-trailer combination was instrumented for the tests (Figure 1). This configuration represents over 60% of heavy trucks on US highways. The truck chosen for the tests was the 2016 Kenworth T680 series model. A Hyundai trailer van with a gross vehicle weight of 65,000 pounds was attached to the tractor. The truck had a compression engine brake with the steer axle featuring Bendix air disc brakes while all other axles were fitted with drum brakes. The truck was instrumented to measure several atmospheric, brake and truck parameters including brake temperature, vehicle speed, deceleration, engine speed, GPS coordinates, brake application pressure, atmospheric pressure, ambient humidity, and number of snubs. Infrared sensors were installed on all ten wheels to measure brake temperatures during the tests. A brake pressure transducer was also connected to the main brake line from the tractor to measure brake application pressure. These were then connected to signal conditioning and power distribution boxes on the tractor and trailer. A connection was made from the signal conditioning and power distribution boxes to a controller box in the cab. Other parameters were measured from the truck engine using the controller area network (CANbus). Data from the sensors and truck engine were all collected by a compact Data Acquisition chassis (cDAQ). The cDAQ was used to control timing, synchronization and data transfers between the different modules of the instrumentation setup. The instruments/sensors and measured parameters are shown in Table 2**: Truck Instrumentation and Measured Parameters**

Measured Parameter	Instrument or Sensor
Brake Temperature	Infrared sensor
Vehicle Speed	Controller Area Network (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

. All the data collected was transmitted to a laptop running a proprietary software (MICAS-X). A schematic of the instrumentation setup is shown in Figure 2 and a screen shot of the MICAS-X software is shown in Figure 3.

Brake burnish and balance tests were conducted to prepare the vehicle brakes for the field testing. The burnish tests involved applying many braking cycles to new brakes to cause wear and tear such that a steady state is achieved to ensure repeatable braking forces for a given application of pressure. The balancing test was done to properly distribute brake forces in proportion to the axle loads. This test was conducted indirectly by measuring brake temperatures and adjusting air pressure to brakes until temperature differences were minimal. Brake temperatures that differed by approximately 50ºF side-to-side after burnishing indicated an imbalance. Air pressure was adjusted to the brakes to minimize this imbalance.

Figure 1: Test Truck

Table 2: Truck Instrumentation and Measured Parameters

Measured Parameter	Instrument or Sensor
Brake Temperature	Infrared sensor
Vehicle Speed	Controller Area Network (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

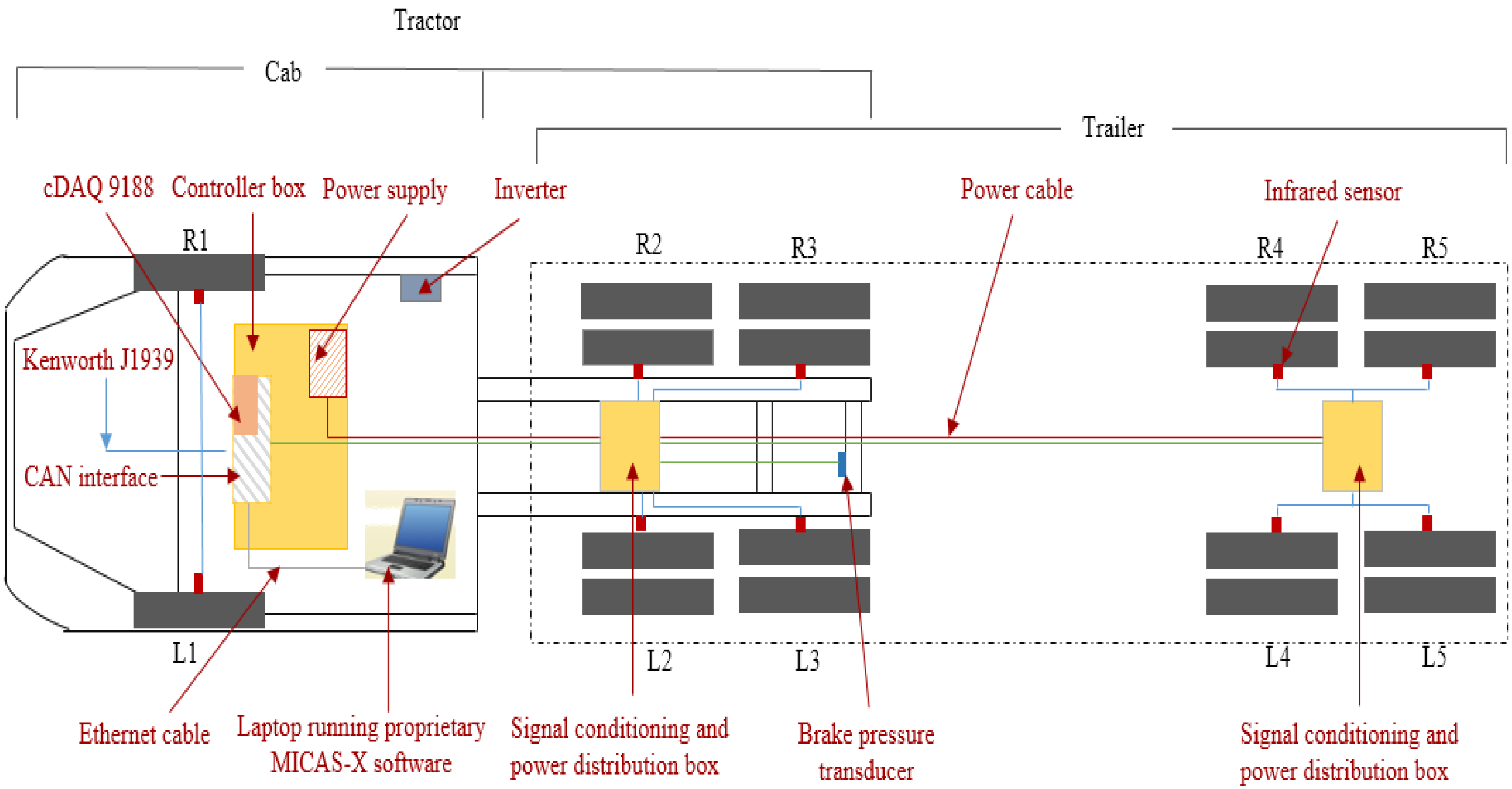


Figure 2: Schematic of Truck Instrumentation for GSRS Field Tests

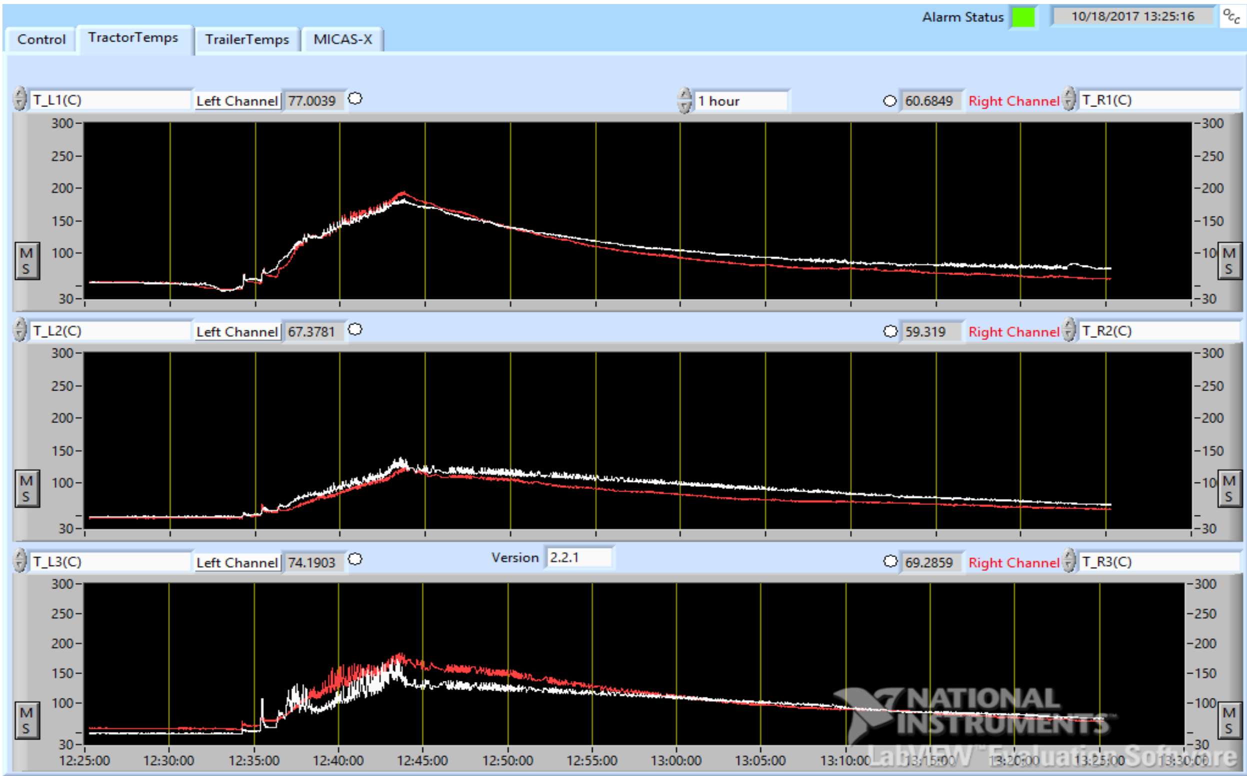


Figure 3: MICAS-X Software

The main tests conducted were coast-down, cool-down and hill descent tests along with a validation test. The coast-down tests were undertaken to determine the sum of non-brake forces acting on the truck, and retarding horsepower from the truck's engine. The test for determining drag forces consists of launching a vehicle from a predetermined speed on a level road with the engine disengaged and ascertaining the current speed and distance covered during the free rolling, till the vehicle stops. To determine the engine brake force, the test vehicle is driven with the gear and compression brake engaged.

The cool-down tests were conducted to determine the brake heat transfer properties of the truck brakes and to express the effective total heat transfer coefficient of the truck as a function of speed. This was done by heating the brakes and driving the truck at different constant speeds while measuring the cooling rates of the brakes. The purpose of the hill-descent tests were to define the heating characteristics of the brake system as a function of weight, grade percent and length, engine braking and descent speed. The test is conducted by descending different hills while maintaining constant speeds by modulating brake pressure. The compression brake was used to simulate changes in truck weight to speed up the test program.

After collecting the required data from the field tests, the model parameters of the FHWA GSRS were updated. The updated GSRS model could now be used for predicting final brake temperatures on downgrades and thus maximum safe speeds. It is also important to note that the updated model accounted for the temperature rise in the braking system that will occur from making an emergency stop on a downgrade. The updated parameters of the GSRS are shown in Table 3. Using the updated GSRS model, maximum safe speed plots were generated for different downgrade and weight conditions. These speed plots are used to derive maximum descent speeds for trucks based on the downgrade characteristics.

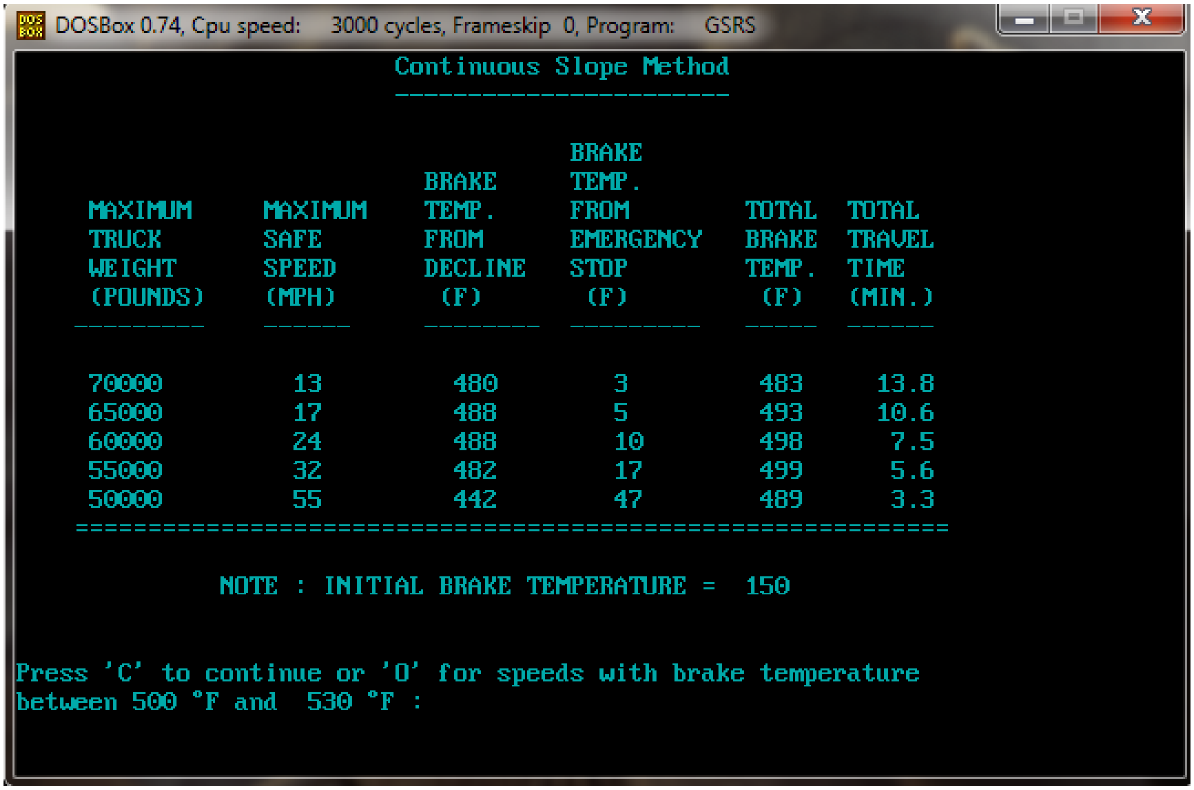
Table 3 : Updated GSRS Model Parameters (Moomen, Apronti, Molan, & Ksaibati, 2018)

Parameter	Expression/Value	Units
Diffusivity constant (K_1)	$K_1 = 1.1852 + 0.0331V$	1/hr
Heat transfer parameter (K_2)	$K_2 = \frac{1}{hA_c} = (0.1602 + 0.0078V)^{-1}$	°F/hp
Drag forces (F_{drag})	$F_{drag} = 459.35 + 0.132V^2$	lb
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

A validation test was then conducted to test the robustness of the updated GSRS model. The validation test was conducted in a similar manner to the hill descent tests. The test vehicle was loaded to 74,000 pounds and driven along the eastern face of US highway 16 in Wyoming at a constant speed of 45 mph. The brake system temperature was measured continuously during the test and was compared to predicted brake temperatures from the updated GSRS model. The comparison showed a close match between the predicted and field brake temperatures indicating the updated model was accurate.

4.4 Automating the Formulation of WSS Signs

Following the development of the GSRS by the FHWA, a DOS computer program was developed in 1990 to enable its implementation. The procedure to formulate WSS signs using the DOS program was contained in a GSRS user's manual (Bowman, 1989). The program took inputs of truck weight, speed, and the physical characteristics of the downgrade (length and percent). This information was used to generate outputs of maximum safe speeds, brake temperatures and total travel time for different truck weights (Figure 4). This GSRS program was critical for multigrades because the derivation of maximum safe speeds for such grades also involves an optimization criteria that cannot be done manually. That is, what combination of maximum safe speeds ensures the fastest descent of the grade while keeping the brake system below the fade temperature?



DOSBox 0.74, Cpu speed: 3000 cycles, Frameskip 0, Program: GSRS

Continuous Slope Method

MAXIMUM TRUCK WEIGHT (POUNDS)	MAXIMUM SAFE SPEED (MPH)	BRAKE TEMP. FROM DECLINE (F)	BRAKE TEMP. FROM EMERGENCY STOP (F)	TOTAL BRAKE TEMP. (F)	TOTAL TRAVEL TIME (MIN.)
70000	13	480	3	483	13.8
65000	17	488	5	493	10.6
60000	24	488	10	498	7.5
55000	32	482	17	499	5.6
50000	55	442	47	489	3.3

NOTE : INITIAL BRAKE TEMPERATURE = 150

Press 'C' to continue or 'O' for speeds with brake temperature between 500 °F and 530 °F :

Figure 4: FHWA GSRS DOS Program Output

Importantly, in addition to the long and steep downgrades, most mountain passes are characterized by horizontal curves. The presence of horizontal curves increases the risk of a rollover crash for trucks due to their higher center of gravity. Additionally, truck crashes due to brake heating and failure on downgrades are usually accompanied by rollovers due to an inability to regain control of the vehicle. It is therefore important to account for the presence of horizontal curves in the formulation of WSS signs.

A discussion is provided below on automating the formulation of WSS signs following the work of Johnson et al., 1982 and Bowman, 1989. The type of GSRS analysis to determine an appropriate WSS signing strategy depends on the physical characteristics of the downgrade.

Multigrade hills can be categorized in two; those that contain nonbraking intervals (upgrades and level sections) (Figure 5) and those that do not (**Error! Reference source not found.**). For multigrades with the presence of nonbraking intervals (Figure 5), grade descent can be done with gear ratio changes, and hence, different speeds along the downgrade. The multigrade is considered as a series individual downgrades separated by inclines or level sections where trucks have high initial brake temperatures. Trucks can therefore descend each downgrade at a different speed because the nonbraking intervals allow for downshifting. The WSS signing strategy adopted for such multigrades is referred to as the separate downgrade method (Bowman, 1989). The GSRS program developed for IBM computers in 1989 was used to estimate maximum descent speeds for multigrades.

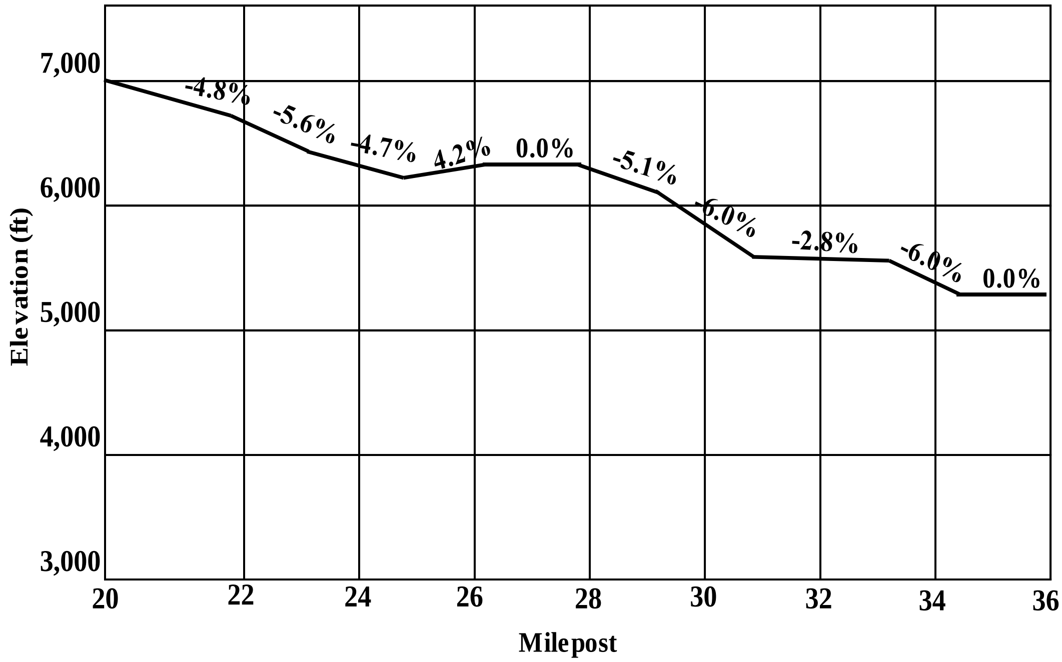


Figure 5: An Example of a Multigrade with Nonbraking Intervals (Not Drawn to Scale)

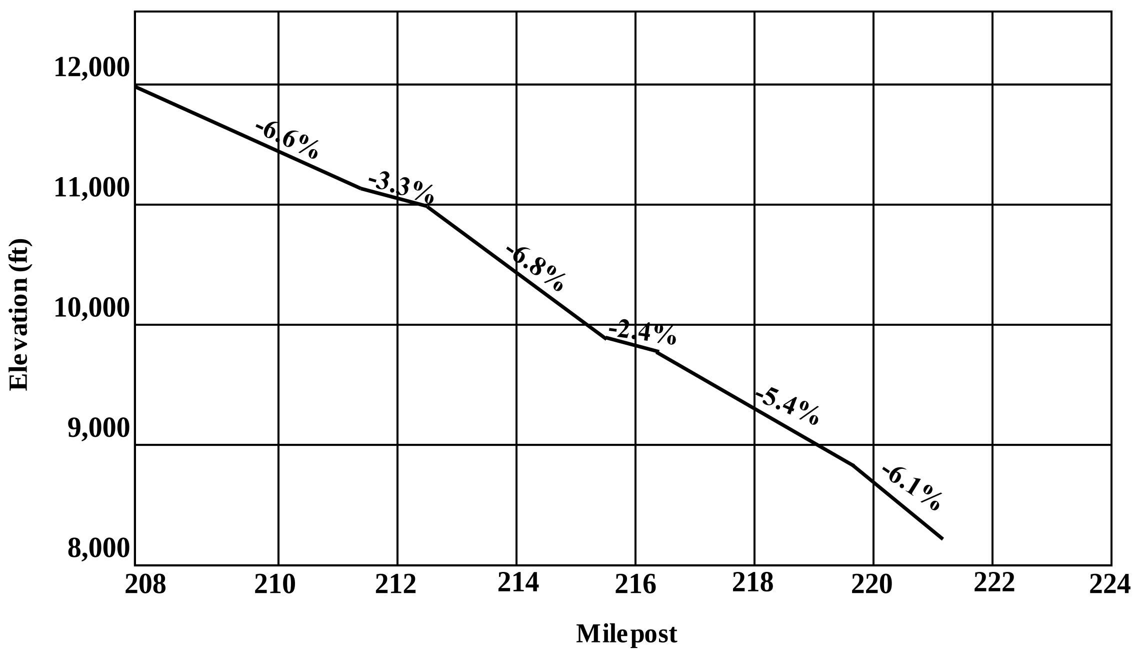


Figure 6: An Example of a Continuous Downgrade without Nonbraking Intervals (Not Drawn to Scale)

Grades with no braking intervals make it impossible for drivers to safely shift the truck transmission into lower gears. Accordingly, the gear and associated speed selected at the beginning of the downgrade will be the lowest that will be maintained in the absence of nonbraking intervals. The WSS signing strategy adopted for such multigrades is referred to as the continuous downgrade method (Bowman, 1989).

4.4.1 Separate Downgrade Method

The separate downgrade method is utilized to optimize travel time by analyzing a multigrade as a series of constant-speed braking downgrades separated by nonbraking intervals. For the braking intervals, the brake temperature increases as energy is absorbed by the brake system with brake cooling occurring on nonbraking intervals and downshifting is allowed.

The separate grade method enables the selection of speed scenarios that can reduce the total travel time. The requirement of the GSRS is therefore to enable the driver to select an appropriate speed for each group of downgrades. The use of the GSRS' automated program enables an automatic determination of a maximum safe speed for the group of downgrades, while estimating the heat dissipation of the brake system. The resultant brake temperature is used as the initial brake temperature for the next group of downgrades (Bowman & Coleman, 1989). In estimating maximum safe speeds, the program permits trucks to descend the first group of downgrades quickly. The speed is then lowered continuously for the next group of downgrades using 5 mph variations. The process is continued until the end of the downgrade. This method is only applied to a specified weight with maximum speeds presented for each succeeding group of downgrades. A separate WSS sign is therefore placed at the end of each non-braking interval displaying the recommended speed.

4.4.2 Continuous Downgrade Method

The continuous downgrade method estimates one safe speed for each 5000 pound vehicle weight decrement that has to be maintained for the entire slope. This speed is to be held constant regardless of the number of downgrades. This method is used when nonbraking segments of sufficient length to permit safe downshifting do not exist within the downgrade. The GSRS program produced an output of one speed for each 5000 pound decrement from the maximum vehicle weight until the speed limit was reached.

4.5 Incorporating Horizontal Curves into the Formulation of WSS Signs

The presence of sharp horizontal curves on most mountain passes justifies incorporating them into the implementation of the GSRS. Generally, drivers tend to slow on sharp horizontal curves. When the curves are located on steep grades, trucks have a lower margin of safety in comparison to level roadways.

The current AASHTO policy represents a vehicle on a horizontal curve as a point mass. The lateral acceleration of a point mass traveling at a constant speed on a circular path is represented as:

$$f = \frac{V^2}{g.R} - 0.01e \qquad (1)$$

Where; f is the side friction factor representing the portion of lateral acceleration not balanced by superelevation (ft/s^2), V represents a constant vehicle velocity (ft/s), is the acceleration due to gravity (ft/s^2), R is the radius of the curve (ft), and e is superelevation of the roadway (ft/ft).

The side friction factor is critical to preventing vehicle skidding and rollover. In terms of rollover, the tendency of the vehicle to overturn must be resisted by the roll stability of the vehicle for safe operations (Harwood & Mason, 1994). In other words, the vehicle will rollover if $f > f_{rollover}$, where $f_{rollover}$ is the maximum lateral acceleration that a vehicle can experience without overturning (Torbic et al., 2014). The term $f_{rollover}$ is considered as the rollover threshold of the vehicle which is based on vehicle design and loading.

The procedure for including horizontal curves into the GSRS procedure will be to define a specified value of f_{max} and limit the values of f based on recommended speeds from the GSRS. In other words, maximum descent speeds recommended by the GSRS model will be tested to ensure that the value of f is always less that f_{max}. In situations where the recommended speed results in $f > f_{max}$, a speed corresponding to f_{max} will be chosen as the recommended speed.

5 Methodology

The methodology adopted for this study is aimed at meeting three objectives. These are validation of the GSRS model for trucks fitted with only drum brakes, incorporating curves into the GSRS procedure, and automating WSS sign formulation. The methodology is summarized in Figure 7.

Validating the GSRS model for trucks fitted with only drum brakes will involve loading a truck at different weights to perform field tests. Data collected from the field tests will be used to modify the GSRS procedure for formulating WSS signs. The field tests will not need truck instrumentation.

Incorporating curves into the GSRS program will require the testing and selection of an appropriate formula for vehicle rollover and the development of a robust procedure to include curves when developing WSS signs. The truck speed on a downgrade that ensures that a rollover does not occur on curves whiles keeping brake temperatures below the fade temperature will be the recommended speed for that downgrade.

The third objective of the study is to develop a program that automates the implementation of the GSRS and development of WSS signs. This objective will be achieved by developing a program with a graphical user interface (GUI) that will permit inputs of downgrade physical characteristics, curve radii, maximum load limit and the speed limits for mountain passes. The maximum safe speeds for each 5000 pound increment from the maximum load limit, temperature rise due to emergency stopping, total brake temperature, and descent time will be automatically displayed as outputs. Given the recommended speed, the program will determine the maximum speed threshold that will not result in a rollover.

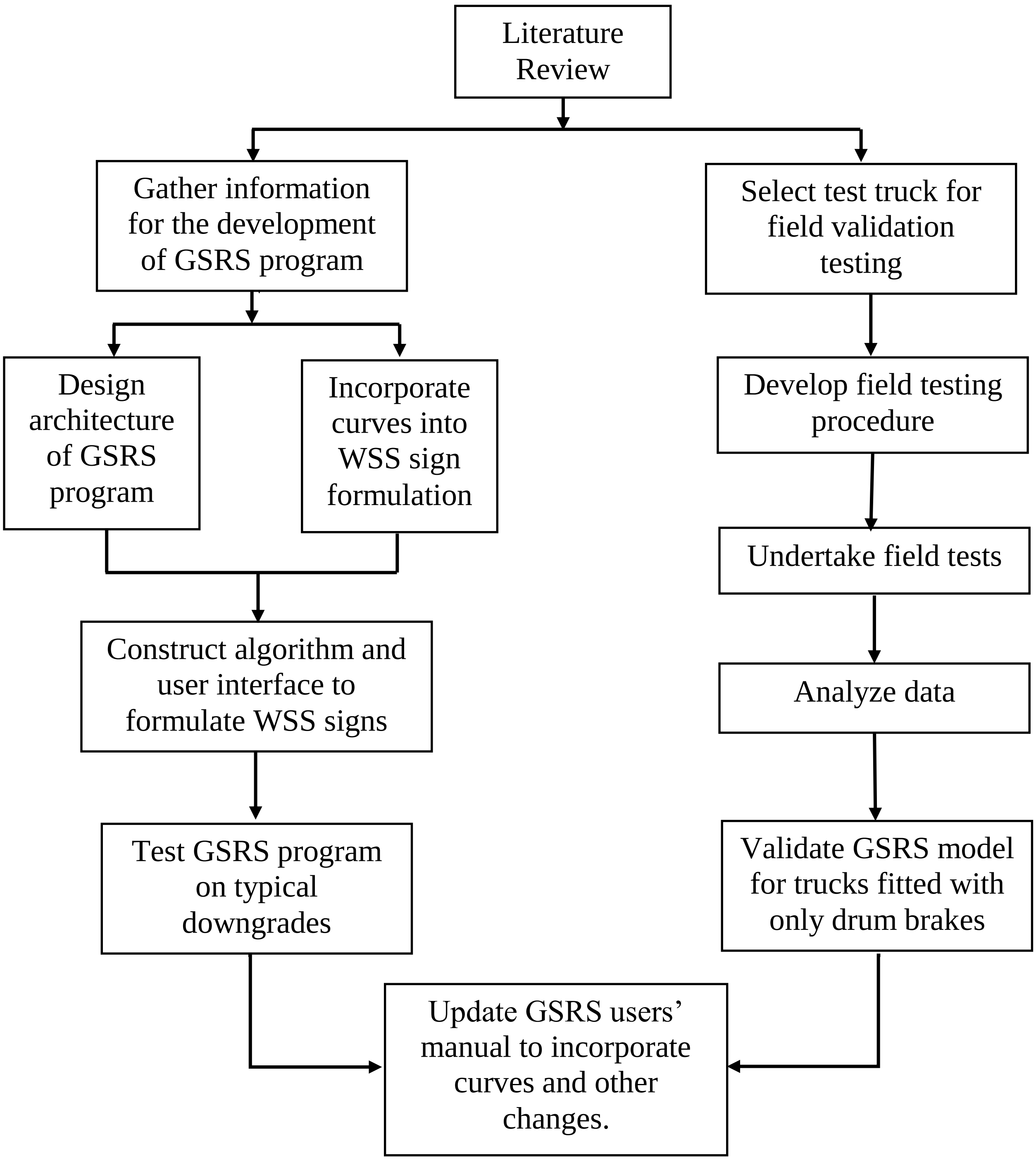


Figure 7: Study Methodology

6 Study Tasks

The tasks to be undertaken to successfully implement the study are detailed as follows:

Task 1: Literature Review

The literature review will be conducted to gain an understanding of issues related to the mechanics of truck operations on downgrades with horizontal curves and other considerations related to incorporating horizontal curves into the GSRS program. Also the literature review will seek to find information about the previous GSRS program developed in 1989, its drawbacks, and areas with the potential for improvement. Important factors to be considered in building the architecture and GUI of the GSRS program will identified from the literature review.

Task 2: Validate the GSRS Model for Trucks Fitted with Only Drum Brakes

Task 2.1: Select Test Truck

A test truck will be selected for the validation tests. This truck will be selected such that it has only drum brakes fitted on all its axles. This will permit for the validation of the GSRS for trucks with only drum brakes which currently dominate the US market.

Task 2.2: Develop Field Testing Protocol

The field testing protocol will be developed to guide the testing procedure. The protocol will consider the number of tests required to validate the GSRS model, traffic control needed, and locations where the tests will be conducted. Also, announcements will have to be made on local radio stations informing the public about routes and the days testing will be conducted.

Task 2.3: Conduct Field Tests and Analyze Data

Field tests will be undertaken by loading the test truck to different weights and descending several downgrades at a constant speed. A full instrumentation of the test truck is not required and the full range of tests conducted in the previous GSRS study will also not be needed. Instead, only a loaded truck and one type of simple test will be done for the validation. Initial and final brake temperatures of the truck will be measured before and after each descent respectively. The simplified tests will be conducted for several weights and speeds. Hand-held infrared sensors will be used to measure the brake temperatures during the field testing. A hand-held sensor is shown in Figure 8.

Task 2.4: Analyze Data and Validate GSRS Model

The measurement data from the field tests will be analyzed after being collected. The GSRS model will be modified if significant differences are found between temperature measurements of trucks fitted with disc brakes on the steer axles (measured in previous testing) and those trucks with only drum brakes.

Figure 8 A Hand-Held Infrared Sensor

Task 3: Incorporate Curves into WSS Sign Formulation

This task will involve clearly defined procedures to incorporate curves into the formulation of WSS signs. This will be an addition to the previous methods set out for implementing the GSRS.

Task 4: Develop a Program to Automate Formulation of WSS Signs

Task 4.1: Gather Information Required for Developing GSRS Program

During this task, a framework will be established for the development of the GSRS program. This task is also important to understand and document what is required by the engineers who will use the program. A roadmap will be developed detailing all the required steps for the program development and implementation to meet the expectation of users.

Task 4.2: Design Architecture of Program

This task will define how different aspects of the program will combine to produce a useable product. As part of this task, an evaluation will be carried out to identify important elements that must be included in the GSRS program.

Task 4.3: Program Algorithm and Design GUI for Use in Implementing GSRS

An algorithm will be programmed for implementing the GSRS. Additionally, an interactive and intuitive GUI will be designed for the program. The GUI will be designed to use dialog boxes to guide users in providing required information such as downgrade characteristics, weight limit, and speed. Feedback from the program will consist of outputs including recommended maximum speeds, brake temperatures, and descent time estimated automatically and displayed on windows of the program. The algorithm will be programmed to identify grade types (single or multigrade) and show results for either the continuous grade or separate grade methods.

Task 4.4: Test GSRS Program on Typical Downgrade Sections

After its development, the GSRS program will be run for several downgrades. These will include single and multigrades. Also, the reasonableness of speeds derived from the test runs will be assessed for this task.

Task 5: Update the GSRS Users' Manual

The previous users' manual developed for implementing the GSRS will be updated. The new manual will include procedures for incorporating curves into the formulation of WSS signs and deriving maximum downgrade speeds using the new GSRS program.

Task 6: Prepare Final Report and Present Findings and Recommendations

A final report will be prepared documenting the processes used to validate the GSRS model and automate the development of WSS signs. Also, an updated GSRS users' manual will be produced based on the automated program to guide in implementing the GSRS for mountain passes.

7 Timeline and Staffing

The entire study is expected to be completed in 24 months beginning May 1, 2020. A final report and presentations to appropriate WYDOT personnel will be done at the conclusion of the study. The presentations will demonstrate the implementation of the GSRS using the program developed for the study. The proposed timeline of the study is shown in Figure 9.

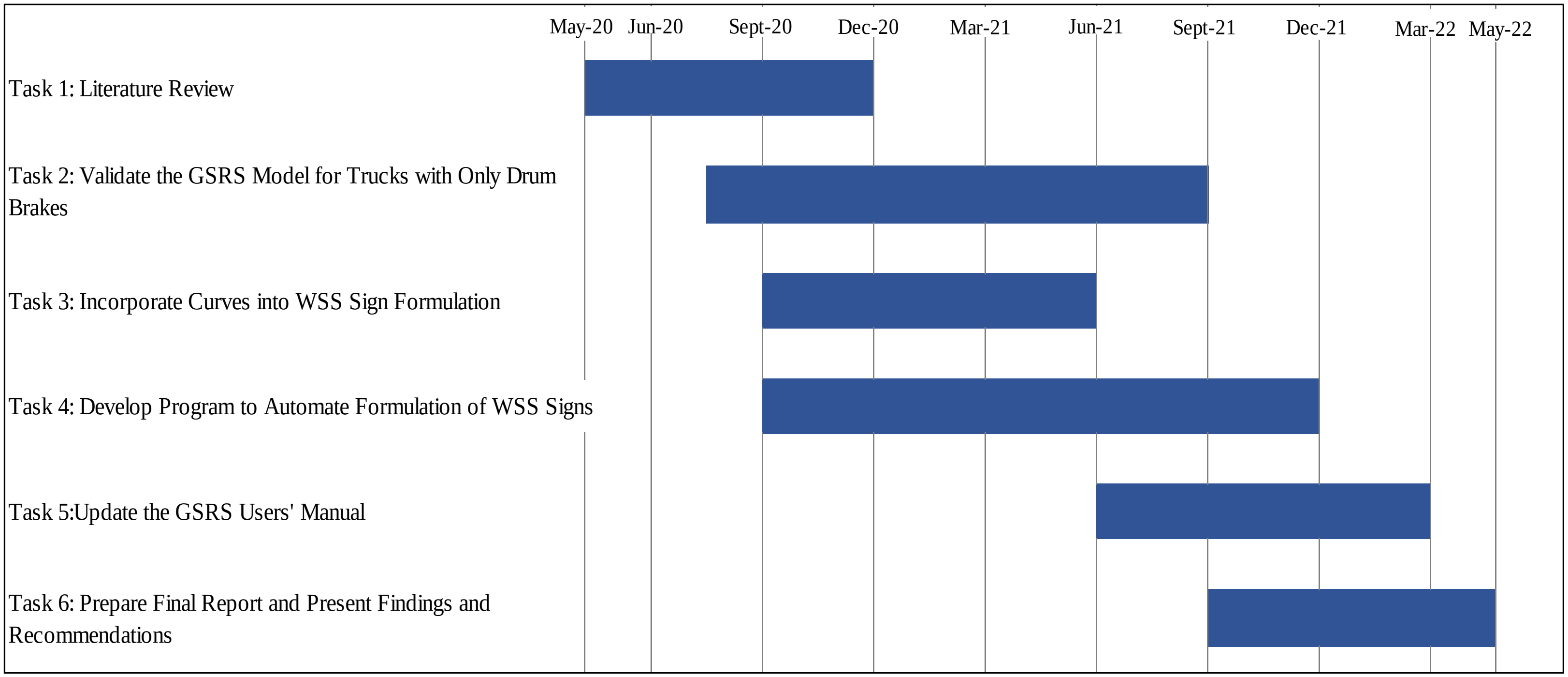


Figure 9: Proposed Study Timeline

8 Budget

The total budget for this study 152,565. The WYDOT portion is only $79,565. MPC will provide the matching fund of $73,000. The breakdown of the study cost is shown in Table 4.

Table 4. Study Budget

Categories	MPC	WYDOT	Total
Center Director Salary			
Faculty Salaries	$10,000	$20,500	$30,500
Engineer/ Post Doc	$500	$16,000	$16,500
Faculty/Engineer Fringe Benefits (43.3%)	$4,547	$15,805	$20,351
Student Salaries	$24,000	$0	$24,000
Student Fringe Benefits (3.9%)	$936	$0	$936
Total Personnel Salaries	$34,500	$36,500	$71,000
Total Fringe Benefits	$5,483	$15,805	$21,287
TOTAL Salaries & Fringe Benefits	**$39,983**	**$52,305**	**$92,287**
Travel	$2,000	$12,000	$14,000
Equipment	$0	$0	$0
Supplies	$3,000	$2,000	$5,000
Contractual			
Construction			
Other Direct Costs (Specify)*	$8,000	$0	$8,000
TOTAL Direct Costs	**$52,983**	**$66,305**	**$119,287**
F&A (Indirect) Costs	$20,017	$13,261	$33,278
TOTAL COSTS	**$73,000**	**$79,565**	**$152,565**

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