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AUTOMATING THE IMPLEMENTATION OF THE UPDATED GRADE SEVERITY RATING SYSTEM (GSRS) FOR WYOMING MOUNTAIN PASSES

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16. Abstract

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 cause a devastating toll 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. This study sought to fulfill Phase II of the GSRS study and was aimed at achieving three objectives. The first objective was to validate the GSRS model for trucks that have only drum brakes installed. The second objective was to make the updated GSRS fully implementable by incorporating horizontal curves into the formulation of the weight-specific speed (WSS) signs. The final objective was to develop a software that simplifies the implementation of the GSRS and the formulation of WSS signs by generating maximum descent speeds for different weight categories as output.

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

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Disclaimer

ABSTRACT

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 cause a devastating toll 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. This study sought to fulfill Phase II of the GSRS study and was aimed at achieving three objectives. The first objective was to validate the GSRS model for trucks that have only drum brakes installed. The second objective was to make the updated GSRS fully implementable by incorporating horizontal curves into the formulation of the weight-specific speed (WSS) signs. The final objective was to develop a software that simplifies the implementation of the GSRS and the formulation of WSS signs by generating maximum descent speeds for different weight categories as output.

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EXECUTIVE SUMMARY

The trucking industry is described as the sum of all owners/operators of trucks, tractors, and trailers involved in the transportation of freight or goods irrespective of whether payment is received for such services. Two basic components of the industry are the for-hire segment and the private segment. The for-hire segment is defined as vehicle owners/operators who carry freight for compensation. The private segment of the industry consists of vehicle owners/operators who carry their own freight. The core function of the private segment is to provide logistical support service to its proprietary shipper. This definition, however, does not omit the possibility of a private carrier either receiving revenue or generating profit from transport operations.

Updating and Implementing the Grade Severity Rating System (GSRS) for Wyoming Mountain Passes (Phase 1) was a study commissioned by the Wyoming Department of Transportation (WYDOT) in 2016, and it dealt with the process of updating the GSRS model parameters. Phase 1 entailed fitting a truck with disc brakes on the front axle and drum brakes on the rear axle, fully instrumenting it, and then taking it through several field tests. Finally, a validation test was conducted to evaluate the robustness of the updated model through a comparison of the field brake temperatures and the predicted temperatures. The GSRS model was determined to be accurate because the predicted temperatures were close to the field temperatures. However, some limitations of this study included environmental and time constraints. To avoid these limitations and to extend the testing range, software simulations were run. The GSRS model developed in Phase 1 considered changes in truck characteristics, where the test truck was equipped with disc brakes on the front axle and drum brakes on the rear axle. However, because disc brakes represent only about 20% of the brake market, the model needed to be validated for trucks fitted with only drum brakes that constitute the clear majority in the U.S.

The purpose of this research project was to validate the GSRS model for trucks that have only drum brakes installed, incorporate horizontal curves into the formulation of weight-specific speed (WSS) signs, and develop a program that automates the implementation of the GSRS. This way, the implementation of the GSRS for Wyoming mountain passes could be updated.

The GSRS validation was achieved by conducting field tests, specifically, the Hill Descent and Validation Tests with a fully loaded truck fitted with only drum brakes. The main objective of the field tests was to derive an equation for the heat coefficient, K_2, and then compare it to the K_2 obtained from the field tests conducted in 2016. The K_2 value derived from the tests was minimally different from that computed for the scenario of the test truck equipped with both disc and drum brakes. This was established by examining the maximum safe descent speeds generated by the previous updated model and the model developed in this study. They were found essentially the same.

The use of WSS signs generated from the Grade Severity Rating System (GSRS) developed by the Federal Highway Administration (FHWA) led to the realization that it was an effective remedy in reducing the incidence of runaway truck crashes. Through a series of research initiatives starting in the 1980s, WYDOT developed a GSRS model to estimate the maximum safe speed for trucks during downgrade descent. In this study, the GSRS model was updated, and the updated mathematical model was automated through an interactive, intuitive, aesthetically appealing, and user-friendly objected-oriented Visual Basic.net software. Additional research on the GSRS model was accomplished to account for large truck vehicle stability, specifically, rollovers and skidding/side slip during grade descent. These scenarios become relevant in the presence of horizontal curves. Consequently, this latest mathematical model has been automated to simplify the computation of maximum safe descent speed on the downgrades combined with curves, all based on the truck weight.

To factor in the influence of horizontal curves on the maximum safe speed of descent of the truck with respect to vehicle stability—specifically, rollover and skidding—simulations were run on TruckSim® 2020 for a variety of rollover margins, super-elevations, truck weights, deflection angles of the horizontal curves, longitudinal grades, speeds, and radii of curvature of the horizontal curve. Similar simulations were carried out to generate the associated skidding coefficients for the same variables. In all, 300 data points were obtained for each variable based on 300 simulation runs. Ten different radii for the horizontal curves were included in the simulations, as well as eight different super-elevations, 10 different longitudinal grades, six different truck weights, and 10 different speeds.

As was the case in the previous version of the software, this version provides functionality for both the continuous slope and the separate downgrade method. This upgraded software version will enable WYDOT and other highway agencies to easily estimate the maximum safe speed of descent for various weight categories considering horizontal curves and roadway geometry, thus producing WSS signs for each multi-grade section. Documentation, including a complete user manual for the use of the software, is included in the Appendix of this report.

1. INTRODUCTION

This chapter begins with background information about the trucking industry and truck safety on mountainous downgrades. The problem statements and study objectives are also discussed. The chapter then presents the organization of the report.

1.1 Background of the Trucking Industry and Truck Safety on Mountainous Downgrades

The trucking industry is described as the sum of all owners/operators of trucks, tractors, and trailers involved in the transportation of freight or goods irrespective of whether payment is received for such services. Two basic components of the industry exist: the for-hire segment and the private segment. The for-hire segment is defined as vehicle owners/operators who carry freight for compensation. The private segment of the industry consists of vehicle owners/operators who carry their own freight. The core function of the private segment is to provide logistical support service to its proprietary shipper. This definition, however, does not omit the possibility of a private carrier either receiving revenue or generating profit from transport operations (*1*).

Moreover, the trucking industry is a core pillar of the U.S. economy, which although underestimated, is responsible for transporting 70% of all freight (*2*). U.S. communities depend heavily on trucks for the delivery of everyday goods ranging from food, medicine, raw materials, and much more. Almost every sector of the American economy relies on trucking. Regular life would be heavily impacted in the absence of the trucking industry. Heavy industries, inclusive of which are mining, construction, utilities, and infrastructure, would all collapse without the delivery of commodities necessary for them to function. Power outages resulting from a deficit in electricity supply at home and in hospitals would occur. Moreover, large amounts of job losses would occur since the trucking industry employs approximately 7 million people, half of whom are truck drivers (*2*).

Out of the approximately 499,000 police-reported crashes involving large trucks in 2018, there were 4,415 (1%) fatal crashes and 107,000 (21%) injury crashes (*3*). Nationwide, Wyoming has considerably higher fatality rates for crashes overall (24.7 deaths per 100,000 people), as well as truck-related crash rates in the U.S. (1.82%) per annum (*4*). These high rates are primarily accounted for by the presence of heavy truck traffic on Wyoming's interstates and mountainous highways due mainly to the oil drilling and coal mining activities in the state (*1*). Secondary to this is the challenging roadway geometry consisting of steep downgrades and curves. Trucks are highly vulnerable to downgrade crashes due to their heavy loads and large sizes. They are also taller, raising their center of gravity, and as a result, their odds of overturning increase.

1.2 Problem Statement

Updating and implementing the Grade Severity Rating System (GSRS) for Wyoming mountain passes (Phase 1) was a study commissioned by the Wyoming Department of Transportation (WYDOT) in 2016 (*5*), and it dealt with the process of updating the GSRS model parameters. Phase 1 entailed fitting a truck with disc brakes on the front axle and drum brakes on the rear axle, fully instrumenting it, and then taking it through several field tests. Finally, a validation test was conducted to evaluate the robustness of the updated model through a comparison of the field brake temperatures and the predicted temperatures. The GSRS model was determined to be accurate because the predicted temperatures were close to the field temperatures. However, some limitations of this study included environmental and time constraints. To avoid these limitations and to extend the testing range, software simulations were run. The GSRS model developed in Phase 1 considered changes in truck characteristics, where the test truck was equipped with disc brakes on the front axle and drum brakes on the rear axle. However, because disc brakes represent only about 20% of the brake market, the model needed to be validated for trucks fitted with only drum brakes that constitute the clear majority in the U.S.

1.3 Study Objectives

The purpose of this research project was to validate the GSRS model for trucks that have only drum brakes installed, incorporate horizontal curves into the formulation of weight-specific speed (WSS) signs, and develop a program that automates the implementation of the GSRS. This way, the implementation of the GSRS for Wyoming mountain passes could be updated.

1.4 Report Organization

This report is organized into five chapters. Chapter 1 introduces the trucking industry and truck safety on downgrades, the problem statement, and the study objectives. Chapter 2 comprises a review of previous studies related to this research project. Chapter 3 describes the GSRS validation test conducted for trucks equipped with only drum brakes. Chapter 4 describes the procedures for the incorporation of horizontal curves and roadway geometrics into the updated GSRS and the development of the algorithms upon which the GSRS automation software is based. Finally, Chapter 5 discusses the conclusions and recommendations for future work.

2. LITERATURE REVIEW

This chapter presents topics essential to establish the need for development and upgrade of the GSRS starting with a brief discussion of WSS signs on truck downgrades and emergency braking temperatures. Previous studies on grade severity rating systems leading up to the present GSRS study are discussed along with their limitations. This is followed by a description on the numerous changes in trucks that have occurred since the prior GSRS study and their implications, inclusive of which was the research study commissioned by WYDOT to update the GSRS in the fall of 2017. The study then analyzes crashes occurring on downgrades featuring compound alignments in which curves from the road's horizontal alignment are overlain with vertical curves. Following from this, to meet the vehicle stability criterion, the relationship between the demanded lateral friction, speed, radius, and grade is derived from existing literature. The equation assists the basis for the derivation of the relationships between rollover margins or skidding coefficient, and the speed, radius, longitudinal grade, super elevation of the roadway, and degree of curvature of the horizontal curves. After the software based on the developed algorithms underlying the mathematical equations is developed, general guidelines instructing software engineering researchers on proper practices for the preparation of software engineering papers are discussed.

2.1 Importance of the GSRS

The use of WSS signs generated from the GSRS developed by the Federal Highway Administration (FHWA) led to the realization that it was an effective remedy in reducing the incidence of runaway truck crashes. The GSRS is a mathematical model capable of predicting brake temperature during a gradual descent. The GSRS model solves the "inverse problem," which is essentially a way to say it computes the corresponding speeds for a given final brake temperature given a particular downgrade at a given weight. Therefore, in the specific instance of preventing brake fade, a maximum safe final brake temperature is defined that corresponds to the maximum safe speed for that specific downgrade at a specific weight. Based on this, a WSS sign recommending maximum speeds that would be kept constant throughout the duration of the downgrade for several truck weights is erected (*6*).

Johnson et al. (1982) noted that it was relevant for sufficient braking to be available at any point along the downgrade to enable an emergency stop (*7*). Their conclusion was based on the notion that it was possible for a truck to have enough braking capacity to maintain a steady descent but lack sufficient capacity to slow in time to avoid a hazard on the downgrade. The heat energy arising from the extra burden of emergency braking added to the heat from the constant descent is likely to result in brake fade and failure when the braking requirement is most critical. As a result, the GSRS model was modified to account for the temperature rise resulting from an emergency stop (*6*).

2.2 Previous GSRS Studies

As truck drivers descend steep downgrades, they continuously apply the brake system to regulate the truck's speed. This tends to elevate the brake temperature, leading to the distortion and expansion of the drum brakes from the brake linings, which in turn leads to a reduction in the quality of surface-to-surface contact between the linings and brake drums. As a result, it requires progressively more actuator travel to maintain braking force, potentially reaching the limit of actuator travel in severe cases. This contact progressively decreases until braking efficiency is lost. The drivers encountering this scenario may continue either descending the grade, wagering on whatever residual braking power persists, or attempt to stop, thereby allowing the brakes to cool (*5*). If the residual braking power is inadequate to control the speed or stop the truck, a phenomenon referred to as truck runaway takes place.

To minimize the risk of a runaway truck crash, highway agencies attempt to provide quality information to the driver. Typically, this includes the use of warning signs or other measures, such as intelligent transportation systems (ITS). Previously, systems were developed to evaluate downgrades for their severity. These ratings were intended to relate the degree of hazard presented by the downgrade to the driver so he could select a safe descent speed. Over the years, several types of downgrade rating systems have been developed to achieve this objective.

The Bureau of Public Roads (BPR) Grade Rating System was one of the earliest grade rating systems developed by the BPR in the 1950s. This system merged the length and slope of the grades to alert drivers about the severity of grade descents (*8*). This system also organized grades into three separate classifications: greater than 3% and longer than 10 miles; greater than 6% and longer than 1 mile; and greater than 10% and longer than 0.5 miles. In 1963, Hykes suggested an improvement over the BPR grade rating system to enable a finer spectrum of grade severity (*8*). His system was based on a grade ability procedure developed from an earlier study (*9*). Hykes' contribution to this study was to expand the grade ability formula to create a downhill energy equation that embodied retarding horsepower from the brakes, rolling resistance, chassis friction, air resistance, engine friction, and retarders. Field tests were implemented to validate this system. However, one key drawback of this model is that the model's ratings were inaccurate for tractor-trailer combinations, resulting from poor brake balance between the tractor and trailer and the trailer axle hop and bounce caused by the suspension type used.

Lill (1973-1976) suggested a grade rating system to enhance the grade ability formula in the 1970s (*10*). Lill's model was an improvement over previous models as it was built on three essential concepts:

- First, assessing hills based on their effect on a representative truck
- Second, including the influence of hill length by considering brake fade effects
- Third, using a stopping distance benchmark to measure the available braking capacity

The approach applied the work-kinetic energy equation to solve the maximum descent speed that enabled stopping in a criterion distance of 250 ft. to braking on a grade. Lill's GSRS model was initiated with different speed bands to indicate grade severity. Higher speed bands corresponded to the least severe grades and vice versa (*8*).

Finally, the FHWA expanded on the preceding models to advance a GSRS based on brake temperature in the early 1980s. Accomplishing this required that various field tests be conducted to define the parameters of the brake temperature equation. The FHWA GSRS model takes into consideration the gross truck weight in addition to the percent downgrade and truck braking length in order to propose safe descent speeds (*11*). One of the basic assumptions of the GSRS is a constant descent speed. Other assumptions include the fact that the engine retarding horsepower is maintained close to the allowable maximum for the engine, and the presence of a five-axle truck (*12*).

It is essential to note that the GSRS was developed to define the retarding forces preventing heavy vehicles from accelerating on downgrades. In the context of descending at a constant speed on a downgrade, the force due to gravity is equilibrated by all the forces resisting forward motion, such as aerodynamic drag, tire rolling resistance, chassis friction, engine braking force, resistive forces from retarders (assuming the truck is equipped), and braking forces at the wheels when the driver applies the brakes. Other significant factors in the GSRS model include the brake system's cooling parameter (diffusivity), and a parameter to define the brake heat transfer characteristics.

Forty years have passed since the GSRS was first developed. Within this time, truck designs have experienced significant modifications. These changes have led to a reduction in non-brake forces retarding a truck's motion. These include reduced frontal areas resulting from streamlined tractor designs, improved airfoils, and changes to the trailer design. Moreover, using add-on devices such as sleeper roof fairings, chassis skirts, air tabs, and cab extenders has reduced the aerodynamic drag on trucks between 6% and 20% (*13*). Besides, the trucking industry has adopted radial tires in place of bias-ply tires. Radial tires rotate faster and have smaller diameters compared with regular tires. This has led to modifications in the rate of kinetic energy absorption, resulting in more work required of the brakes to dissipate energy. By using radial tires, truck fleets have now adopted higher trailer boxes capable of hauling loads 2 inches higher while maintaining required height restrictions (*12*).

Engine designs and power absorption have also been modified over the decades. For instance, in 1974, a standard 290 horsepower (hp) engine absorbed approximately 113 hp, and this was inclusive of the effects of driveline efficiency and accessory power. A 300 hp engine built in 1980 produced close to 75 hp of retardation due to friction and accessory use (*11*). Therefore, manufacturers of truck engines have decided to target a reduction in friction within the bearings, valve trains, and the piston-to-liner interface to improve efficiency.

To reduce engine drag even further, the development of heavy-duty oils has likewise shown significant promise (*13*). Generally, these enhancements have progressively decreased the engine friction and subsequent retardation from the engine in addition to the development of new engines. As a result, additional braking effort is required to enable the brake system to descend the downgrade safely. Moreover, the Federal Motor Vehicle Safety Standards (FMVSS) has mandated a change in the stopping distance of trucks by up to 30%. This has led to modifications in truck braking systems; specifically, an enlargement of brakes and the adoption of disc brakes in order to comply with the stopping rule. These changes have resulted in the GSRS' recommended speeds as being too conservative and, as a result, increasing the risk of truck drivers ignoring recommended speeds as unrealistic and disregarding the GSRS altogether, thus reducing downgrade safety.

2.3 Updating the GSRS to Account for Rollover and Side-slipping due to Horizontal Curves

Crash analysis of highways running through rural areas indicates that the vast majority of crashes take place on horizontal curves when the vehicle is subject to lateral forces, increasing the probability of skidding (*14*). For downgrades featuring compound alignments in which curves from the roads' horizontal alignment are overlain with constant grades or vertical curves, the probability of skidding increases due to increases of longitudinal forces on the vehicle. One such study (*15*) utilized a vehicle multi-body simulation modeling software with several scenarios defined to assess the outcome when horizontal curves are combined with vertical sag curves for three different types of vehicles: a sedan, a sports utility vehicle, and a truck. The maximum lateral friction demand between the surface of the road and vehicle tires was computed for various speeds. Finally, by using regression analysis, a model was developed according to the response and predictor variables of the simulation model to determine the maximum lateral friction demand under various conditions (*15*). Hasan et al. (1998) demonstrated that the point mass model is inefficient in computing the radius of a horizontal curve accurately due to the impact of several critical road-vehicle parameters, especially with respect to their interaction, which was ignored (*16*). In summary, the most significant drawbacks of the point mass model include:

- Critical parameters from the vehicle dynamics, such as vehicle mass, are ignored.
- The effect of force distribution among the vehicle's different wheels is likewise ignored.
- The effect of the interaction imposed from the geometry of compound curves, specifically on vehicle stability, is effectively disregarded.
- The longitudinal design of the roadway environment is assumed to be flat.

Tavassoli, Kallebasti, and Abdi Kordani (2018) computed the tire-road side friction demands for compound alignments created by horizontal curves on various longitudinal grades using a simulated model (*14*). They concluded that the effects of grades for trucks and sedan passenger cars are much more critical as compared with sports utility vehicles (SUVs). The models based on which side friction demand is delivered for cases of sedan passenger cars, SUVs, and trucks are outlined in the equations below:

$$\mathrm{f} = 3.769 - 3.108\mathrm{In\ v0.1} - \ 0.03\mathrm{g} \qquad \text{(Sedan)} \qquad (1)$$

$$\mathrm{f}\ = 0.663 - 0.12\mathrm{In\ v} + 7.479\mathrm{E} - 7\mathrm{g3} \qquad \text{(SUVs)} \qquad (2)$$

$$\mathrm{f} = 0.827 - 0.155\mathrm{In\ v} - 0.001\mathrm{g} \qquad \text{(Trucks)} \qquad (3)$$

Where, f is the side friction demand, v is the speed (km/h), and g is the grade (percent).

The authors recommended placing warning signs a specified distance before the beginning of the horizontal curve to reduce the speed of vehicles entering a combined curve (longitudinal grade coupled with horizontal curve) before entering the danger zone (*15*).

In recent times, tractor-semitrailer safety on combined downgrades of freeways has been an issue of serious concern in China, primarily because of overloading and relatively poor vehicle performance. Based on statistics provided through a survey of serious and major traffic accidents on national highways between 2010-2014, tractor-semitrailers accounted for 38% of all crash vehicles, killing 1,520 people, a mortality rate of 32%. Rear-end collisions, fixed-object crashes, and rollover crashes are the main types of tractor-semitrailer crashes with a 73.2% rate. In response to this, a study conducted by Qu et al. (2018) used TruckSim® 2020 multi-body vehicle dynamics software to establish the driver-vehicle-road dynamic simulation model in which they investigated a Suzuki QL4250SKFZ three-axle semitrailer and a Huajun ZCZ9390 three-axle semitrailer commonly used in China (*17*). After the simulation results were obtained, multiple linear regression analysis was conducted to develop new models of maximum wheel side friction demand (f_D) and load transfer ratio (LTR) for a six-axle tractor semitrailer by selecting the radius, longitudinal grade, and vehicle speed as the independent variables. Based on these models, the risk analysis of a vehicle on a wet road surface was conducted and safe speed limits were specified. The final equations for f_D and LTR on curved downgrades are indicated in equations (4) and (5) (*17*).

$$\boldsymbol{LTR = 0.022 \times \left(\frac{V^2}{R}\right) - 0.025i + 0.112} \qquad \mathbf{(4)}$$

$$f_D = 0.018 \times \left(\frac{V^2}{R}\right) - 0.020i + 0.022 \qquad (5)$$

Where *LTR* ranges from 0.6 to 0.8 for a modest potentiality in the occurrence of a rollover, 0.8 to 0.1 for a definite potentiality in rollover occurrence and 1 for the critical state of a rollover, *V* is the speed (km/h), *i* is the grade (percent), and *R* is the radius (m).

In additional research conducted by Qu et al. (2018), the sideslip mechanism of a six-axle semitrailer combination on a curved downslope expressway segment was simulated based on the vehicle dynamics theory using TruckSim® 2020 (*17*). The impacts of horizontal radius, longitudinal grade, speed, and gross vehicle weight on the side-slope were analyzed. The final side friction factor regression model was found to be:

$$f_y = 0.017 \times \left(\frac{V^2}{R}\right) - 0.035i + 0.017M - 0.302 \qquad (6)$$

Where f_y is the side friction factor, *R* is the horizontal curve radius (m), *i* is the longitudinal grade (percent), *V* is the speed (km/h), and *M* is the gross vehicle weight (Mt).

Hassan et al. developed a probabilistic safety-explicit design approach of horizontal curves on two-lane rural highways using naturalistic driving data to model vehicle speed and driver comfort distributions (*16*). The outputs of CarSIM simulation runs were used to model the lateral friction demand and lateral acceleration. Reliability analysis was then used to determine the probabilities of failure and reliability indices for four design criteria. Finally, safety performance functions were developed considering exposure variables, curve geometry, and reliability indices. For the vehicle stability criterion, equation 7 was developed:

$$f_D = \left(\frac{0.009V^{1.879}}{R^{0.886}} - 0.947e^{0.928} + 2.6 \times 10^{-5}G\right) \tag{7}$$

Where f_D is the demanded lateral friction for a passenger car, V is the speed (km/h), R is the radius (m), and G is the grade (percent) (*18*).

In 1990, following the development of the GSRS by FHWA, a console-based software application was developed for the disc operating system (DOS) to allow for its implementation. The application would request input parameters, such as truck weight, speed limit and the physical characteristics of the downgrade, specifically length and slope, and use that information to compute maximum safe speeds, brake temperatures, and total travel time for various truck weights. This program was indispensable for multi-grade segments since the computation of maximum safe speeds for such grades relied on optimization criteria, which could not be accomplished manually. It sought to answer the question: "Which combination of maximum safe speeds will ensure the fastest descent of the grade while keeping the brake system below the brake fade temperature?"

In Moomen et al., a 2018 study, a five-axle semitrailer class 8 truck was instrumented to measure important parameters (*5*). Three main field tests were conducted to update the GSRS model. These were the coast-down, cool-down, and hill descent tests. Maximum safe descent speeds and descent times from the updated model were compared with the same measures from the previous FHWA GSRS model. The results showed that the speeds resulting from the updated model were higher but did not lead to brake temperatures exceeding the limiting temperature threshold of 500˚F. This reduced the probability that truck drivers would ignore the speed (*19*).

2.4 Developing the Updated GSRS Software and Writing the Research Paper

Aiming at assisting software engineering researchers and engineers in developing specialized software, Mary Shaw presented "Writing Good Software Engineering Research Papers" in 2003. She deconstructed the abstracts of the papers submitted to the 2002 International Conference of Software Engineering (ICSE) to determine trends in research question type, contribution type, and validation approach. Shaw concluded that every research paper based on software engineering needed to answer three important questions:

1. "What precisely was your contribution?"
2. "What is your new result?"
3. "Why should the reader believe your result?"

A general categorization scheme used to classify papers along four main dimensions was also proposed following Shaw's work. These dimensions are explained below:

1. Problem: What issue the paper would like to solve or the question the paper would like to answer.
2. Contribution: What is the main result presented in the paper?
3. Validation: What evidence the paper shows that the contribution is valid.
4. Topic: What is the main topic the paper addresses?

Of the four types of categorization, the researcher's choice of validation technique was found to be the most crucial factor determining whether a paper would be accepted or otherwise (*20*).

2.5 Chapter Summary

This chapter discusses the essence and relevance of the GSRS, and the necessity to upgrade it. The history and evolution of the studies aimed at enhancing grade severity and eventually leading up to the GSRS is also discussed. Several changes in truck characteristics have occurred since the previous GSRS developed in the 1980s, leading to a mismatch between the GSRS and the current truck characteristics. Specifically, GSRS underpredicted the maximum descent speeds, causing truck drivers to trivialize these values, and hence, ignore them. This worsened the state of truck safety on downgrades. Because of this worsening in truck downgrade safety and the associated increase in truck crashes as a result, a research study was commissioned by WYDOT to update the GSRS in the fall of 2017 to account for modern truck configurations.

The chapter then discusses the prevalence of combined downgrades on US-16, in Wyoming, and the manner in which the introduction of horizontal curves within truck downgrades leads to questions of vehicle stability, specifically, rollovers and sideslipping. A procedure for introducing vehicle stability considerations into the existing GSRS mathematical model based on multiple linear regression between the skidding coefficient/rollover margin and the speed, radius, longitudinal grade, superelevation of the roadway, and the degree of curvature of the horizontal curves is discussed. The procedure for generating the data points for this modeling using the TruckSim® 2020 multibody vehicle dynamics software is described as well.

After the mathematical models were generated, they were converted into Visual Basic.net algorithms, therefore, forming the basis of the GSRS software. Finally, the general guidelines instructing software engineering researchers on best practices for preparing software engineering papers are discussed.

3. COMPARING GRADE SEVERITY RATING SYSTEM (GSRS) MODEL FOR TRUCKS FITTED WITH DRUM BRAKES VERSUS DISC BRAKES

This chapter examines the current distribution of disc brakes versus drum brakes on the market and attempts to define an equation for the heating coefficient for trucks equipped with only drum brakes. This is because, in the U.S., these are in the clear majority. The chapter describes a series of hill-descent and validation tests, defines the various segments for each test, defines the stopping/brake heat measuring locations, the number of test runs per segment, and the various speeds per test run. The analyses of the data collected from the experiment generates heating coefficients for each test run and then eventually generates an expression for the heating coefficient in terms of the truck speed. This expression is substituted into the brake temperature model to determine the brake temperatures at the end of various grades of the multi-grade segment used for the validation tests. These temperatures were then compared with the measured field brake temperatures to determine if the model is robust. Finally, the determined value of the heating coefficient was used to determine the maximum safe speed of descent for the updated model and the older model and comparisons were drawn.

3.1 Background

Steep grades occurring on mountain passes present significant challenges to trucks. The union of heavy loads and steep and lengthy downgrades increases the probability of brake failure resulting from brake heating. Trucks at the top of downgrades represent significant potential energy that manifests kinetic energy as speed increases in the downgrade. As heat absorption increases, braking efficiency decreases, and a phenomenon called “brake fade” occurs. As the brake system temperature continues to increase, the condition advances from brake fade to brake failure, resulting in an “out-of-control” or “runaway” truck. 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 (*21*). As a result of the excessive speed and loss of directional control, runaway truck crashes are typically catastrophic.

3.2 Wyoming GSRS Study

Considering all the changes listed in the literature review, a research study was initiated by WYDOT and conducted by the University of Wyoming (UW) in 2016 to update the GSRS in order to adapt it 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 supporting the GSRS. These tests measured factors such as economy, simplicity, time constraints, accuracy requirements, and compliance with current published standards.

A typical five-axle truck semitrailer combination was instrumented for the 2016 tests. The rationale for selecting this truck had to do with the fact that over 60% of heavy trucks on U.S. highways possess this configuration. The truck selected to perform the tests was the 2016 Kenworth T680 series model. A Hyundai trailer van with a gross vehicle weight of 65,000 lbs. was attached to the tractor. The truck possessed a compression engine brake with the steer axle featuring Bendix air disc brakes, whereas 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 10 wheels to measure brake temperatures as well. A brake pressure transducer was 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 to a controller area network (CANbus). Data from the sensors and truck engine were 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. All the data collected were transmitted to a laptop running proprietary software (MICAS-X). The various parameters of the updated GSRS model following experimentation are indicated in Table 3.1.

Table 3.1 Updated GSRS model parameters (*12*)

Parameter	Expression/Value	Units
Brake temperature equation	$T_f = T_o + [T_\infty - T_o + K_2 HP_B][1 - e^{-K1L/V}]$	° F
Horsepower into brakes (HP_B)	$HP_B = (W\theta - F_{drag})*V/375 - HP_{eng}$	hp
Drag forces (F_{drag})	$(F_{drag}) = 459.35 + 0.132V^2$	lb
Diffusivity constant (K_1)	$K_1 = 1.5x(1.1852 + 0.0331V)$	1/hr
Heat transfer parameter (K_2)	$K_2 = 1/hAc = (0.1602 + 0.0078V)^{-1}$	° F/hp
Engine brake force (HP_{eng})	$HP_{eng} = 63.3$	hp
Temperature from emergency stopping (T_E)	$T_E = 3.11 \text{ x } 10^{\wedge -7} WV^2$	° F
Ambient temperature (T_∞)	$T_\infty = 90$	° F
Initial brake temperature (T_o)	$T_o = 150$	° F
Velocity (V)	V	mph

Note: Wθ is a term in the "horsepower into brake;" HP_B equation representing the product of the weight and the slope.

Because disc brakes represent only about 20% of the truck brake market, our field tests were performed on trucks fitted with only drum brakes. This procedure was achieved by conducting field tests, specifically, the hill descent and validation tests with a fully loaded truck fitted with only drum brakes. The main objective of the field tests was to derive an equation for the heat coefficient, K_2, and then compare it to the K_2 obtained from the field tests conducted in 2016. It is useful to note that the expression for K_2 involves an expression for h = effective heat transfer coefficient of the brake system (lb/ft-°F-h), and Ac = effective heat transfer area of brakes (ft^2). The methodology for these experiments is discussed in the next section.

3.3 Methodology

The methodology is subdivided into test vehicle preparation and equipment, testing location, testing procedures including brake burnish and balance tests, and, finally, the hill descent and the validation tests.

3.3.1 Test Vehicle Preparation and Equipment

The test truck used in this study was a 2010 Freightliner Cascadia with sleeper in a 3-axle all drum configuration and a 53' dry van trailer with a 2-axle all drum configuration. The truck was provided by Admiral Transport Corporation, Worland, Wyoming. Truck instrumentation was not required for these field tests because the relevant K_2 parameter to be computed was a function only of brake temperature, which simple hand-held devices could measure. WYDOT provided traffic control. Radio broadcasts were made to inform residents within the vicinity of the test locations. Table 3.2 describes the characteristics of the test truck used for the experiments.

Table 3.2 Characteristics of test truck used for the experiments

Make/Model	Freightliner Cascadia (2010)
Cab Style	Sleeper
Trailer type	Van
Gross vehicle weight rating	36,287 kg (80,000 lb)
Number of axles	5
Trailer length	53 ft
Service brakes (steer axle)	Drum brakes
Service brakes (drive and trailer axle)	Drum brakes

The equipment utilized in this experiment were hand-held sensors and ambient temperature measuring devices (such as on smartphone apps). Two readers took the readings sequentially (moving from axle to axle). Each had two sensors, and both were used to take the readings one after the other. The measurements were taken on the outer portion of the drum, with the sensors aimed through the wheel. The durations per reading were so short that readings recorded by both readers per axle was within 0.1˚F of each other.

The hill descent tests were conducted on the first day. The test procedure consisted of driving the test vehicle down some grades of known constant slopes at constant speeds and measuring the brake temperatures on each axle at the beginning and end of each grade. At every stop, the temperature on each axle was measured four times using two different devices. Brake temperature readings for each axle were then averaged. Figure 3.1 shows an image of the test truck and hand-held sensor used for the tests.

Figure 3.1 Test truck and hand-held sensor used for hill-descent and validation tests

3.3.2 Testing Locations

Overall, five segments were chosen for the tests: three for the hill-descent tests and two for the validation tests. The various locations for the tests were chosen based on three primary criteria. The first was their suitability to accommodate the full length and width of the truck for the period during which temperatures were being taken. The second was the ease of making U-turns during successive phases of each test. The third was safety considerations since US-16 has moderately heavy traffic and is subject to several road maintenance activities during that time of the year. Table 3.3 indicates the selected segments for the hill-descent and validation tests, relevant mileposts (MP), and the associated coordinates.

Table 3.3 Segments for hill-descent and validation tests

Segment for Hill-Descent (HD) Test	**Spot ID**	**Coordinates**
HD – I	HD 1-1 (MP 37.98)	(44.108523, -107.269592)
	HD 1-2 (MP 33.88)	(44.076075, -107.331767)
HD – II	HD 2-1 (MP 66.93)	(44.171708, -106.912747)
	HD 2-2 (MP 74.69)	(44.249467, -106.940798)
HD – III	HD 3-1 (MP 82.30)	(44.323139, -106.890345)
	HD 3-2 (MP 88.28)	(44.337336, -106.770569)
Segment for Validation (V) Test	**Spot ID**	**Coordinates**
1) V 1 – V 2 2) V 2 – V 3	V 1 (MP 74.69)	(44.249467, -106.940798)
	V 2 (MP 78.77)	(44.294364, -106.946179)
	V 3 (MP 82.30)	(44.323139, -106.890345)

Figure 3.2 shows a pictorial representation of the region within which the experiments were conducted. Indicated are the various stopping locations, segments, and direction of travel of the test truck. The notations illustrated on the map are described in Table 3-3 above. Figure 3-3 shows an example of turning locations for the hill-descent and validation tests, along with an arrow indicating the direction of travel of the test truck.

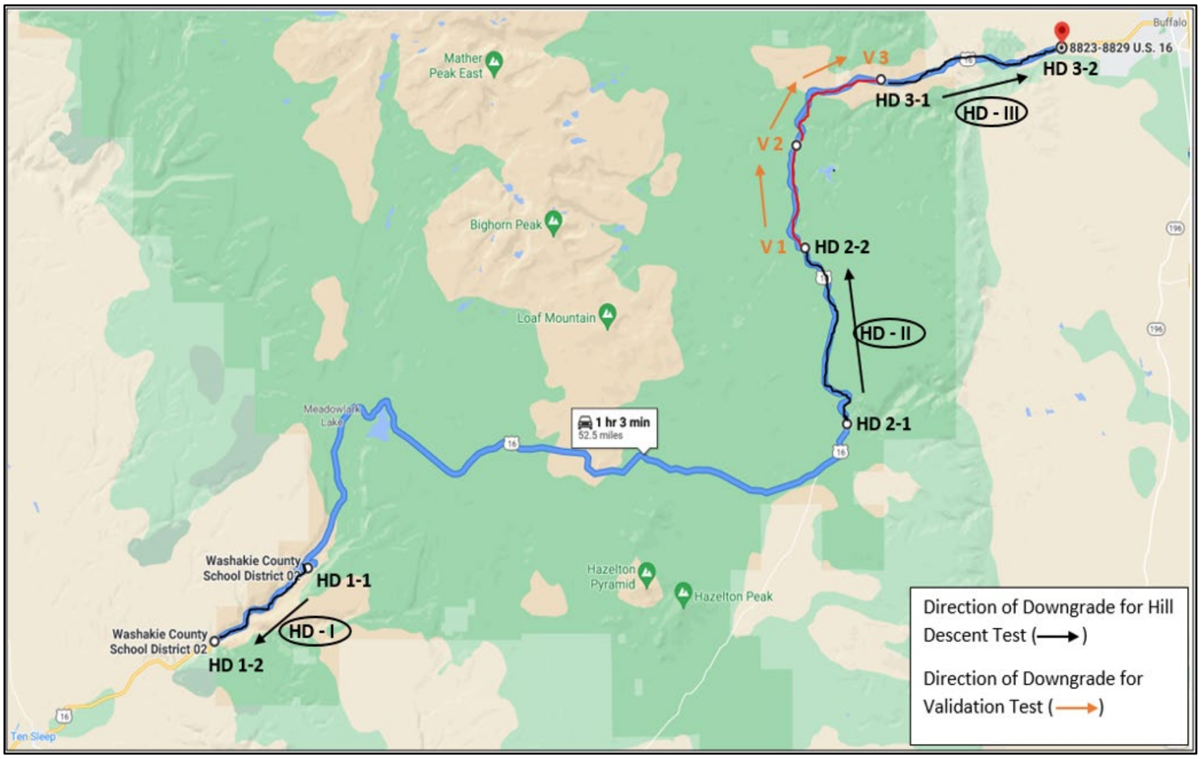


Figure 3.2 Test location map. © Google Maps altered

Figure 3.3 An example of some turning locations

3.3.3 Brake Burnish and Balance Tests

Typically, new brakes must undergo many brake application cycles, so that wear and heating effects cause the brake systems to reach a steady state such that braking forces are repeatable. This should take at least 200 runs. Since the drum-brakes used in this set of experiments were not new, the brake burnish tests were conducted for just 30 runs. The tests were split into two phases: the pre-burnish phase and the burnish phase. The pre-burnish phase required 10 snubs, during which time the truck traveled at 10 mph. In between snubs of 1 mile each, the truck traveled at 10 mph. The burnish phase consisted of two phases. The first phase consisted of 25 snubs, during which time the truck traveled at 30 mph. In between snubs, the truck likewise traveled at 30 mph and the distance between snubs was 1.5 miles. The second phase consisted of five snubs, during which time the truck traveled at 30 mph. As was the case in the first phase, the truck traveled at 30 mph in between snubs. The brake balance test was conducted to ensure that the brakes were balanced. Practically speaking, this can be achieved by comparing the differential temperature between the left and right sides of each successive axle to 50˚F. If this differential temperature exceeds 50˚F, the brake is imbalanced; otherwise, it is balanced. The brake balance can be determined by measuring the brake temperature between the front left brake and each left brake on successive axles and computing their differential temperatures and then comparing this differential temperature to 100˚F.

3.3.4 Hill-Descent Test

The purpose of this test was to find the variation of brake pressure and temperature during a steady hill descent as a function of weight, grade percent, grade length, engine braking, and descent speed. The test is also required to determine the total convective heat transfer parameter and the brake force as a function of pressure, speed, and temperature. For this, the test vehicle was loaded to 80,000 lbs. The testing procedure is briefly discussed below:

1. Measure brake temperature before commencing tests.
2. Ensure that brakes are cool (T < 200˚F on hottest brake). This can be achieved by driving the vehicle for some time to allow convection to cool the brakes.
3. Set engine brake to appropriate setting (No brake in this specific instance).
4. Accelerate vehicle to a speed 5 mph above the test speed.
5. Descend hill, maintaining speed constant by modulating brake pressure.
6. Measure brake temperature at the bottom of the downhill.
7. Conduct tests on different selected downgrades (3 downgrades), as determined in test locations.
8. Allow brakes to cool (T < 200˚F on hottest brake) before each hill descent.
9. Conduct tests at different typical truck operating speeds on downgrade (30-50 mph).

In summary, the hill-descent tests consisted of three separate segments with six turning spots and two test runs per segment. Segment 1 was run at 30 and 40 mph, Segment 2 was run at 35 and 45 mph, and Segment 3 was run at 40 and 50 mph.

3.3.5 Validation Test

The validation tests were performed on a multi-grade segment consisting of downgrades (braking segments) interspersed with level terrain or upgrades (non-braking segments). The test was conducted in a manner similar to the hill-descent tests. The test vehicle was loaded to 70,000 lbs. and driven along two continuous segments with three stopping spots. There were three test runs for the entire segment and speeds ran at 35 mph, 40 mph, and 45 mph, respectively.

3.4 Results and Discussions

The relationship between brake temperature and power into brakes is achieved by rearranging the brake temperature equation to put the brake power absorption function $F_B V$ on one side of the equation and all other variables, including the thermodynamic variables, collectively named T^* on the other side. This is expressed as follows:

$$T^* = T - (T_0/(1 - e^{-k1*L/V})) + (T_0 - T_\infty) = K_2 F_B V. \tag{8}$$

This relation can be simplified as

$$T^* = K_2 HP_B \tag{9}$$

Where T^* represents the temperature at the base of the downgrade, T_o represents the initial brake temperature at the summit of the grade, K_1 represents the diffusivity constant, L represents the length of the downgrade, V represents the speed of descent, K_2 represents the heat transfer parameter, and HP_B represents the power into the brakes.

From this equation, if a plot is made of T^* computed for each hill descent against HP_B, K_2 will be the slope of the graph.

From the equation, a plot of T^* against HP_B should result in a straight line through the origin. However, looking at the downhill plots, as illustrated in Figures 3-4 through 3-6, this is not the case. The differences in the theoretical framework and the output from the field tests are likely due to measurement errors, assumptions to simplify the brake temperature model, and non-linearity between observations. However, the authors believed that these errors and the associated issues were not sufficiently significant to affect predictions made by the resulting brake temperature model. Figures 3.4 through 3.6 show plots of temperature parameters versus power into brakes at 32.5 mph, 37.5 mph, and 47.5 mph, respectively.

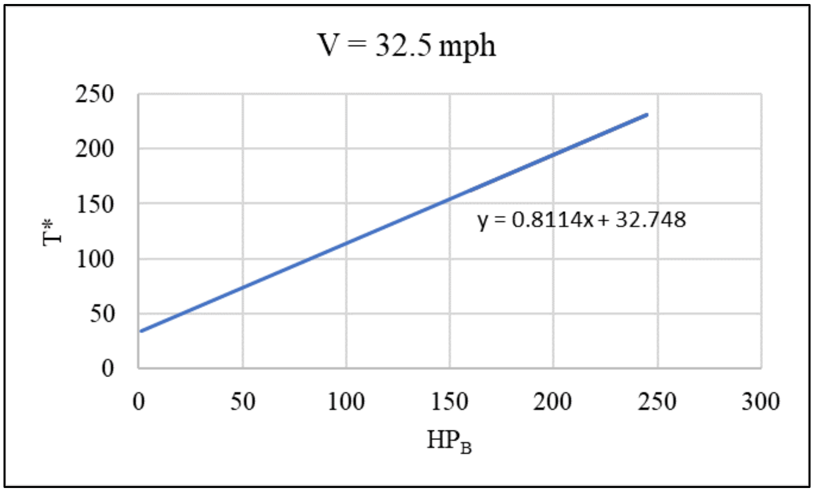


Figure 3.4 Temperature parameter versus power into brakes at 32.5 mph

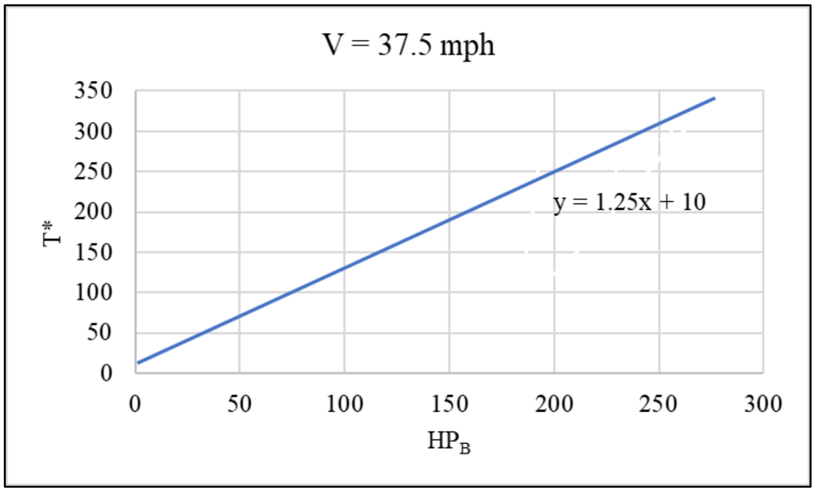


Figure 3.5 Temperature parameter versus power into brakes at 37.5 mph

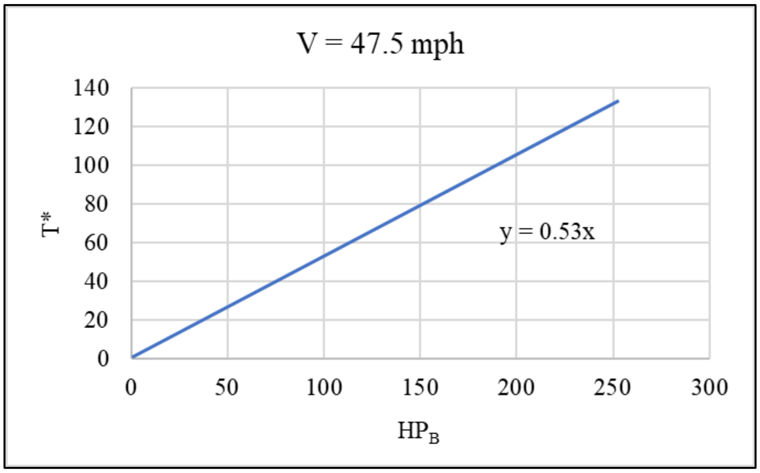


Figure 3.6 Temperature parameter versus power into brakes at 47.5 mph

After extracting K_2 at 32.5 mph (0.8), 37.5 mph (1.25), and 47.5 mph (0.53), a straight line was fitted to a plot of the inverse slopes ($1/K_2$) against corresponding speeds V as shown in Figure 3.7. The plot shows that the heat transferred due to power into the brakes increases linearly with speed (V).

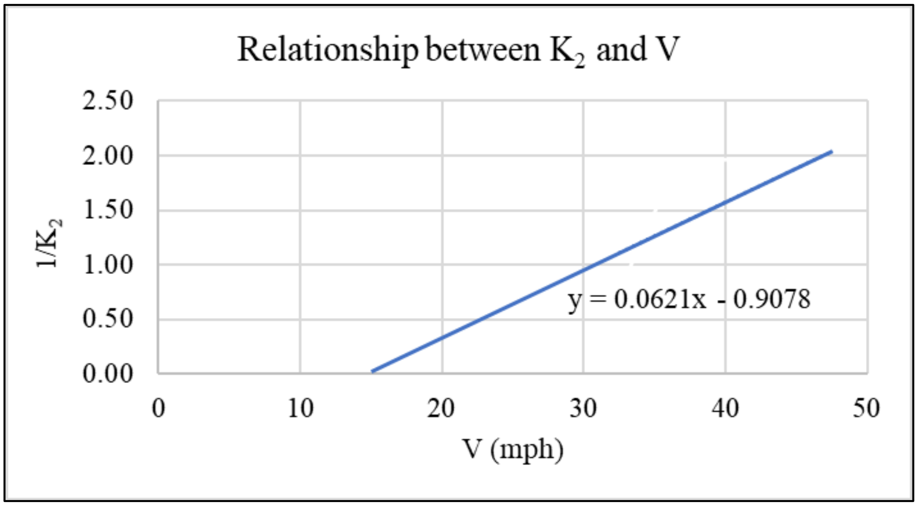


Figure 3.7 Variation of heat transfer parameter with speed

An equation relating $1/K_2$ to V is obtained as follows:

$$\frac{1}{K_2} = 0.0621\mathrm{V} - 0.9078, \text{Thus } K_2 = (0.0621\mathrm{V} - 0.9078)^{-1} \tag{10}$$

The previous experiments derived the expression for K_2 as follows:

$$\mathrm{K}_2 = \frac{1}{hAc} = (0.1602 + 0.0078\mathrm{V})^{-1} \tag{11}$$

The inverse relationship between K_2 and V suggests that as the truck speed increases, the heating coefficient reduces. The positive intercept (0.1602) represents the value of the heating coefficient when the truck is stationary.

After obtaining an expression for K_2 in terms of V, it was plugged into the brake temperature equation in Table 3-1 to obtain the updated brake temperature model.

$$\mathrm{T_f} = \mathrm{T_0} + [\mathrm{T_\infty} - \mathrm{T_0} + \mathrm{K_2HP_B}][1 - \mathrm{e}^{-\frac{\mathrm{K_1L}}{\mathrm{V}}}] \tag{12}$$

Based on this equation, the predicted brake temperature at the end of each run for the validation test is computed and compared with the measured brake temperature in the field.

Table 3.4 summarizes the validation test results showing the difference between the field brake temperature and the predicted brake temperature. In Table 3.4, T_o (˚F) represents the initial brake temperature (˚F), Ta (˚F) represents the ambient temperature (˚F), T_{FB} (˚F) represents the field brake temperature, T_{PB} (˚F) represents the predicted brake temperature (˚F), and *Abs* represents the absolute percentage difference between the field brake temperature and the predicted brake temperature.

The following observations attempt to explain the table output in terms of the road and vehicle characteristics:

- Since all the sections involved are downgrades, brake heating is expected as the brakes will be engaged to maintain the truck at a constant speed. Thus, we should expect the brakes to heat up between sections (1-2), (3-4), and (5-6). This pattern is clearly seen from readings of the initial brake temperatures.
- Even though the grade declines from 5.7% to 4.3% at each speed level, the net effect on the truck will be counterbalanced by the fact that the length of the grade also increases from 3.7 miles to 4.4 miles. Yet, as grades decline from 5.7% to 4.3%, relatively less braking effort is needed to maintain a constant speed. In general, however, a higher braking effort will be required to maintain the truck at a lower constant speed than a higher one, causing the brake temperature differential between grades to decrease as the constant speed increases. Evidence of this is provided by examining the temperature differential at each of the three speeds, which are 71.68˚F, 46.36˚F, and 42.64˚F, respectively.
- It should be noted that as per the testing procedure, the truck descends the downgrade going through two slopes at a constant speed (35 mph), turns around and climbs back and descends at another constant speed (40 mph), turns around and climbs back and then descends at a final constant speed (45 mph). This implies that for slopes of 5.7% and 4.3% at speeds of 35, 40, and 45 mph, the measured field brake temperature at V2 should equal to the initial brake temperature for slopes of 5.7% and 4.3%, and speeds of 35, 40, and 45 mph. Evidence of this is seen in the table by comparing T_o to T_{FB}.

Figure 3.8 shows a plot of the validation test results and illustrates how the field brake temperature is mostly higher than the predicted temperatures for most of the downgrade sections. The brake temperature model was validated by driving the test vehicle over an 8.1-mile multi-grade hill at a loading of 70,000 lbs. The multi-grade section selected for the hill descent consisted of several grades on the eastern face of US-16 (MP 74.69 - 82.30) with upgrades interspersed with downgrades. These were averaged out, thus resulting in two downgrade sections of 5.7% and 4.3%, respectively. Downgrades represent heating sections because of the need to brake to regulate the speed resulting from acceleration due to gravity during grade descent. The temperatures measured from the validation test were compared with predicted temperatures from the updated model. The average percentage difference between the two was computed to be 7.06%. Therefore, the validation test results showed a close match between brake temperatures observed in the field and predicted temperatures from the updated model.

Table 3.4 Summary of validation test results

Section No.	Distance (miles)	Grade (percent)	Speed (mph)	K_1	K_2	HP_B	T_o (˚F)	T_a (˚F)	T_{FB} (˚F)	T_{PB} (˚F)	Abs
1 (V1 - V2)	3.7	5.7	35	3.5	0.79	270.74	98.32	82	170.04	159.42	6.63
2 (V2 - V3)	4.4	4.3	35	3.5	0.79	160.34	170.00	82	195.03	183.77	6.11
3 (V1 - V2)	3.7	5.7	40	3.8	0.63	313	153.89	82	200.25	191.44	4.60
4 (V2 - V3)	4.4	4.3	40	3.8	0.63	187	200.25	82	215.02	200.38	7.29
5 (V1 - V2)	3.7	5.7	45	4	0.53	353.5	178.24	82	220.88	203.78	8.39
6 (V2 - V3)	4.4	4.3	45	4	0.53	211.6	220.88	82	232.01	212.23	9.32

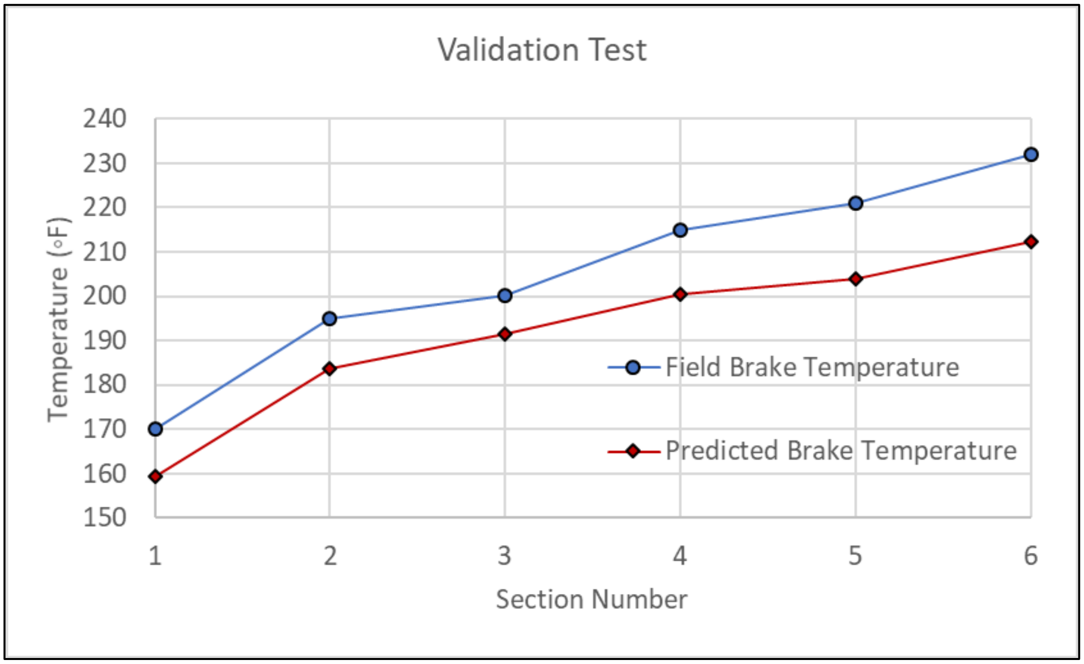


Figure 3.8 Comparison of field brake temperatures and predicted brake temperatures

Now that the GSRS has been upgraded for truck semitrailers fitted with only drum brakes, the logical next step would be to compare the descent speeds and time derived from the updated GSRS model for trucks fitted with both disc brakes and drum brakes to the same parameters in this latest model. This was achieved by comparing the maximum descent speeds for different weight categories obtained from applying the two temperature models to some fictitious but realistic grades, which are part of a continuous downgrade segment. This downgrade consisted of seven declines and did not have any cooling sections between them. The maximum descent speeds obtained from the 2016 study to update the GSRS and the new model proposed in this study are indicated in Table 3.5 and Table 3.6, respectively. Examining the output in Table 3.5 and Table 3.6 suggests that they consist of the maximum weight, max weight (in lb), the corresponding maximum speed, max speed (in mph), the temperature at which each weight is descending the downgrade, T Desc (in ˚F), the emergency stopping temperature for each truck weight category, T Emerge (in ˚F), the total of the two preceding temperatures, T Final (in ˚F), and the time required to descend the downgrade, time (in minutes). These speeds were derived from the brake temperature equation shown in Table 3.1 and consisted of the input parameters specified in Tables 3.7 and 38.

Table 3.5 Maximum descent speeds corresponding to various weight categories from the updated GSRS (2016)

Max Weight (lb)	Max Speed (mph)	T Desc (˚F)	T Emerge (˚F)	T Final (˚F)	Time (min)
80000	60	252	90	342	03
75000	61	245	87	332	03
70000	63	238	86	324	03
65000	65	230	85	315	03

Table 3.6 Maximum descent speeds corresponding to various weight categories from the GSRS based on this study (2021)

Max Weight (lb)	Max Speed (mph)	T Desc (˚F)	T Emerge (˚F)	T Final (˚F)	Time (min)
80000	60	252	90	342	03
75000	61	245	87	332	03
70000	63	238	86	324	03
65000	65	230	85	315	03

Table 3.7 Input parameters of the truck, temperature, and roadway used to compare the results of the two temperature models

Variable	Value
Number of segments	7
Maximum brake temperature (˚F)	500
Maximum weight for downgrade (lb)	80,000
Maximum descent speed (mph)	65
Initial brake temperature (˚F)	200
Ambient temperature (˚F)	90

Table 3.8 Geometric information of the selected segment used for the comparison

Grade	Length (miles)	Radius (ft)	Super elevation (percent)	Degree of curvature (degree)
0.01	0.006	100	0.04	81
0.01	0.040	154	0.04	80
0.02	0.123	371	0.04	100
0.03	0.690	1,500	0.04	140
0.04	0.040	144	0.06	75
0.05	0.112	340	0.06	100
0.06	0.660	1,660	0.06	120

Degree of curve or degree of curvature is a measure of curvature of a circular arc used in civil engineering for its easy use in layout surveying. The degree of curvature is defined as the central angle to the ends of an agreed length of either an arc or a chord.

A comparison between Tables 3.5 and 3.6 indicates that the GSRS model for trucks equipped with only drum brakes provided essentially the same maximum descent speeds as those outputted from the updated GSRS model for trucks equipped with both disc brakes and drum brakes.

3.5 Chapter Summary

The 2016 WYDOT-initiated study to update the GSRS applied to trucks equipped with disc brakes on their front axle and drum brakes on their rear axle. The vast majority of trucks on U.S. roadways, however, consist of drum brakes. This current study, therefore, determined the brake heating coefficient for a truck semitrailer equipped with only drum brakes and then validated it by comparing the predicted brake temperatures based on this coefficient to the measured brake temperatures on the field. It was determined that, on average, the measured field temperatures deviated from the temperatures predicted by the brake temperature equation by 7.06%, which suggests a very high predictive accuracy. In addition, the heating coefficient K_2 computed for the model in this study did not lead to any noticeable difference between the maximum descent speeds it was based on, and the speeds computed for K_2 in the previous updated model. Thus, it was concluded that equipping a truck semitrailer with only drum brakes did not differ substantially from equipping it with both disc and drum brakes in the relevant aspects—specifically, its tolerance to brake fade, and related to that, the maximum safe descent speed it could descend a downgrade.

Changing truck characteristics and roadway geometrics are therefore the more significant factors that affect K_2—much more than the type of braking system, which this study sought to investigate. Moreover, the study determined that the field brake temperature is slightly higher than the predicted temperatures for most of the downgrade sections.

It should be noted that some assumptions are made about the brake cooling parameters (K_1 and K_2), as well as some other parameters that may be difficult to generalize beyond certain truck configurations (5-axle trucks). Also, there is a growing number of fully electric trucks on the market, which have unique interpretations needed (ReGEN provides significant “engine braking” but decreases as battery SOC increases). Addressing electric vehicles is logically beyond the scope of the present work but it bears mentioning as a limitation. Documentation from the validation tests is included in the Appendix of this report.

4. SOFTWARE DEVELOPMENT BY INCORPORATING HORIZONTAL CURVES INTO THE UPDATED GSRS MODEL

This chapter begins with a discussion on the computerization of the earlier GSRS in order to execute the continuous slope and separate downgrade method. It further discusses downgrade truck crashes on sharp horizontal curves and elaborates on a procedure for integrating horizontal curvature and roadway geometrics into the updated GSRS model from the WYDOT study initiated in 2016. This procedure involved running simulations on the multibody vehicle dynamics software TruckSim® 2020 for a variety of truck weights, truck speeds, radii of horizontal curves, super elevation of roadways and longitudinal grades along the downgrade, and obtaining the associated rollover margins and skidding coefficients for each simulation run. Multiple linear regression models were then run with the skidding coefficients and rollover margins as the response and the remaining variables as independent variables in order to derive the relationship between these variables. These equations were then built into the existing updated GSRS mathematical model and then converted into Visual Basic.net algorithms, from which it was converted into the latest updated GSRS software featuring both the continuous slope and the braking and non-braking phases of the separate downgrade method.

4.1 Background

The GSRS program developed for IBM computers in 1989 estimated the maximum descent speeds for multi-grades. The program requested input parameters of truck weight, speed, and the physical characteristics of the downgrade, specifically length and slope, and used that information to compute maximum safe speeds, brake temperatures, and total travel time for different truck weights. This current study is aimed at automating the latest version of the GSRS model through an interactive, intuitive, aesthetically appealing, and user-friendly Visual Basic.net objected-oriented programming language to simplify the computation of the maximum safe descent speed on the downgrades based on the truck weight for researchers and engineers. Automating the GSRS will entail the formulation of two types of analyses based on the physical characteristics of the multi-grade downgrade. Multi-grade hills are categorized into two areas: those containing non-braking phases (upgrades and level sections), and those containing braking phases (downgrades). For multi-grades containing both non-braking and braking intervals, the separate downgrade method of analysis was utilized. This method was used to optimize travel time by analyzing a multi-grade as a series of constant-speed braking downgrades separated by non-braking intervals. The separate downgrade method enables the selection of speed scenarios capable of reducing the total travel time. The GSRS requirement therefore enables the driver to select an appropriate speed for each group of downgrades. Automating the GSRS will enable an automatic determination of maximum safe speeds for the downgrade group while computing the heat dissipation of the brake system. The resulting brake temperature is then used as the initial brake temperature for the next group of downgrades. The program permits trucks to descend the first group of downgrades quickly and then lowers the speed in 5-mph decrements until the end of the downgrade. For this method, only a specified weight is analyzed with maximum speeds generated for each subsequent group of downgrades.

Large trucks can run out of control on grades resulting from the presence of sharp horizontal curves or the need for emergency stopping. Thus, there appears to be a relationship between steep grades combined with horizontal curves and an increase in the probability of truck crashes on downgrades. Such impacts of severe downgrades and curves on occupant injury severity were commonly reported in the previous Wyoming studies (*22-27*). To summarize, truck runaways are typically caused by loss of braking ability due to overheating of the brakes, failure to downshift at the appropriate time, mechanical failure, and skidding or rollover resulting from the presence of sharp horizontal curves along the downgrade.

The existence of sharp horizontal curves on the majority of mountain passes justifies integrating them into the GSRS implementation. As drivers approach sharp horizontal curves, they tend to slow down. Curves located on steep downgrades, however, present a challenge as the trucks have a lower margin of safety in comparison with level roadways.

The American Association of State Highway and Transportation Officials (AASHTO) currently uses the point-mass model of a vehicle on a horizontal curve. For a point mass traveling at a constant speed on a circular path, the lateral acceleration is represented as:

$$f = \left(\frac{V^2}{g * R}\right) - 0.01 * e \tag{13}$$

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

For vehicle skidding and rollover in particular, the side friction factor is critical to their prevention. For rollover, the overturning tendency of the vehicle should be resisted by the roll stability of the vehicle for safety purposes. Symbolically, the vehicle will roll over if $f > f_{rollover}$ where $f_{rollover}$ is the maximum lateral acceleration a vehicle can experience without overturning. The term $f_{rollover}$ is referred to as the rollover threshold of the vehicle based on vehicle design and loading (*6*).

This study is intended to upgrade the existing automated GSRS by outlining the methodology for the incorporation of horizontal curves into it. Following from this, the algorithms necessary to develop a user-friendly software can be developed. As a result, WYDOT and other highway agencies can use the software to estimate the maximum safe speed of descent at various weight categories. They can do this for downgrades consisting of various horizontal curves and hence produce WSS signs for each downgrade or a multi-grade section. The contribution of this research is therefore an intersection between statistics, transportation, and software engineering.

4.2 Research Methodology

4.2.1 Data Preparation

For the physical characteristics of the downgrade, the input data required to obtain the maximum safe descent speeds include the radius of the horizontal curve (ft), the super-elevation of the segment (percent), the degree of curvature of the horizontal curve (degree), the longitudinal grade of the segment (percent), and the length of the segment (miles). The software enables either a manual entry of the data or the capability to import the data from an Excel sheet. The degree of curvature of the horizontal curve is obtained from the radius and length of the segment through equation 14.

$$\Delta = (360 \text{ x } Lc/(2 \text{ x } \pi \text{ x } R) \tag{14}$$

Where Δ is the degree of curvature of the horizontal curve, Lc is the length of the curve (ft), and R is the radius of the curve (ft).

4.2.2 The Updated GSRS

The purpose of the algorithm based on the updated GSRS model with horizontal curvature inclusion is to determine the maximum speed at which a truck can descend the combined downgrade and initiate curves without exceeding the maximum temperature limit of the braking system, speed limit of the road, and without overturning or skidding. Based on a study conducted by Johnson et al. (1981), 500˚F or 530˚F were determined as appropriate values for the maximum allowable temperature depending on the lining material (*21*).

Equations (15) through (23) are the equations governing the latest GSRS model prior to the study conducted in this paper.

$$T_f = T_o + [T_\infty - T_o + K_2 HP_B]\left[1 - e^{-K_1 L/V}\right] + T_E \tag{15}$$
$$T_E = 3.11 \times 10^{-7} W V^2 \tag{16}$$
$$HP_B = \left(W\theta - F_{drag}\right)\frac{V}{375} - HP_{eng} \tag{17}$$
$$K_1 = 1.5 \times (1.1852 + 0.0331V) \tag{18}$$
$$K_2 = (0.1602 + 0.0078V)^{-1} \tag{19}$$
$$F_{drag} = 459.35 + 0.132V^2 \tag{20}$$
$$HP_{eng} = 63.3 \tag{21}$$
$$T_\infty = 90 \tag{22}$$
$$T_o = 150 \tag{23}$$

Where T_f is the final temperature at the bottom of the segment (˚F), T_E is the emergency stopping temperature (˚F), HP_B is the horsepower into the brakes (hp), K_1 is diffusivity constant (1/hr), K_2 is the heat transfer parameter (˚F/hp), F_{drag} is drag forces (lbs), HP_{eng} is engine brake force (hp), experimentally determined as 63.3 hp for brake systems of current truck models without retarders engaged, W is weight of truck (lbs), θ is slope of segment (percent), V is the speed of truck (miles per hour), L is the length of segment (miles), T_∞ is the ambient temperature, and T_o is the initial temperature.

There are two analysis options; the continuous slope method and the separate downgrade method.

4.2.3 Continuous Slope Method

This method works for downgrades that have no upgrades or level segments interspersed with them. In addition, upgrades or level segments shorter than 0.5 miles can be ignored in the analysis. A single constant speed of descent is required, but since the grades are different, without applying the brake, the speeds cannot be controlled. Thus, when descending segments, downgrades are referred to as braking segments.

The method works by taking in the following input parameters:

The longitudinal grade (percent), corresponding length (miles), super-elevation (percent), the radius of the horizontal curve (ft), degree of curvature of the horizontal curve along each segment (degree), maximum truck weight (lbs), speed limit (mph), maximum brake temperature (500˚F or 530˚F), initial brake temperature at top of the first segment (˚F), and ambient temperature (˚F).

The algorithm does the following:

(1) Starting from the maximum truck weight,
    a) Test speeds from 1 mph to maximum speed (speed limit) in 1-mph increments. Using the equations (15-23) above.
    b) At each speed, compute the temperature at the bottom of each successive segment starting from the first.
    c) The final temperature at the bottom of the segment becomes the initial temperature for the next segment.
    d) Repeat the process until the bottom of the last segment is at the end of the downgrade. Print the results for weight, speed, temperature at bottom of the downgrade, and time to descend downgrade based on equations (15-23) for each iteration of speed.

(2) Repeat the process in step (1) for each successive decrement in truck weight by 5,000 lbs. until 0 lb.
(3) Print the results for weight, speed, temperature at bottom of the downgrade, and time to descend downgrade based on equations (15-23) for each iteration of speed.
(4) To determine maximum safe speeds for each truck weight, the algorithm enables the results to be filtered through the following steps:
    a) Eliminate all rows with final temperatures greater than the maximum specified temperature (500˚F/530˚F).
    b) At each specified truck weight level, determine the row with maximum speed, compare it with the minimum of the maximum speeds to prevent skidding or overturning as obtained from equations (25) and (27) and select whichever is smaller.
    c) Recompute temperature at bottom of downgrade and time to descend downgrade at the selected speed from (b) using equations (15-23) at each truck weight level.

The algorithm also computes at 0.5-mile intervals along the downgrades, the weight, speed, and distance from the start of a downgrade, grade at that distance, and final temperature at that particular point on the downgrade. By filtering the results via eliminating all temperatures below the maximum temperature limit, the starting point of the downgrade where escape ramps should be located to provide safe havens for faded brakes can be identified. The algorithm also enables temperature-distance plots to be created.

4.2.4 Separate Slope/Downgrade Method

This method works for downgrades that have upgrades or level segments longer than 0.5 miles interspersed with them. This is referred to as a multi-grade. Since the driver does not need to control the speed of the truck due to acceleration from gravity, the driver does not engage the braking system, and thus, upgrades or level segments are referred to as non-braking segments. Brake application leads to temperature increases, brake fade, and ultimately runaway trucks and crashes.

For this method, in addition to the input parameters requested in the continuous grade method, the algorithm also requests the number of grades in the multi-grade.

The algorithm does the following:

First, it groups segments into downgrade segments and upgrades/level segments. Upgrades are successive segments that are either level sections (0% grade) or positive grades greater than 0.5 miles (which are assigned a 0% grade). Typically, the first group of segments is a downgrade. The algorithm next does the following:

(1) At the specified truck weight:
    a) Test speeds reduce from maximum speed (speed limit) to 15 mph in 5-mph decrements.
    b) Follow the rest of the procedure as outlined from (b) of step (1) of the continuous slope method.
(2) The next group are upgrades; (0% grades with associated length).
(3) The algorithm for this method is the exact same procedure as it is for step 1 of the continuous slope method.

After this, the algorithm prompts for selection of the first row, which is the row that prints out the maximum weight of the truck with associated maximum speed, the temperature at the end of the group of segments, and time of travel. Then the algorithm assigns the temperature at the end of this non-braking group to the initial temperature at the top of the next braking segment (if provided temperature is above 90˚F, it assigns the full value, or else it simply assigns 90˚F for technical reasons). It then prompts the user to either enter or import segment lengths, grades, and the radius of horizontal curves, super-elevations, and degrees of curvature of the horizontal curves for the next braking interval, and performs calculations for the downgrade, as illustrated in step 1. The process continues until the maximum number of grades in multi-grade is exceeded, and then it prompts the user to reset the software. The process flow charts for the continuous slope method and the two phases of the separate downgrade method are shown in Figures 4.1 through 4.3.

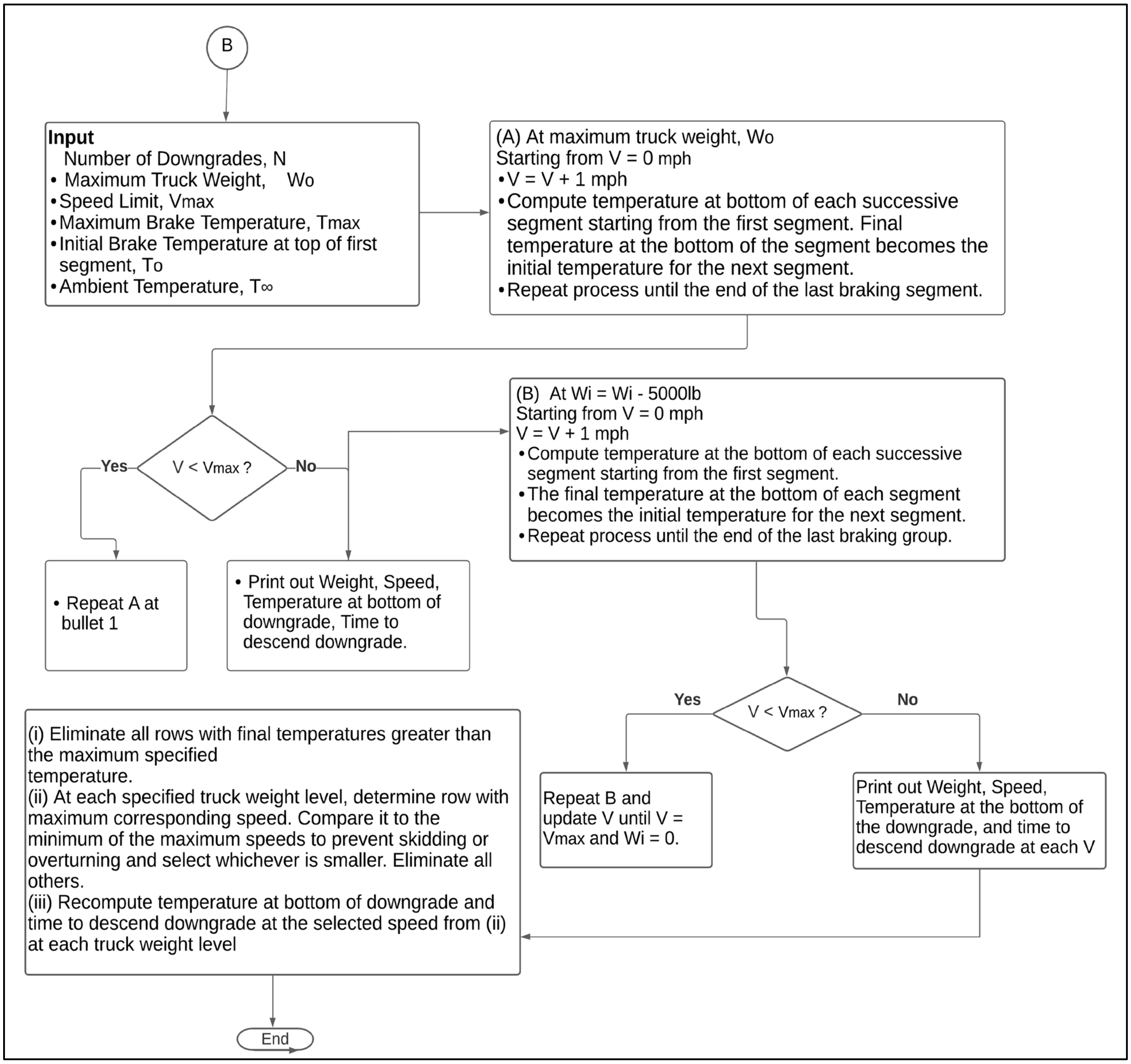


Figure 4.1 Process flow chart for continuous slope method

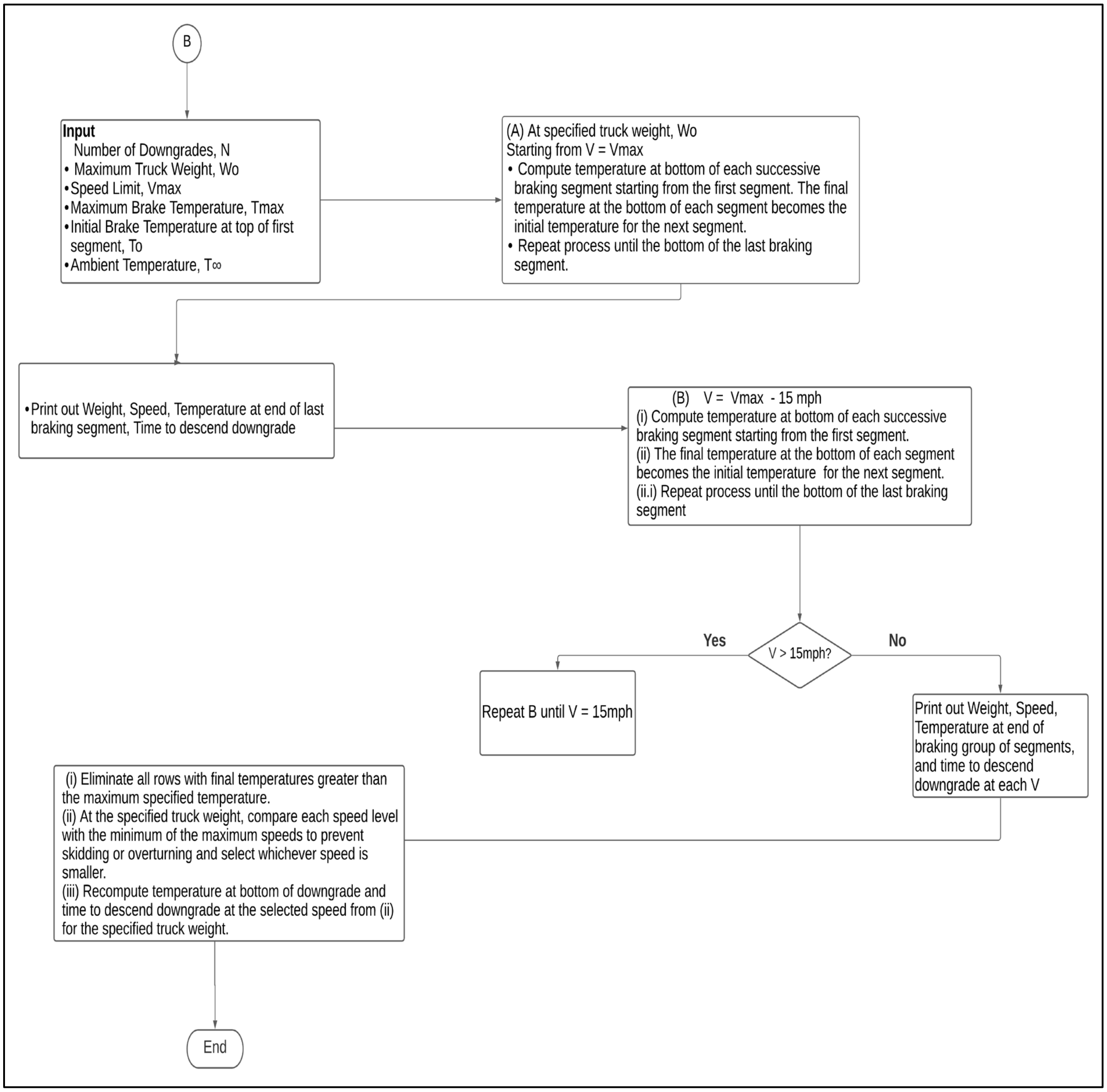


Figure 4.2 Process flow chart for braking group of segments for separate downgrade method

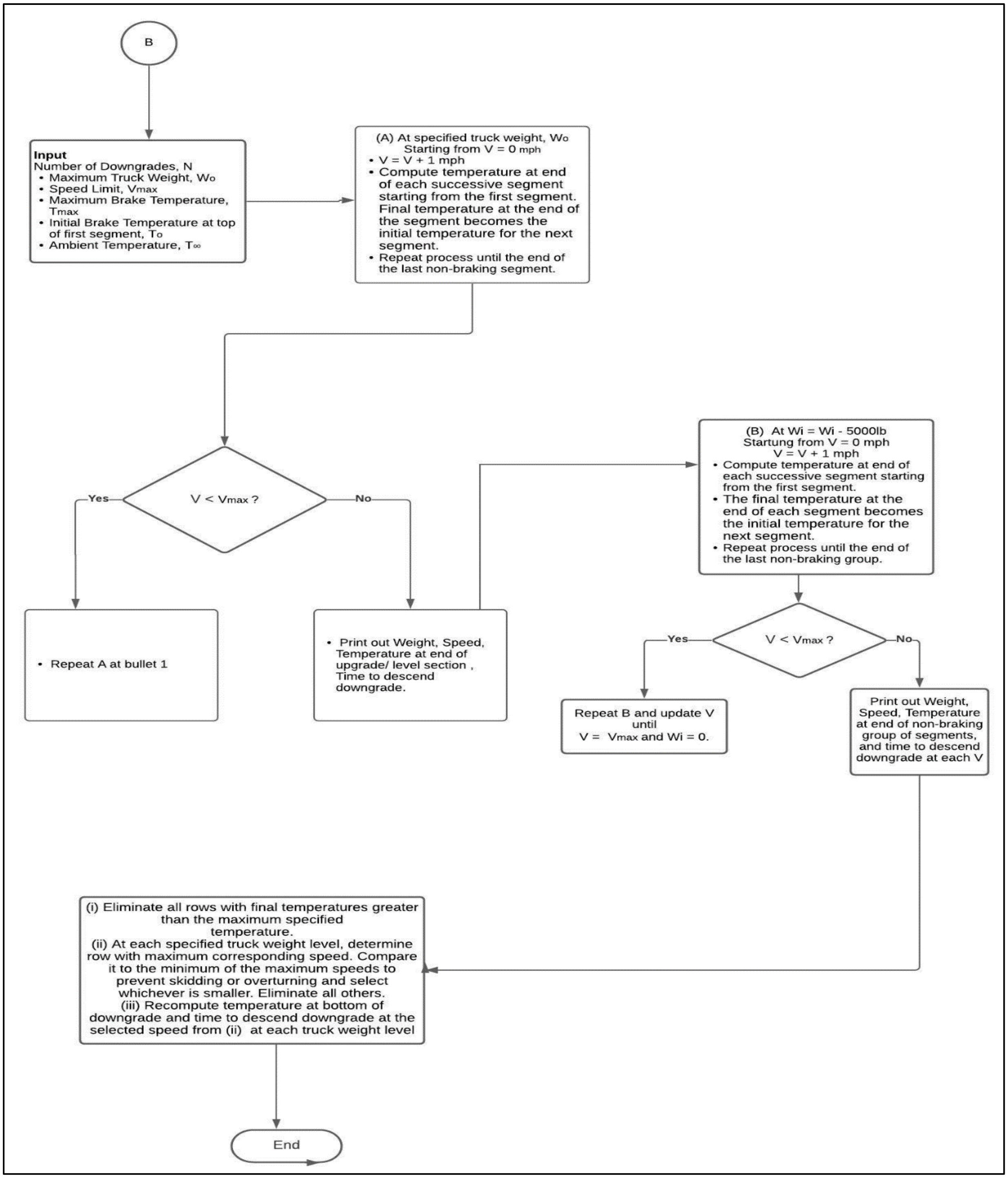


Figure 4.3 Process flow chart for non-braking group of segments for separate downgrade method

4.2.5 Incorporating Horizontal Curves

In order to factor the influence of horizontal curves on the maximum safe speed of descent of the truck with respect to vehicle stability, specifically rollover and skidding, the following procedure was followed based on the literature review.

Simulations were run on TruckSim® 2020 for a variety of super-elevations, truck weights, degree of curvature of the horizontal curves, longitudinal grades, the speed, and the radius of curvature of the horizontal curves. The associated rollover margins were then generated. Similar simulations were carried out for skidding coefficients considering a variety of super-elevations, truck weights, degree of curvature of the horizontal curve, longitudinal grades, the speed of the truck-trailer, and the radius of curvature of the horizontal curve.

In all, 300 data points were obtained for each variable based on 300 simulation runs. Ten different radii for the horizontal curves were included in the simulations. Eight different roadway super-elevations, 10 different longitudinal grades, six different truck weights and 10 different speeds were run during the simulation. Table 4.1 presents these values.

A multiple linear regression model was then run with super-elevation, truck weight, degree of curvature of horizontal curve, longitudinal grade, and the ratio of the square of the speed to the radius of the horizontal curve as the independent variables, and the rollover margin as the response variable was obtained. A similar model was run for the same predictor variables but with skidding coefficient as the response variable. The regression models obtained are described under the results and discussion section. Figure 4.4 is a typical simulation model of a truck semitrailer descending a downgrade using the TruckSim® 2020 software.

Table 4.1 Data table for TruckSim® 2020 input

Radius (ft)	Super elevation (percent)	Grade (percent)	Weight (lb)	Speed (mph)
80.97	7.7	6	26,000	30
483	8.8	5.7	40,000	35
620	8.3	6.4	50,000	40
393	4.5	5	60,000	45
2499	3.6	4	70,000	50
719	10	6.2	80,000	65
557	8.0	5	NA	70
654	1	6.6	NA	75
950	NA	7	NA	80
2800	NA	3.8	NA	85

Figure 4.4 An example of TruckSim Simulation model for the analysis ©TruckSim® 2020

4.3 Results and Discussions

4.3.1 Statistical Analysis for Rollover

The regression model obtained from the rollover simulations is as follows:

$$Rollover\ threshold = \left(0.779 - 0.005 * \Delta - 0.000004 * W - 0.079 * \left(\frac{V^2}{R}\right) - 0.078 * e + 33.770 * g\right) \qquad (24)$$

Thus, the equation for the maximum safe speed, $V_{rollover}$

$$V_{rollover} = (((0.779 - 0.005 * \Delta - 0.000004 * W - 0.078 * e + 33.770 * g)/(0.079)) * R)^{0.5} \qquad (25)$$

Since for worst case scenario, rollover threshold = 0

Where, Δ = degree of curvature of horizontal curve in degrees
W = total gross weight of truck (lbs)
V = speed of truck (mph)
R = radius of horizontal curve (ft)
e = super elevation of roadway (percent)
g = longitudinal grade (percent)

Table 4.2 describes the ANOVA table for the various predictor variables of the rollover threshold.

Table 4.2 ANOVA output for rollover

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Degree of Curvature	1	10.935	10.935	467.190	< 2e-160 ***
Grade	1	0.404	0.404	17.240	4.32e-050 ***
Super Elevation	1	1.285	1.285	54.910	1.35e-120 ***
Weight	1	1.702	1.702	72.720	7.99e-160 ***
Speed^2/Radius	1	0.674	0.674	28.770	1.65e-070***
Residuals	1	294	6.882	0.023	

As can be seen from Table 4.2, all predictor variables are significant at a 5% significance level.

4.3.2 Statistical Analysis for Skidding

The regression model obtained from the skidding simulations is as follows:

$$Skidding\ margin = (0.766 - 0.0002 * \Delta - 0.000002 * W - 0.013 * (V^2/R) - 0.026 * e + 27.680 * g) \tag{26}$$

Thus, the equation for maximum speed, $V_{skidding}$

$$V_{skidding} = ((0.766 - 0.0002 * \Delta - 0.000002 * W - 0.026 * e + 27.680 * g)/(0.013) * R)^{0.5} \tag{27}$$

Since for the worst-case scenario, skidding-margin = 0

Where, Δ = degree of curvature of horizontal curve in degrees
W = total gross weight of truck (lbs)
V = speed of truck (mph)
R = radius of horizontal curve (ft)
e = super elevation of roadway (percent)
g = longitudinal grade (percent)

Table 4.3 describes the ANOVA table for the various predictor variables of the skidding coefficient.

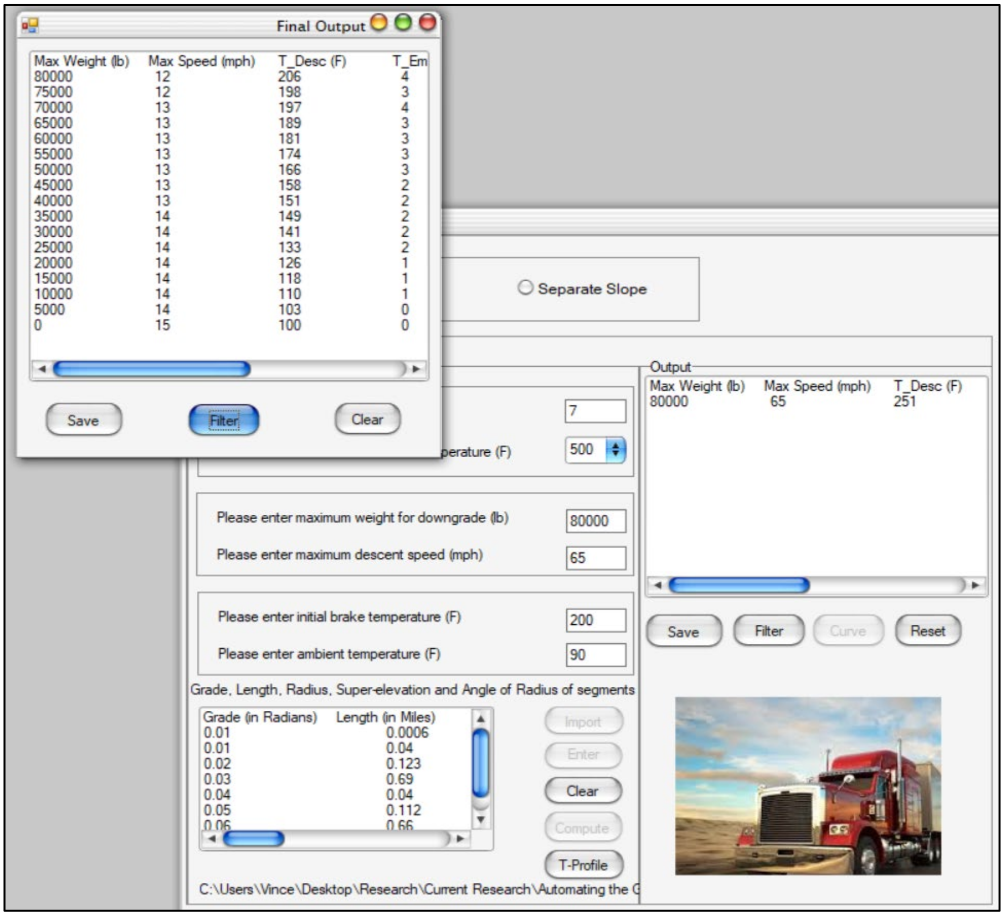
Table 4.3 ANOVA output for skidding

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Degree of Curvature	1	3.331	3.331	166.297	< 2e-160 ***
Grade	1	0.024	0.024	1.204	0.273
Super Elevation	1	0.372	0.372	18.588	2.25e-050 ***
Weight	1	0.470	0.470	23.472	2.05e-060 ***
Speed^2/Radius	1	0.765	0.765	38.168	2.16e-090 ***
Residuals	1	294	5.890	0.020	

As can be seen from Table 4.3, all predictor variables are significant except for grade, but since the plot of residuals does not meet homodescacity for the grade, the conclusion of insignificance is questionable, and so we included it as a predictor to err on the side of caution. Moreover, the literature review suggests including this predictor.

To proceed with the results and discussions, screenshots of various phases of the software implementation are presented and discussed. The format for this discussion is patterned after similar software in various scientific fields (*28-31*).

Figure 4.5 illustrates the output of the continuous slope section of the upgraded GSRS software to incorporate the effects of road geometry and horizontal curvature. As can be seen, for a downgrade with seven segments, 500˚F maximum brake temperature, 80,000 lbs. maximum truck weight, 65 mph speed limit, 200˚F initial brake temperature, and 90˚F ambient temperature, as well as the given grade, super-elevation and length of segments, radii of the horizontal curves comprising the segments, and degrees of curvature of the horizontal curves, the various maximum descent speeds corresponding to the associated weights are given.



```
Max Weight (lb)   Max Speed (mph)   T_Desc (F)   T_Em
80000             12                206          4
75000             12                198          3
70000             13                197          4
65000             13                189          3
60000             13                181          3
55000             13                174          3
50000             13                166          3
45000             13                158          2
40000             13                151          2
35000             14                149          2
30000             14                141          2
25000             14                133          2
20000             14                126          1
15000             14                118          1
10000             14                110          1
5000              14                103          0
0                 15                100          0
```

7

perature (F) 500

Please enter maximum weight for downgrade (lb) 80000

Please enter maximum descent speed (mph) 65

Please enter initial brake temperature (F) 200

Please enter ambient temperature (F) 90

Grade, Length, Radius, Super-elevation and Angle of Radius of segments

```
Grade (in Radians)   Length (in Miles)
0.01                 0.0006
0.01                 0.04
0.02                 0.123
0.03                 0.69
0.04                 0.04
0.05                 0.112
0.06                 0.66
```

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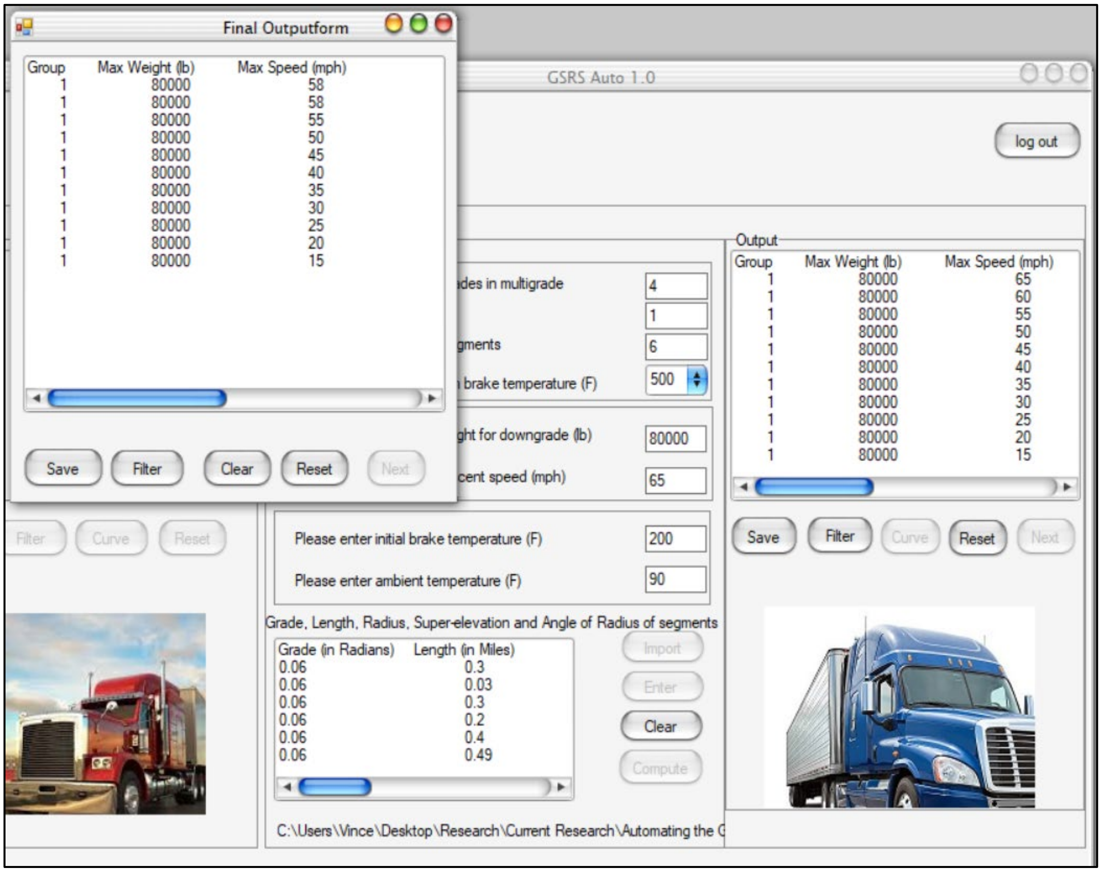
```
Max Weight (lb)   Max Speed (mph)   T_Desc (F)
80000              65               251
```

Figure 4.5 An example of final output of maximum descent speeds and other parameters based on the continuous slope method

Since one fundamental assumption underlying the GSRS is that downshifting is not allowed during the descent of downgrades, the algorithm assigns the controlling maximum descent speed for preventing skidding, rollover, and brake fade (the reduction in stopping power that can occur after repeated or sustained application of the brakes, especially in high-load or high-speed conditions) to the specific weight in question. This controlling speed is the minimum of the maximum speeds preventing skidding, rollover, and brake fade. Typically, this controlling speed arises from vehicle stability considerations (i.e., skidding and rollover), where the major predictor variable for these responses is the radius of the horizontal curve. Therefore, the sharper the curve, the smaller the controlling speed. Although not shown in Figure 4.5, the speed associated with the sharpest curve (radius = 160 ft) is the controlling speed, and as can be seen, the maximum speed of descent for an 80,000-lb. truck with the associated input parameters reduces from 65 mph, which is the maximum descent speed for a plain longitudinal downgrade (without curves), to 12 mph when the curves are introduced. This is an 82% reduction in speed.

Figure 4.6 illustrates the first braking phase of a multi-grade downgrade with the indicated input parameters as well as the final maximum descent speeds to prevent brake fade, rollover, and skidding.



```
Group   Max Weight (lb)   Max Speed (mph)
  1         80000              58
  1         80000              58
  1         80000              55
  1         80000              50
  1         80000              45
  1         80000              40
  1         80000              35
  1         80000              30
  1         80000              25
  1         80000              20
  1         80000              15
```

ades in multigrade 4
1
gments 6
brake temperature (F) 500
ght for downgrade (lb) 80000
cent speed (mph) 65
Please enter initial brake temperature (F) 200
Please enter ambient temperature (F) 90

Grade, Length, Radius, Super-elevation and Angle of Radius of segments

```
Grade (in Radians)   Length (in Miles)
0.06                      0.3
0.06                      0.03
0.06                      0.3
0.06                      0.2
0.06                      0.4
0.06                      0.49
```

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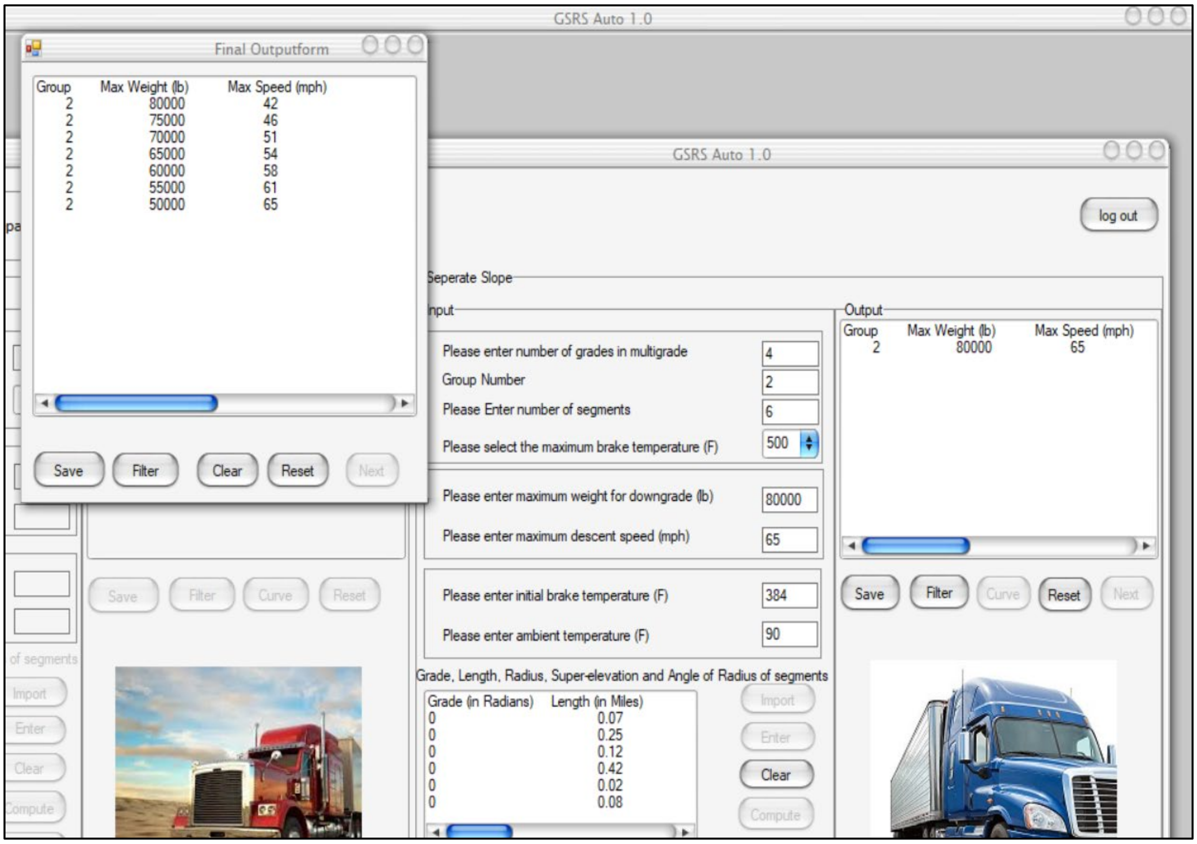
```
Group   Max Weight (lb)   Max Speed (mph)
  1         80000              65
  1         80000              60
  1         80000              55
  1         80000              50
  1         80000              45
  1         80000              40
  1         80000              35
  1         80000              30
  1         80000              25
  1         80000              20
  1         80000              15
```

Figure 4.6 An example of the final output of maximum descent speeds and other parameters for a typical braking phase based on the separate downgrade method

The braking phase of the separate downgrade method for the GSRS typically outputs a single truck weight and associated maximum descent speeds from the speed limit to 15 mph in 5-mph decrements. As can be seen from the final output, after introducing horizontal curves, the maximum descent speed for the given input parameters reduces from 65 mph (without curves) to 58 mph, which is a 7% decrease in speed, implying that the smallest radius of the horizontal curves comprising the segments of the downgrade is relatively mild. The final output also includes the temperature of descent (˚F), emergency braking temperature (˚F), total final temperature (˚F), and time to descend the downgrade (min), although these are not visible from the figure.

Figure 4.7 illustrates the first non-braking phase of a multi-grade downgrade with the indicated input parameters as well as the final maximum descent speeds to prevent brake fade, rollover, and skidding for various weight categories. The algorithm for the non-braking phase of the separate downgrade method for the GSRS is very similar to the continuous slope method.



Final Outputform

```
Group    Max Weight (lb)    Max Speed (mph)
  2           80000              42
  2           75000              46
  2           70000              51
  2           65000              54
  2           60000              58
  2           55000              61
  2           50000              65
```

Seperate Slope

Input

Please enter number of grades in multigrade: 4
Group Number: 2
Please Enter number of segments: 6
Please select the maximum brake temperature (F): 500
Please enter maximum weight for downgrade (lb): 80000
Please enter maximum descent speed (mph): 65
Please enter initial brake temperature (F): 384
Please enter ambient temperature (F): 90

Grade, Length, Radius, Super-elevation and Angle of Radius of segments

```
Grade (in Radians)    Length (in Miles)
0                          0.07
0                          0.25
0                          0.12
0                          0.42
0                          0.02
0                          0.08
```

Output

```
Group    Max Weight (lb)    Max Speed (mph)
  2           80000              65
```

Figure 4.7 An example of final output of maximum descent speeds and other parameters for a typical non-braking phase based on the separate downgrade method

As can be seen from the final output, after introducing horizontal curves, the maximum descent speed for the given input parameters reduces from 65 mph (without curves) to 42 mph for an 80,000-lb. weight category, which is a 35% decrease in speed. This implies that the smallest radius of the horizontal curves comprising the segments of the downgrade is somewhere in between relatively mild and sharp. The final output also includes the temperature of descent (˚F), emergency braking temperature (˚F), total final temperature (˚F), and time to descend the downgrade (min), although it is not visible from the figure.

4.4 Chapter Summary

This chapter examined the automation process of the upgraded GSRS to reflect changes in the software algorithm to output maximum descent speeds, which not only prevent brake fade but rollover and side slip/skidding as well. As was the case in the previous version of the software, this version provides functionality for both the continuous slope and the separate downgrade method. This upgraded version of the software will enable WYDOT and other highway agencies to easily estimate the maximum safe speed of descent for various weight categories considering horizontal curves and roadway geometry, thus producing WSS signs for each multi-grade section.

Simulations were run on TruckSim® 2020 for a variety of super-elevations, truck weights, degrees of curvature of various horizontal curves, longitudinal grades, truck speeds, and the radii of curvature of the horizontal curves. The associated rollover margins are generated. Similar simulations were carried out to obtain skidding coefficients considering a variety of super-elevation, truck weights, degrees of curvature of the horizontal curve, longitudinal grades, truck-trailer speeds, and the radii of curvature of the horizontal curves.

In all, 300 data points were obtained from the simulation runs. A multiple linear regression model was the run with super-elevation, truck weight, degree of curvature of the horizontal curve, longitudinal grade, and the ratio of the square of the speed to the radius of the horizontal curve as the independent variables and the rollover margin as the response variable. Similar analysis was done for the same predictor variables but with skidding coefficient as the response variable. The regression equations were then incorporated into the mathematical model of the GSRS to factor in skidding and rollover effects. Documentation, including a complete user manual for software use, is included in the Appendix of this report.

5. CONCLUSIONS AND RECOMMENDATIONS

This chapter is a summary of the topics covered in this research report, specifically, a comparison between the heating coefficient for a truck equipped with both disc brakes and drum brakes, and ones equipped with only drum brakes. It also describes the procedures involved in the incorporation of horizontal curves and roadway geometrics into the updated GSRS model and the subsequent development of a Visual Basic.net software based on these updates. Recommendations for future study are also provided.

5.1 Conclusions

Truck runaway on downgrades presents a significant obstacle to truck safety in the mountainous regions of Wyoming. Over the years, several models have been proposed to address this problem. In the 1980s, a Grade Severity Rating System (GSRS) was developed by FHWA and automated by an IBM console application. The application collected data such as truck characteristics, speed limit, initial and ambient temperatures, and physical downgrade parameters, such as the slope and length of downgrades, characterizing the downgrade. The application would then calculate the maximum descent speed to prevent the temperature from causing brake fade for different weight categories, and this would then be displayed on WSS signs.

Over the years, however, truck characteristics have undergone several changes. In order to ensure that the GSRS is still relevant for these truck configurations, the FHWA commissioned a research project in 2016 to update the existing GSRS. Thus, in the fall of 2017, an instrumented truck was used to perform both hill descent and validation tests. During the process, the instrumentation collected several parameters that were then used to update the GSRS. The validation tests were then conducted to validate the updated GSRS. It was discovered that the measured field temperatures are identical to the predicted temperatures based on the updated GSRS, thus suggesting that the updated GSRS was largely accurate. This updated GSRS was then automated through an object-oriented Visual BASIC.net application.

In addition, the GSRS model was validated for trucks equipped only with drum brakes since these braking systems accounted for about 80% of the current truck population. This validation test relied on a five-axle semi-truck trailer that was used in hill-descent and validation tests. Heat sensors were used to measure the various temperatures on the brake axles, and these readings were used to derive the value of the heating coefficient K_2. Finally, this value of K_2 was plugged into the updated GSRS and used to determine the maximum speed of descents under differing scenarios. It was realized that the maximum speed of descent for the 2020 GSRS was identical to the 2016 GSRS.

Besides downgrade crashes, it was found that many truck crashes in the mountainous highways of Wyoming were a product of vehicle instability resulting from rollover and skidding/side slipping. Thus, WYDOT sponsored another study in 2020 to update the GSRS model such that horizontal curvature and roadway geometry were integrated. This was accomplished using the multibody vehicle simulation software TruckSim® 2020 and generating rollover margins and skidding coefficients, respectively, from eight different super-elevations, six different truck weights, 10 different longitudinal grades, 10 different speeds, and 10 different radii of curvature of the horizontal curves. Following from this, regression models were used to derive the relationship between the responses (rollover margins/skidding coefficients) and the remaining independent variables. These relationships were then built into the updated GSRS model and automated through an aesthetically appealing and intuitive Visual Basic.net object-oriented software.

5.2 Recommendations

For the study on comparing grade severity rating system models for trucks fitted with drum brakes and disc brakes versus only drum brakes, it is recommended that the newly computed value of K_2 be used to upgrade the corresponding value in the older 2016 GSRS model. Moreover, as part of implementing the updated GSRS in practice, the ongoing study developed and automated the latest version of the GSRS model. This automated software was interactive, intuitive, aesthetically appealing, and user-friendly. It was built by the Visual Basic.net objected-oriented software to simplify the computation of the maximum safe descent speed on these downgrades based on the truck weight. Potential end users of the software (such as transportation engineers) will therefore be able to compute maximum safe speeds for WSS signs for trucks that are in the clear majority on U.S. roadways. This newer software would come with a detailed user manual on how to manipulate the software with a minimum of computer skills. Audio and video training systems can also be provided to enable users to manipulate the product successfully.

For the study on incorporating horizontal curves into the updated GSRS

- An analysis of the ANOVA model residuals produced a lack of homoscedasticity for some of the predictor values of the rollover threshold even after transformation, thus potentially affecting the conclusions of their significance in the regression model. The accuracy of the developed models can be further enhanced in the future by using more sophisticated statistical techniques.
- Currently, the software makes use of list boxes to display imported physical downgrade characteristics and the output of computations for both the continuous slope and separate downgrade method. This limits the number of input parameters to 49. Future upgrades to this software will make use of different controls, such as list views or DataGrid View, that allow a much larger number of input parameters to be imported.
- Future upgrades to the software will entail integrating crystal reports for the display of output.
- By obtaining friction data for specific locations of the horizontal curves instead of simply assuming the side friction factor to be 0 in order to obtain the maximum speed that avoids side slipping, much more accurate results will be obtained.
- The GSRS can also be used to predict maximum weights for specific speed limits on various highways. This can be explored in the future.
- Maximum safe speeds for snowy conditions as obtained in most parts of Wyoming during most parts of the year can also be investigated as a future task.

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APPENDIX A

GSRS AUTOMATOR 1.0

USER MANUAL

Developed By

Wyoming Technology Transfer Center
Wyoming Department of Transportation

PRODUCT INFORMATION

GSRS Automator 1.0 is the maiden version of the Graphical User Interface (GUI)-based software developed to automate the most recent advances in the Grade Severity Rating System primarily for downgrades in the mountainous regions of Wyoming. As opposed to prior console-based versions of the computer program based on older mathematical models, the GSRS Automator provides a much higher level of intuitiveness, aesthetic appeal, interactiveness and user-friendliness through a Graphical User Interface provided by the Visual Basic.net object-oriented programming language. This document details the hardware and operating system requirements for installation of the product for optimal performance, the input parameters and how to interpret the output data generated by the product. The software can only be used on a single computer at a time since this particular version does not support networking.

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END OF TERMS AND CONDITIONS

The product requirements are as follows:

SYSTEM REQUIREMENTS

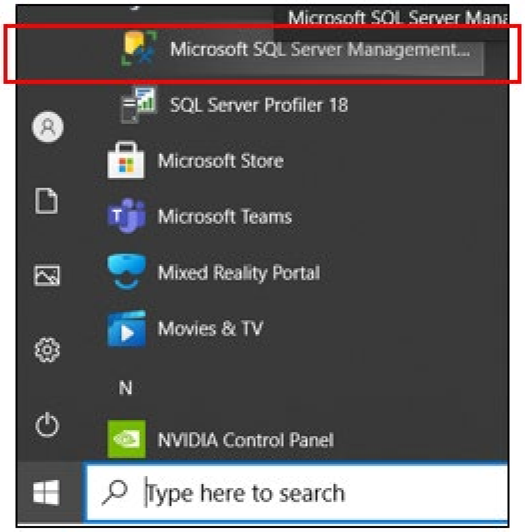
Designed to run optimally on Microsoft Windows version 10.
Minimum of 256 MB RAM is recommended.
Minimum of 3 GB of Hard Disk space required to install this application. A breakdown of the allocation of this space as per required pre-requisite software installations prior to the use of this program is provided in the table below:

HARD DRIVE CAPACITY REQUIREMENTS		
Microsoft VSS writer for SQL Server 2019	1.78	MB
Microsoft SQL Server Management Studio- 18.9.2	2660	MB
Microsoft SQL Server 2019 T- SQL Language Service	9.05	MB
Microsoft SQL Server Setup (English)	184	MB
Microsoft SQL Server 2012 Native Client	8.33	MB
Microsoft OLE DB Driver for SQL Server	8.28	MB
Microsoft ODBC Driver 17 for SQL Server	7.01	MB
GSRS Automator	3.23	MB
Browser for SQL Server 2019	11	MB
Total	2892.68	MB
Total	3	GB

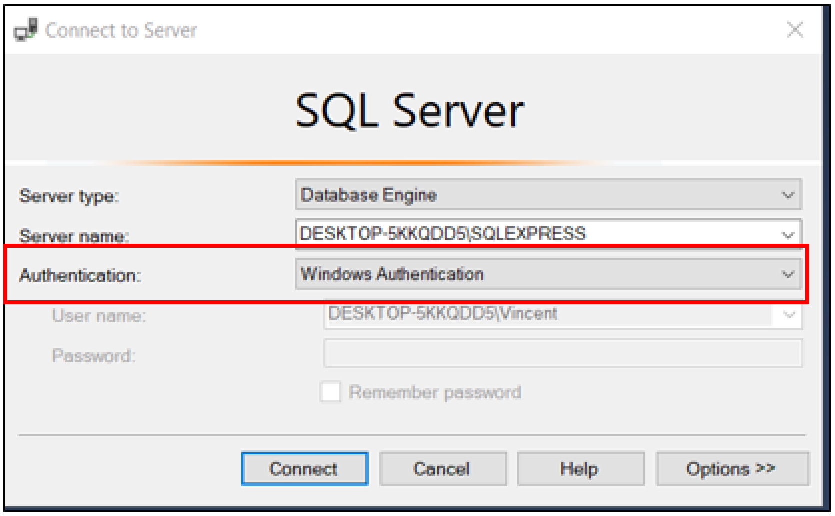
INSTALLATION PROCEDURE

Install Pre-requisites:

1. Unzip “GSRS Setup 2023.rar” to “C:\ drive”
2. Open folder “C:\GSRS Setup 2023”
3. Install SQL Express 2019 by clicking on “SQL2019-SSEI-Expr.exe”
    a. Select Basic Option
    b. Continue with Install process till end
4. Install Microsoft SQL Server Management Studio by clicking on “SSMS-Setup-ENU.exe”. If any errors are encountered in installing this software, please download a new version from the following web location: https://docs.microsoft.com/en-us/sql/ssms/download-sql-server-management-studio-ssms?view=sql-server-ver15
5. Open Microsoft SQL Server Management Studio using the shortcut on the desktop “Microsoft SQL Server Management Studio 18” or access it from the Windows Start menu
    a.

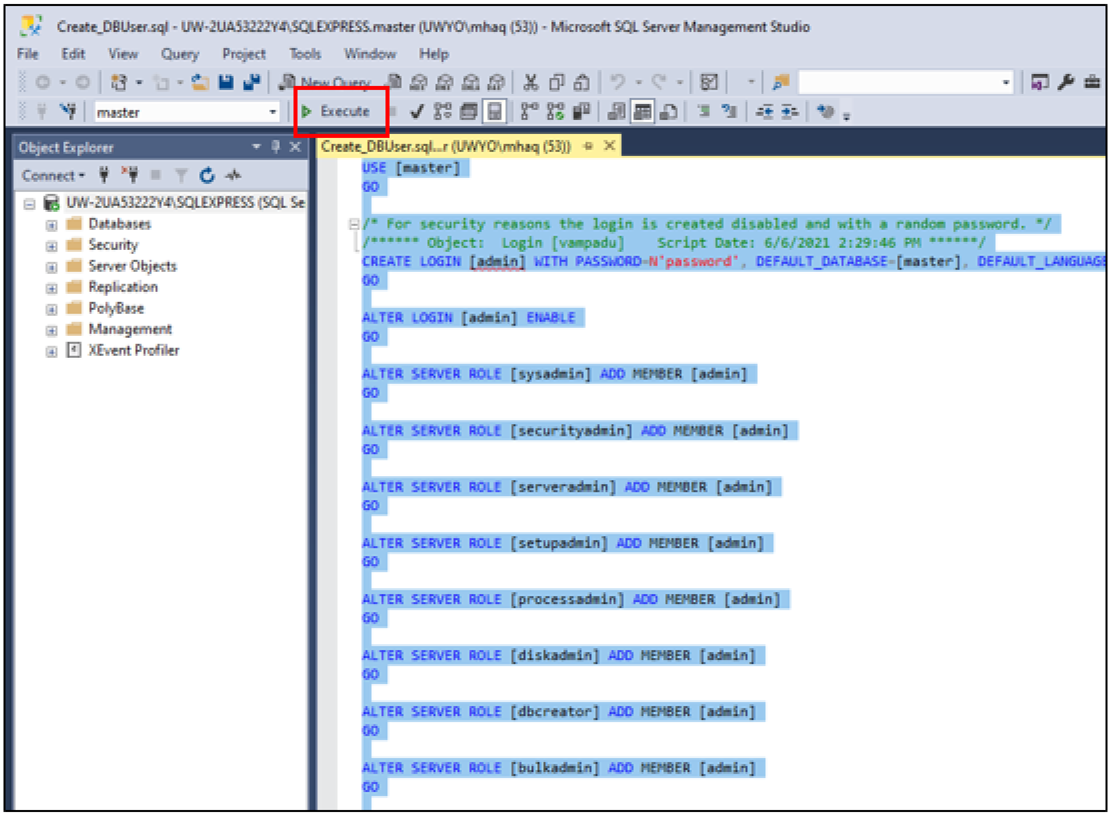


b. Login to the DB server using “Windows Authentication”



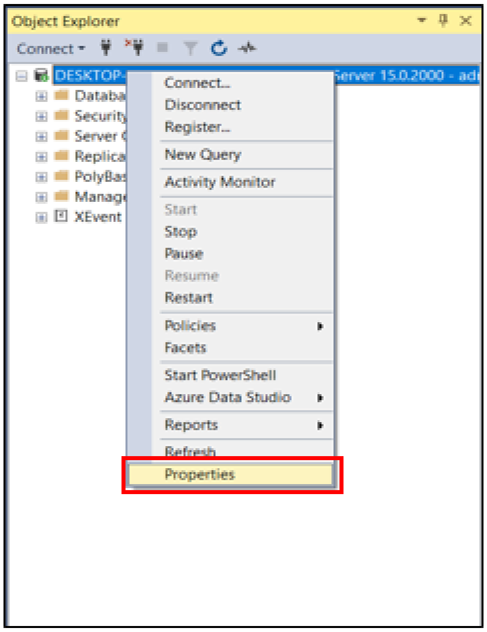
Server type: Database Engine
Server name: DESKTOP-5KKQDD5\SQLEXPRESS
Authentication: Windows Authentication
User name: DESKTOP-5KKQDD5\Vincent
Password:
☐ Remember password

c. After the successful login, create an admin user by following the procedure below;
File → Open → File C:\ GSRS Setup 2023\Create_DBUser.sql
Select all using “CTRL+A” and Click on “Execute” button.

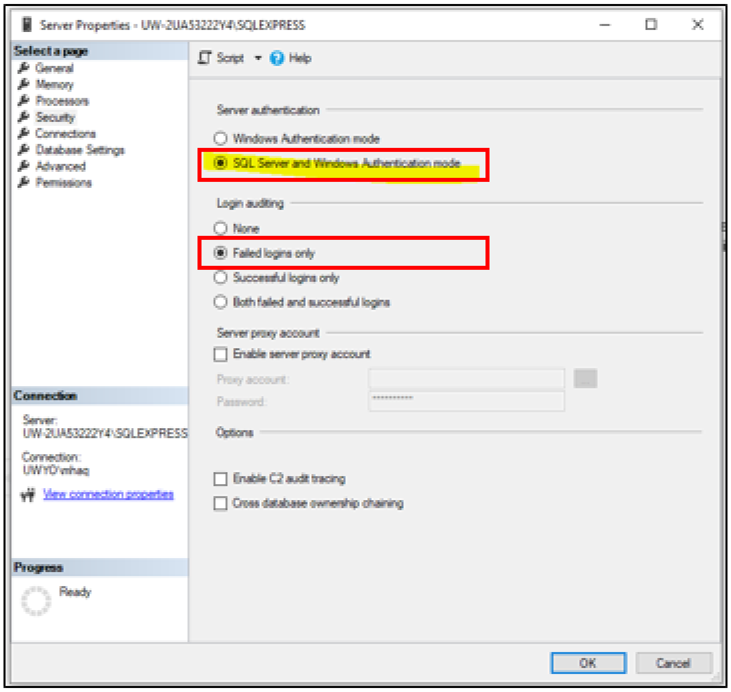


```
USE [master]
GO

/* For security reasons the login is created disabled and with a random password. */
/****** Object:  Login [vampadu]    Script Date: 6/6/2021 2:29:46 PM ******/
CREATE LOGIN [admin] WITH PASSWORD=N'password', DEFAULT_DATABASE=[master], DEFAULT_LANGUAG
GO

ALTER LOGIN [admin] ENABLE
GO

ALTER SERVER ROLE [sysadmin] ADD MEMBER [admin]
GO

ALTER SERVER ROLE [securityadmin] ADD MEMBER [admin]
GO

ALTER SERVER ROLE [serveradmin] ADD MEMBER [admin]
GO

ALTER SERVER ROLE [setupadmin] ADD MEMBER [admin]
GO

ALTER SERVER ROLE [processadmin] ADD MEMBER [admin]
GO

ALTER SERVER ROLE [diskadmin] ADD MEMBER [admin]
GO

ALTER SERVER ROLE [dbcreator] ADD MEMBER [admin]
GO

ALTER SERVER ROLE [bulkadmin] ADD MEMBER [admin]
GO
```

d. Right Click on SQL Express Icon in the left panel, to enable SQL Server Authentication mode



i. Properties → Select Security Tab and Select "SQL Server …" option & "Failed logins only" then click "OK".



Server: UW-2UA53222Y4\SQLEXPRESS

Connection: UWYO\mhaq

Ready

Server authentication

○ Windows Authentication mode

● SQL Server and Windows Authentication mode

Login auditing

○ None

● Failed logins only

○ Successful logins only

○ Both failed and successful logins

Server proxy account

☐ Enable server proxy account

Proxy account:

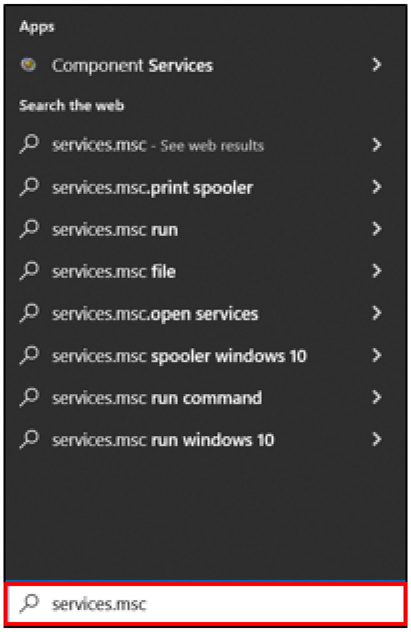
Password: **********

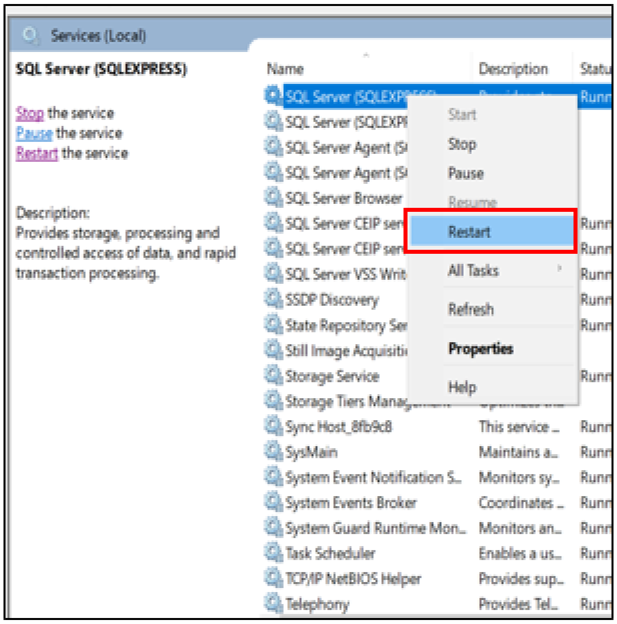
Options

☐ Enable C2 audit tracing

☐ Cross database ownership chaining

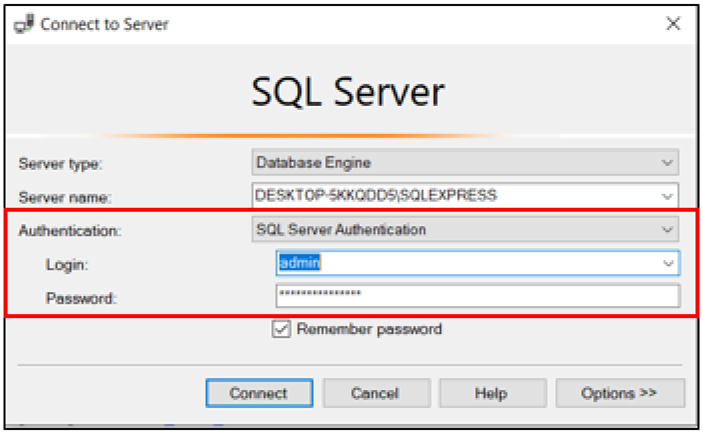
ii. Click OK, and Restart SQL Server Express by following below steps
RUN command → services.msc → Scroll to “SQL Server Express” server and Right click → Restart.





Description:
Provides storage, processing and controlled access of data, and rapid transaction processing.

e. Close Microsoft SQL Server Management Studio and log back in using the Admin User, with SQL Server Authentication as show below;
“Login – admin, Password – password and click on Connect”



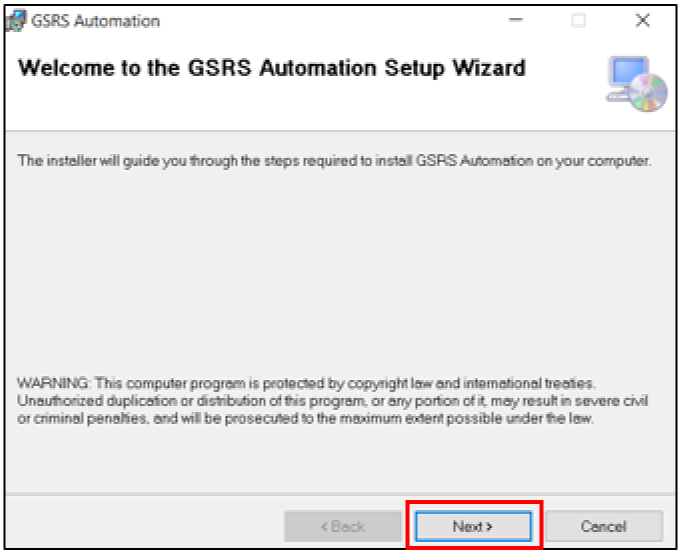
Server type: Database Engine
Server name: DESKTOP-5KKQDD5\SQLEXPRESS
Authentication: SQL Server Authentication
Login: admin
Password: ***************
☑ Remember password

f. Create the GSRS database by executing the query below:
File → Open → File C:\ GSRS Setup 2023\Create_GSRS_Database.sql
Select all using “CTRL+A” and Click on “Execute” button

g. Run GSRS DB Scripts to create necessary tables and stored procedures by following the procedure below:
File → Open → File C:\ GSRS Setup 2023\ Create_GSRS_Tables_SP_Scripts.sql
Select all using “CTRL+A” and Click on “Execute” button, and then close the file.

6. Install the .Net Framework 4.7.2 by clicking on “C:\ GSRS Setup 2023\.Net Framework 4.7.2.exe” and follow the instructions. If .NET framework is already installed, ignore this step.

7. Install GSRS Automation software by clicking on “C:\ GSRS Setup 2023\GSRS Setup.msi”
    a. Click Next

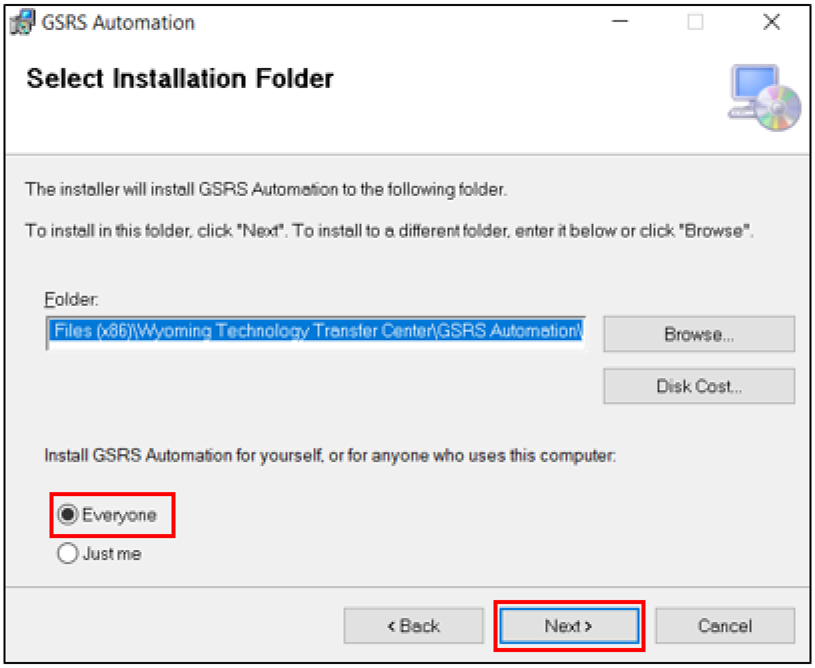


Welcome to the GSRS Automation Setup Wizard

The installer will guide you through the steps required to install GSRS Automation on your computer.

WARNING: This computer program is protected by copyright law and international treaties. Unauthorized duplication or distribution of this program, or any portion of it, may result in severe civil or criminal penalties, and will be prosecuted to the maximum extent possible under the law.

    b. Choose “Everyone” and leave the default path "C:\Program Files (x86)\,” Click Next



Select Installation Folder

The installer will install GSRS Automation to the following folder.

To install in this folder, click "Next". To install to a different folder, enter it below or click "Browse".

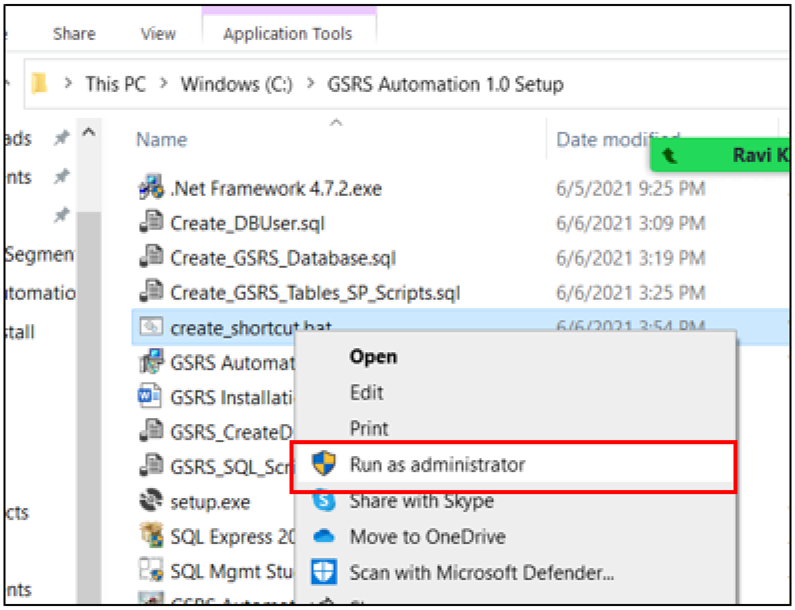
Folder: Files (x86)\Wyoming Technology Transfer Center\GSRS Automation\

Install GSRS Automation for yourself, or for anyone who uses this computer:

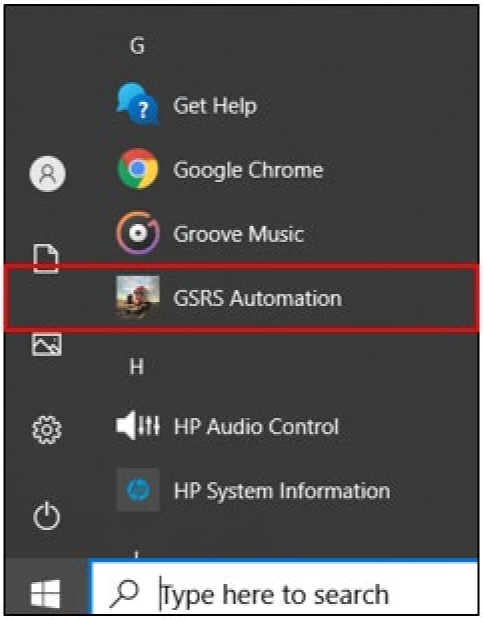
● Everyone
○ Just me

    c. Click Yes or Next on “next” screens and finally close the application. (Windows might indicate that “This is an unreliable source to be installed on your computer”). On encountering this, proceed to click “RUN ANYWAY” since no harm is associated with this action.

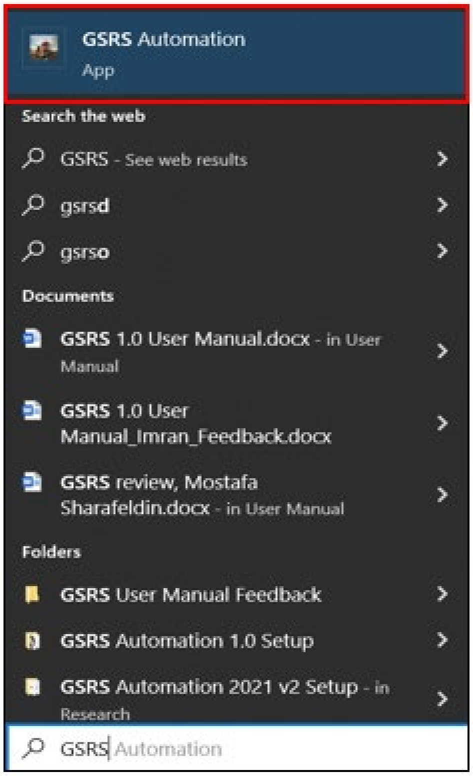
8. Create GSRS Automation software shortcut in start menu
    a. Right click on C:\ GSRS Setup 2023\create_shortcut.bat and “Run as Administrator.. The software should launch at this point



b. Alternatively, click on the GSRS Automation icon on the Windows start menu to launch the application.



c. As a final option, type “GSRS….” in the search bar in order to locate the software icon to launch it.



GSRS Automation
App

Search the web

GSRS - See web results

gsrsd

gsrso

Documents

GSRS 1.0 User Manual.docx - in User Manual

GSRS 1.0 User Manual_Imran_Feedback.docx

GSRS review, Mostafa Sharafeldin.docx - in User Manual

Folders

GSRS User Manual Feedback

GSRS Automation 1.0 Setup

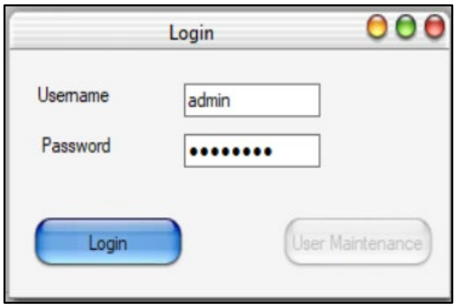
GSRS Automation 2021 v2 Setup - in Research

GSRS Automation

PRODUCT FEATURES

Below is a brief manual describing the features for the GSRS 1.0 software that should enable any user regardless of their software usage skill level to successfully manipulate the product.
After installation and launching of the product, the login page is the first form that loads. For initial use of the product, the admin and username should be supplied as shown in Figure A.1.

Username -> admin
Password -> password

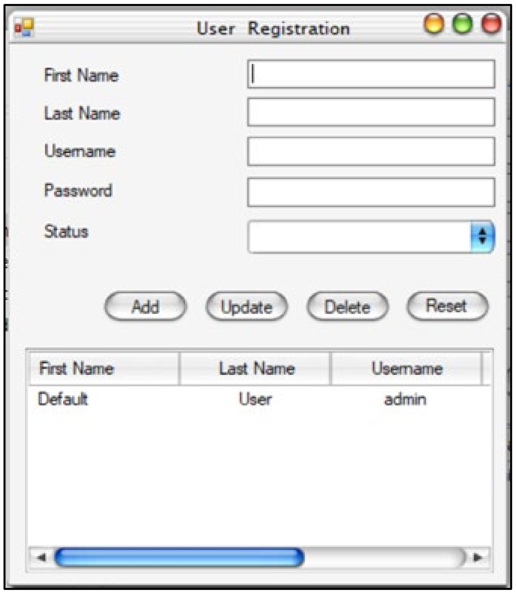


Username: admin
Password: ••••••••

Figure A.1 Login Page

Supplying this information and clicking “Login” launches the application. The “User Maintenance” button on the form is now enabled because the default login credentials have been pre-assigned administrative privileges. This can be observed by minimizing or logging out of the “GSRS Auto 1.0” main form.

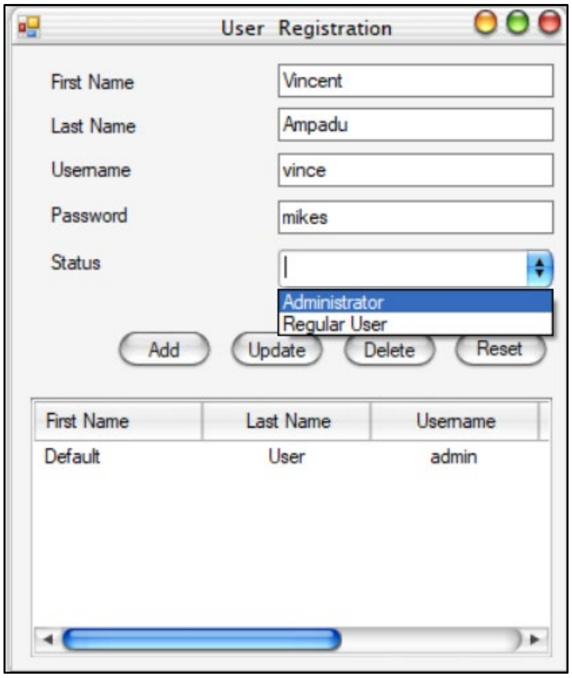
In order to register additional users of the software and specify their software usage privileges, click on “User Maintenance” (as an administrator). The form shown in Figure A.2 below loads



First Name	Last Name	Username
Default	User	admin

Figure A.2 User Registration Form

The default “Last Name” and “Username” of the software is shown in the Listview box. To add additional users, the textboxes representing “First Name,” “Last Name,” “Username,” “Password” and “Status” are populated accordingly. Figure A.3 shows a snapshot of one such data entry process



First Name	Vincent
Last Name	Ampadu
Username	vince
Password	mikes
Status	

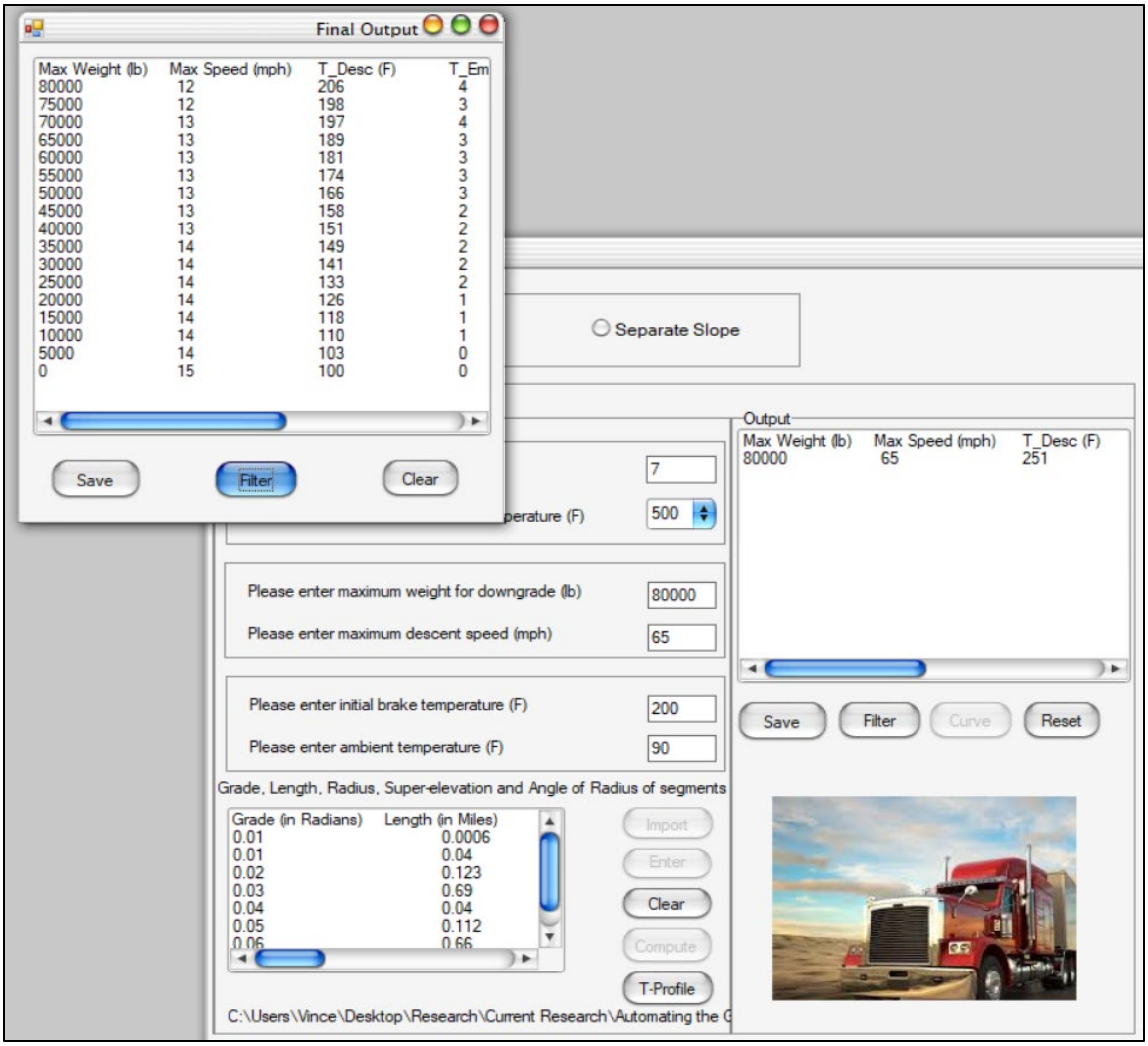
First Name	Last Name	Username
Default	User	admin

Figure A.3 User Registration Form illustrating a data-entry process

It should be noted that under status, the administrator has only two options- to register the user as “Administrator” or “Regular User.” Should he/she register the user as an administrator, that user should be able to both sign into and use the application and have access to the User Maintenance section to manipulate user attributes. On the other hand, if the administrator only grants “Regular User” privileges to a specific user, then even though that user should be able to sign into and use the software, the “User Maintenance” button on the login page would be disabled.

In general, for the User Registration form, besides the default values, in order to update a particular record, click on that record in the listview, modify the relevant field above, click on “Update” and confirm when prompted by the dialogue box to update the record in the database. To delete a record, click on it in the listview, click the delete button and confirm when prompted by the dialogue box. Clicking on “Reset” clears all fields of entries.

Figure A.4 shows the continuous slope section of the GSRS software and indicates both the input form on the bottom right and the output form on the top left section. As can be seen, the user is analyzing a downgrade with 7 segments, 500˚F maximum brake temperature, 80,000 lbs maximum truck weight, 65 mph maximum descent speed, 200˚F initial brake temperature, and 90˚F ambient temperature. These fields should be populated by the user based on his knowledge of the relevant variables.



```
Max Weight (lb)   Max Speed (mph)   T_Desc (F)   T_Em
80000              12               206           4
75000              12               198           3
70000              13               197           4
65000              13               189           3
60000              13               181           3
55000              13               174           3
50000              13               166           3
45000              13               158           2
40000              13               151           2
35000              14               149           2
30000              14               141           2
25000              14               133           2
20000              14               126           1
15000              14               118           1
10000              14               110           1
5000               14               103           0
0                  15               100           0
```

7

perature (F) 500

Please enter maximum weight for downgrade (lb) 80000

Please enter maximum descent speed (mph) 65

Please enter initial brake temperature (F) 200

Please enter ambient temperature (F) 90

Grade, Length, Radius, Super-elevation and Angle of Radius of segments

```
Grade (in Radians)   Length (in Miles)
0.01                     0.0006
0.01                     0.04
0.02                     0.123
0.03                     0.69
0.04                     0.04
0.05                     0.112
0.06                     0.66
```

Output

```
Max Weight (lb)   Max Speed (mph)   T_Desc (F)
80000              65               251
```

C:\Users\Vince\Desktop\Research\Current Research\Automating the G

Figure A.4 An example of final output of maximum descent speeds and other parameters based on the continuous slope method

The following table represents both a sample and ideal range of values that a knowledgeable user could typically use as input parameters for the continuous slope section of the software.

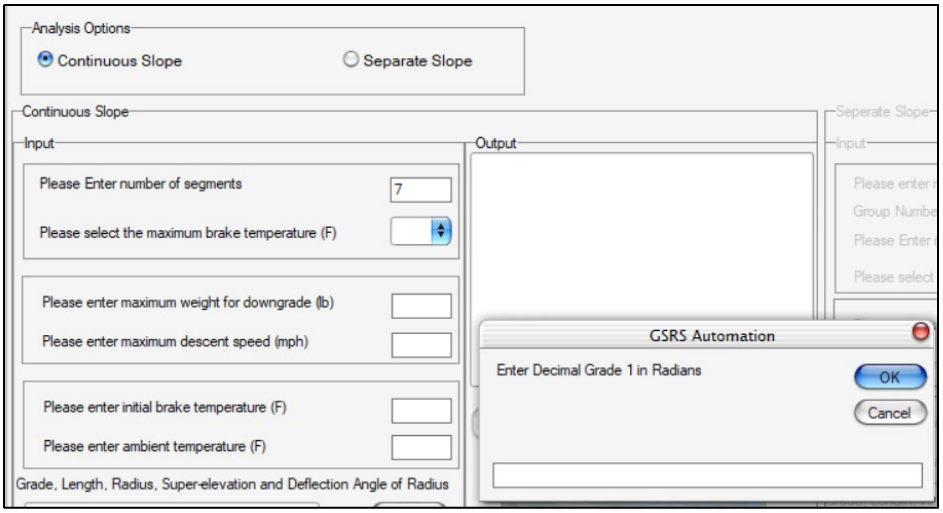
Parameter	**Sample**	**Ideal**
Maximum brake temperature (˚F)	500	500/530
Maximum downgrade weight (lb)	80,000	50,000 - 100,000
Maximum descent speed (mph)	65	35 - 65
Initial brake temperature (˚F)	200	150
Ambient temperature (˚F)	90	90

DATA PREPARATION

In order to prepare the data that constitutes the physical characteristics of the downgrade, the following procedure is followed:

For the physical characteristics of the downgrade, the input data required to obtain the maximum safe descent speeds include the longitudinal grade of the segment (percent), the length of the segment (miles), radius of the horizontal curve (ft), the super-elevation of the segment (percent) and the degree of curvature of the horizontal curve (degree). The software enables either a manual entry of the data or the capability to import the data from an Excel sheet.

In order to use the manual entry feature of the software, the user should click the “Enter” button. A dialogue box pops up and prompts him to enter the number of segments if he has not already done so. If the number of segments entered is less than or equal to 6, successive dialogue boxes appear and collect all the physical downgrade data for each successive segment. It should be noted that the user needs to complete the entire data collection cycle before being allowed to exit the input box. If the number of segments entered is more than 6, a dialogue box pops up and queries the user if he would like to import the data. If he clicks on “no,” several dialogue boxes manually requesting for data one segment at a time pop up as before. Figure A.5 represents a snapshot data entry stage of the software input for this specific instance of the data collection stage.



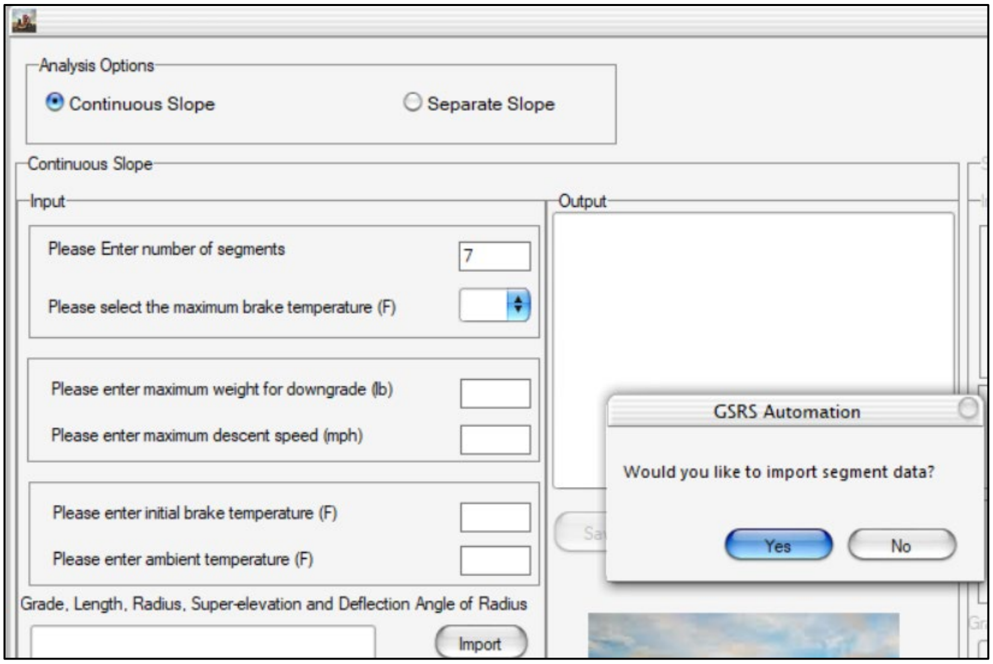
● Continuous Slope ○ Separate Slope

Please Enter number of segments 7

Enter Decimal Grade 1 in Radians

Figure A.5 Entering the physical downgrade parameters manually

If he clicks on “yes,” then an open dialogue box appears to allow him to navigate to the Excel file into which he has collated all the segment data. This step is indicated in Figure A.6 below:



Analysis Options

● Continuous Slope ○ Separate Slope

Continuous Slope

Input

Please Enter number of segments: 7

Please select the maximum brake temperature (F)

Please enter maximum weight for downgrade (lb)

Please enter maximum descent speed (mph)

Please enter initial brake temperature (F)

Please enter ambient temperature (F)

Grade, Length, Radius, Super-elevation and Deflection Angle of Radius

Output

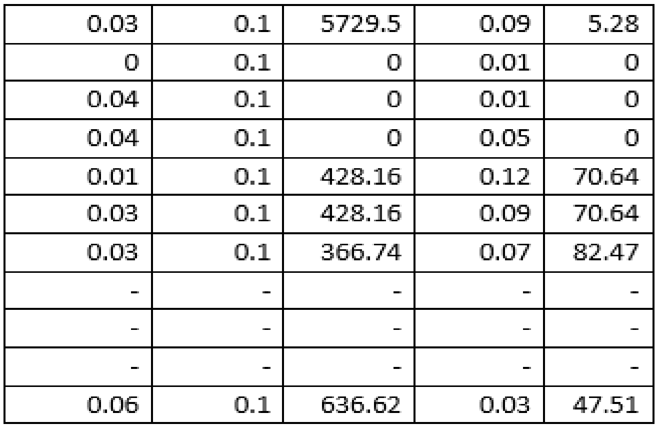
GSRS Automation

Would you like to import segment data?

Figure A.6 Importing the physical downgrade parameters from Excel

Figure A.7 represents a snapshot for an Excel datasheet showing a typical structure for the input data representing the physical characteristics of the downgrade and the roadway geometry ready for importation into the software.

As stated before, the data required to populate the Excel sheets prior to importation are the grade, segment length, radius of horizontal curve, super-elevation of the segment and the degree of curvature of the horizontal curve. These should be entered from the first to the fifth column; with each row collecting the data for each segment.



0.03	0.1	5729.5	0.09	5.28
0	0.1	0	0.01	0
0.04	0.1	0	0.01	0
0.04	0.1	0	0.05	0
0.01	0.1	428.16	0.12	70.64
0.03	0.1	428.16	0.09	70.64
0.03	0.1	366.74	0.07	82.47
-	-	-	-	-
-	-	-	-	-
-	-	-	-	-
0.06	0.1	636.62	0.03	47.51

Figure A.7 A Snapshot for a sample Excel datasheet representing the physical characteristics of the downgrade and the roadway geometry

The degree of curvature of the horizontal curve can be calculated from the radius and length of the segment through equation 14 repeated below;

$$\Delta = (360 \times Lc/(2 \times \pi \times R) \quad (14)$$

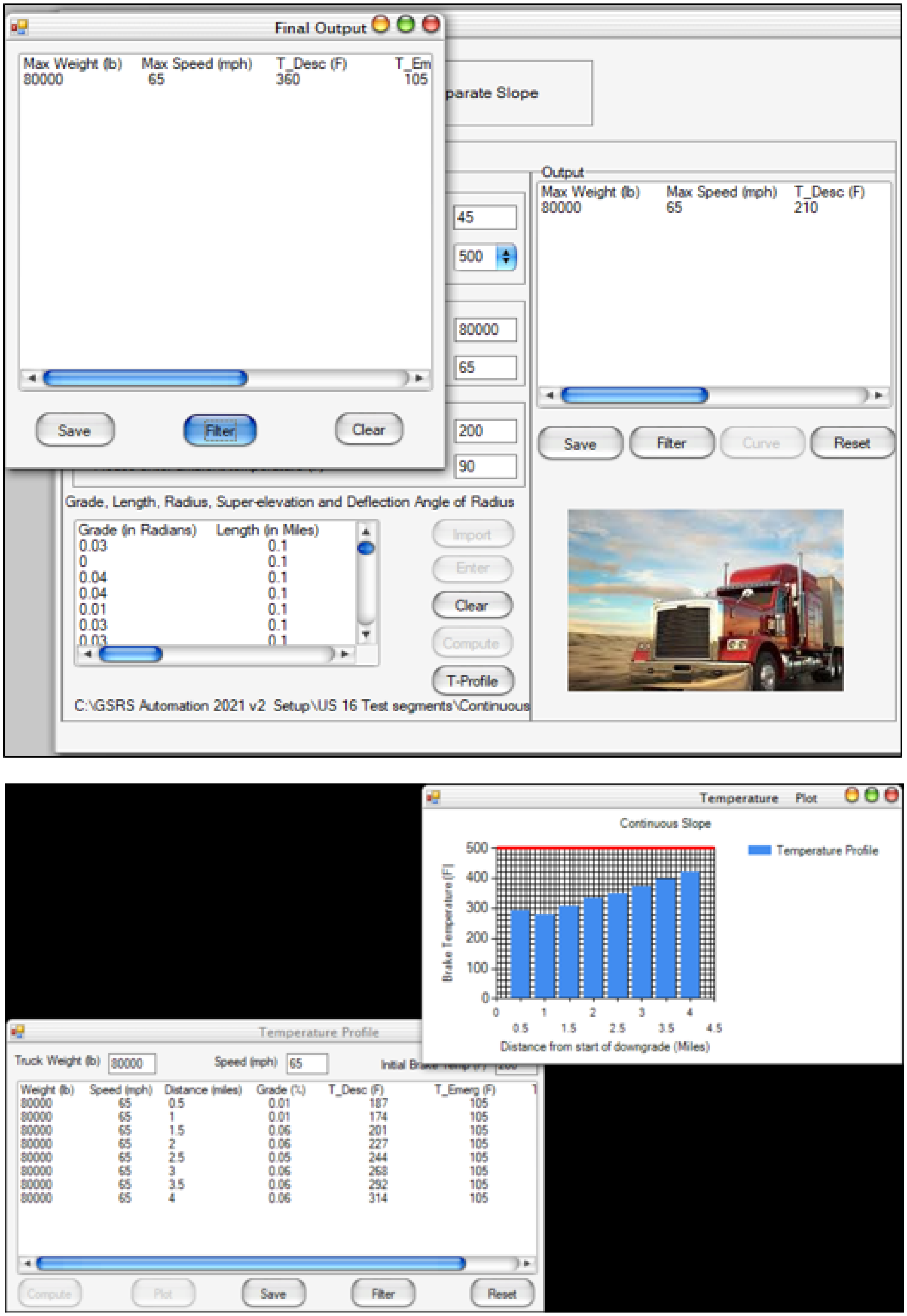
Where Δ is the degree of curvature of the horizontal curve, Lc is the length of the curve (ft), and R is the radius of the curve (ft).

CONTINUOUS SLOPE METHOD

After the data is imported or manually entered, whichever is the case, the user clicks on “Compute” and the Output field is populated by the output of the continuous slope method which consists of the Maximum Weight, Maximum Speed, Descent Temperature, Emergency braking Temperature, Final brake Temperature and Time to descend the downgrade. At this juncture, the user can either click on “Save” to save the output or “Filter” to filter down the output to the values of these parameters at each weight category from the maximum weight to 0 lb. It should be noted that the horizontal curve input parameters are excluded from the computation of these results- (Radius of horizontal curve, super-elevation of the segment and the deflection angle of the horizontal curve).

By clicking on “Curve,” the overall output is computed- this time incorporating the input parameters introduced by considering horizontal curves. As before, the user can click on “Save” to save the output or “Filter” to filter the results in order to pare down the output to the values for each weight category from the maximum weight to zero, as shown in Figure A.8.

If the user wants to determine the Temperature profile for the grade descent, he clicks on the “T-Profile” button and the form on the left of bottom image of Figure 8 pops up. He then clicks on “Compute” and the form shows all the results for the output inclusive of which is the Maximum Weight, the Speed, the Distance (in miles) from the start of descent (in 0.5-mile increments), the grade, the descent temperature, the emergency braking temperature, and final braking temperature. As before, the user can save this output or filter it to pare down the results to only those with final brake temperature below 500F by clicking on the corresponding buttons on the form. The temperature plot on the right shows the graphical portrayal of the temperature profile based on distance from the start of the downgrade in miles. This form pops up when the user clicks on “Plot.” The red line indicated the maximum brake temperature (500˚F).



Max Weight (lb)	Max Speed (mph)	T_Desc (F)	T_Em
80000	65	360	105

Output

Max Weight (lb)	Max Speed (mph)	T_Desc (F)
80000	65	210

Grade, Length, Radius, Super-elevation and Deflection Angle of Radius

Grade (in Radians)	Length (in Miles)
0.03	0.1
0	0.1
0.04	0.1
0.04	0.1
0.01	0.1
0.03	0.1
0.03	0.1

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Truck Weight (lb) 80000
Speed (mph) 65

Weight (lb)	Speed (mph)	Distance (miles)	Grade (%)	T_Desc (F)	T_Emerg (F)
80000	65	0.5	0.01	187	105
80000	65	1	0.01	174	105
80000	65	1.5	0.06	201	105
80000	65	2	0.06	227	105
80000	65	2.5	0.05	244	105
80000	65	3	0.06	268	105
80000	65	3.5	0.06	292	105
80000	65	4	0.06	314	105

Figure A.8 An example of final output and temperature profile of maximum descent speeds based on the continuous slope method

SEPARATE DOWNGRADE METHOD

The separate downgrade method is used for multi-grade segments composed of clusters of braking and non-braking segments. Braking segments are typically downgrades composed of segments with lengths greater than 0.5 miles whereas non-braking segments are typically upgrades, level segments or downgrades with segment lengths less than 0.5 miles. Figure A.9 illustrates an example of multi-grade segment which is a typical candidate for the separate downgrade method.

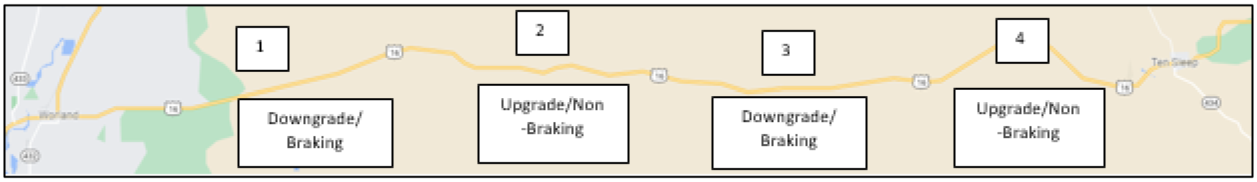
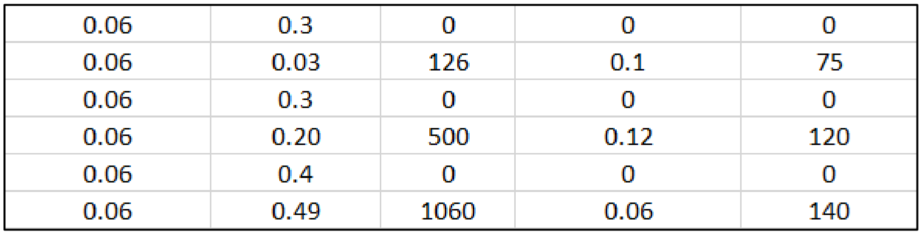


Figure A.9 Aerial view of a typical multigrade segment

Braking Phase

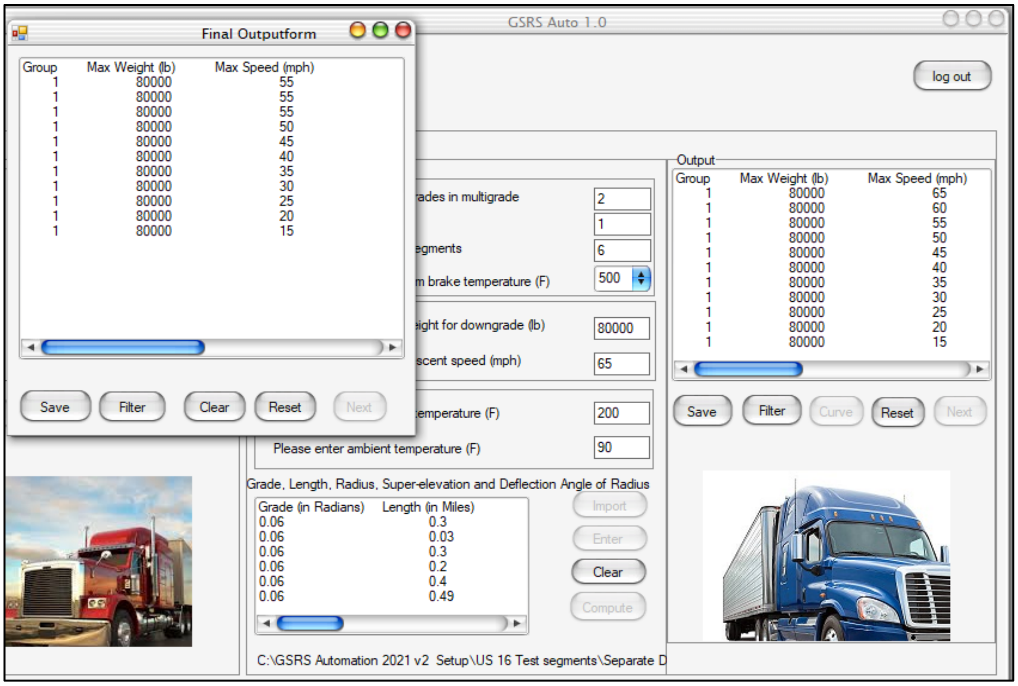
Figure A.10 illustrates a snapshot of the Excel data file containing the physical input parameters of the downgrade for this phase. Beneath it is Figure A.11 that illustrates the first braking phase of a 2-grade multi-grade with the indicated input parameters on the bottom right as well as the final maximum descent speeds to prevent brake fade, rollover, and skidding on the top left.



0.06	0.3	0	0	0
0.06	0.03	126	0.1	75
0.06	0.3	0	0	0
0.06	0.20	500	0.12	120
0.06	0.4	0	0	0
0.06	0.49	1060	0.06	140

Figure A.10 A snapshot for a sample Excel datasheet representing the physical input parameters for the braking phase

The input parameters besides those of the physical downgrade are mostly the same as those requested for and fed into the continuous slope method. Similarly, the buttons do the exact same thing as described in the preceding sections. The only difference is this method requests for the number of grades (i.e., segments) in the multi-grade.



```
Group   Max Weight (lb)   Max Speed (mph)
1       80000             55
1       80000             55
1       80000             55
1       80000             50
1       80000             45
1       80000             40
1       80000             35
1       80000             30
1       80000             25
1       80000             20
1       80000             15
```

ades in multigrade: 2

1

egments: 6

m brake temperature (F): 500

ight for downgrade (lb): 80000

scent speed (mph): 65

emperature (F): 200

Please enter ambient temperature (F): 90

Grade, Length, Radius, Super-elevation and Deflection Angle of Radius

```
Grade (in Radians)   Length (in Miles)
0.06                 0.3
0.06                 0.03
0.06                 0.3
0.06                 0.2
0.06                 0.4
0.06                 0.49
```

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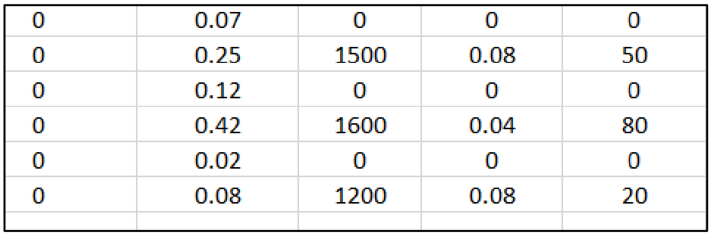
```
Group   Max Weight (lb)   Max Speed (mph)
1       80000             65
1       80000             60
1       80000             55
1       80000             50
1       80000             45
1       80000             40
1       80000             35
1       80000             30
1       80000             25
1       80000             20
1       80000             15
```

Figure A.11 An example of the final output of maximum descent speeds and other parameters for a typical braking phase based on the separate downgrade method

The braking phases of the separate downgrade method for the GSRS is signified by odd group numbers (1, 3, 5,….) and typically outputs a single truck weight and associated maximum descent speeds from the speed limit to 15 mph in 5 mph decrements. The final output also includes the temperature of descent (˚F), emergency braking temperature (˚F), total final temperature (˚F), and time to descend the downgrade (min). The "Filter" and "Save" buttons serve the same function as described in the continuous slope method. Moreover, the "Curve" button outputs the results for these given set of input parameters with the horizontal curve parameters included. The "Save" and "Filter" buttons have the same function as before. To proceed to the next group of segments in the non-braking phase, the "Next" button is clicked.

Non-Braking Phase

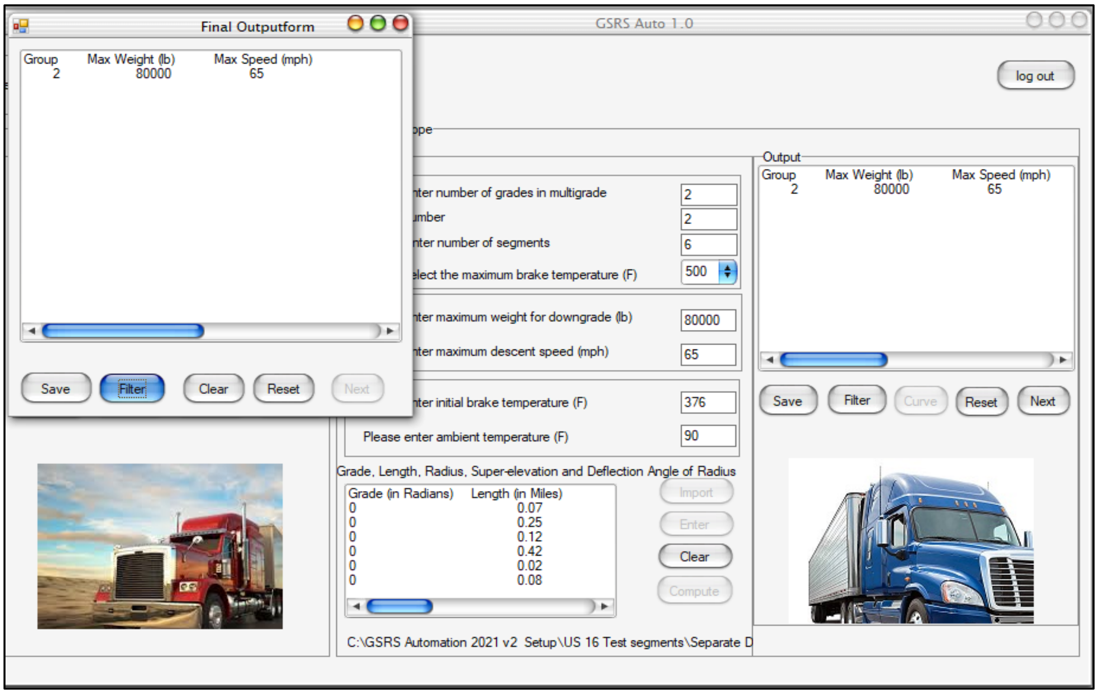
Figure A.9 illustrates a snapshot of the Excel data file containing the physical input parameters for the non-braking phase.



0	0.07	0	0	0
0	0.25	1500	0.08	50
0	0.12	0	0	0
0	0.42	1600	0.04	80
0	0.02	0	0	0
0	0.08	1200	0.08	20

Figure A.12 A snapshot of the Excel data file containing the physical input parameters of the non-braking phase

Figure A.13 illustrates the first non-braking phase of the same two-grade multi-grade with the indicated input parameters as well as the final maximum descent speed to prevent brake fade, rollover, and skidding for various weight categories on the bottom right and top left respectively (In this specific scenario, this maximum descent speed is equivalent to the speed limit for the maximum weight category and hence all lower weight categories can descend safely at the speed limit hence why they aren't indicated in the display). The functionality for the non-braking phase of the separate downgrade method (with even group numbers- 2, 4, 6, 8 …) for the GSRS is very similar to the continuous slope method. The distinguishing feature of the input parameters for a non-braking phase of a multi-grade downgrade is the "0" grade value for each segment.



Group	Max Weight (lb)	Max Speed (mph)
2	80000	65

ope

nter number of grades in multigrade: 2

umber: 2

nter number of segments: 6

elect the maximum brake temperature (F): 500

nter maximum weight for downgrade (lb): 80000

nter maximum descent speed (mph): 65

nter initial brake temperature (F): 376

Please enter ambient temperature (F): 90

Grade, Length, Radius, Super-elevation and Deflection Angle of Radius

Grade (in Radians)	Length (in Miles)
0	0.07
0	0.25
0	0.12
0	0.42
0	0.02
0	0.08

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Output

Group	Max Weight (lb)	Max Speed (mph)
2	80000	65

Figure A.13 An example of final output of maximum descent speeds and other parameters for a typical non-braking phase based on the separate downgrade method

All buttons have the same functionality as is described in preceding sections. The final output involved in both considering and excluding horizontal curve parameters respectively includes the Maximum Weight, Maximum Speed, Temperature of descent (˚F), Emergency braking temperature (˚F), Total final temperature (˚F), and Time to descend the downgrade (min).

By clicking on the "Next" button on the output form which pops up after clicking on "Curve," one can navigate to the next group of segments. This process is continued until the maximum number of grades in the multi-grade is exhausted. Clicking "Next" following this should generate a dialogue box that alerts the user to the fact that the maximum number of downgrades has been reached and requests to terminate the process and reset all fields.

ERROR HANDLING

During either the braking or non-braking phase of the continuous/separate downgrade section of the software, it is possible for the user to import a spreadsheet in which any one of the input parameters violates criteria for the appropriate format specified in the algorithm. In this instance, an error dialogue box pops up as illustrated in Figure A.14.

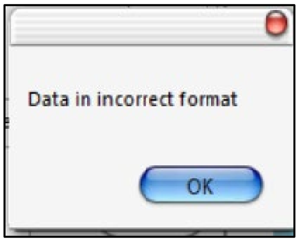
Data in incorrect format

Figure A.14 Error Dialogue box for data entered in incorrect format

Alternatively, the spreadsheet may contain downgrade physical characteristic values that violate criteria for satisfying relevant equations. In this scenario, the error indicated in Figure A.15 is triggered. The user will therefore be required to reduce the length of the segments and recompute the degree of Δ using equation (14) iteratively until the software no longer triggers that error. To reiterate, equation (14) is listed underneath as follows:

$$\Delta = (360 \mathrm{\ x\ } Lc/(2 \mathrm{\ x\ } \pi \mathrm{\ x\ } R) \qquad (14)$$

It is important that the user notes how changing the length of the segment will influence other parameters associated with it such as the radius, grade and super-elevation of this new length and modify it accordingly in the datasheet.


Alert!

Error! Check your input variables- Shorten segments and recompute angles!

Figure A.15 Error Dialogue box for data values violating criteria for in-built equations

An audio-video version of this user manual will be available to provide better guidance to the user soon.

APPENDIX B

Appendix B includes various images associated with the Hill Descent and Validation tests. More specifically, it includes the test truck, drum-braking system, traffic control truck to coordinate traffic on test day, temperature measuring device, the various brake temperature measuring locations, and other pictures associated with the build up to the day of testing.

Figure B.1 2010 Freightliner Cascadia with sleeper in a 3-axle all drum configuration + 53' dry van trailer with a 2-axle all drum configuration + drum brake

Figure B.2 WYDOT testing traffic control truck

Figure B.3 Hand-held sensors used to take brake temperatures

Figure B.4 Brake measuring locations for Hill Descent 1 showing direction of truck travel

Figure B.5 Brake measuring locations for Hill Descent 2 showing direction of truck travel

Figure B.6 Brake measuring locations for Hill Descent 3 showing direction of truck travel

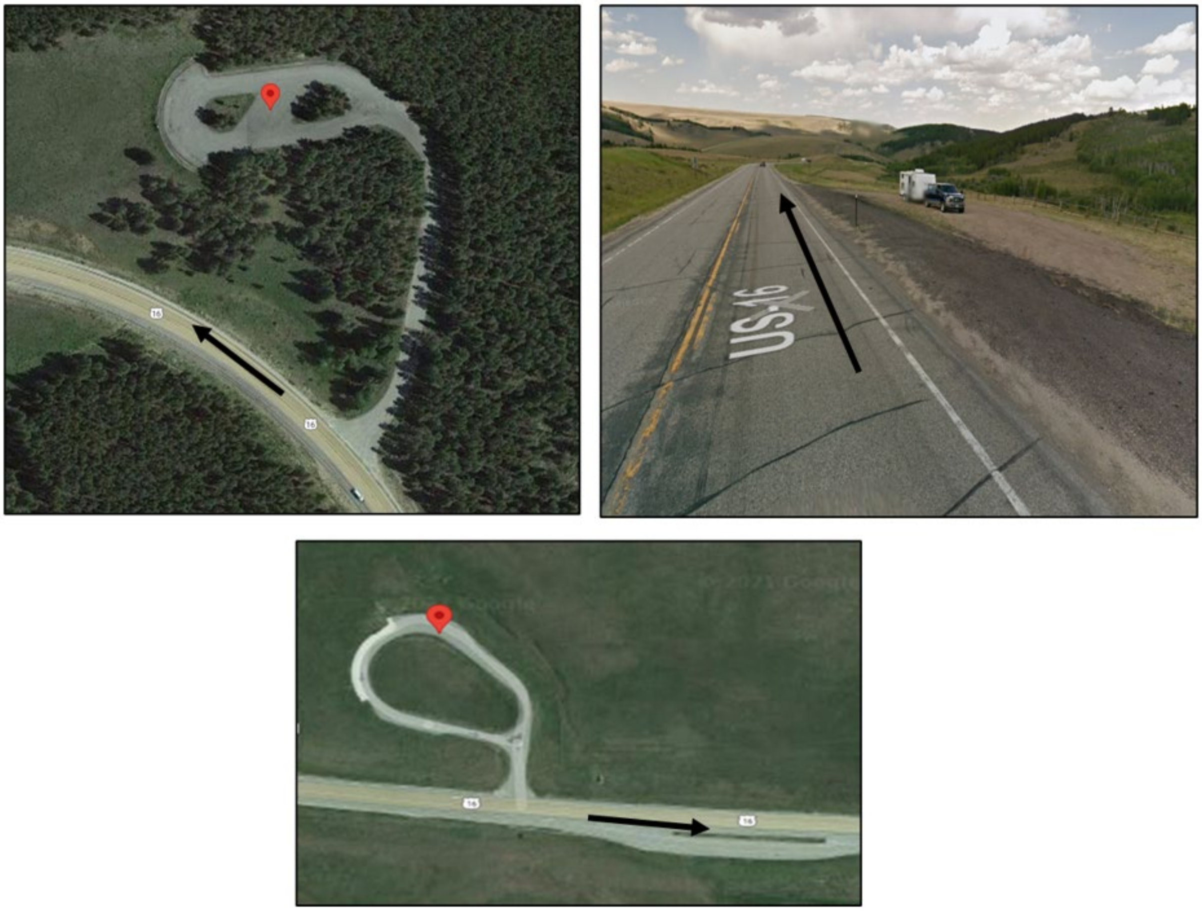

Figure B.7 Brake measuring locations for validation tests showing direction of truck travel

Table B.1 Data collection form for Hill Descent test

Segment	Spot ID	Air Temp (˚F)	Brake Temperature (˚F)									
			Brake 1	Brake 2	Brake 3	Brake 4	Brake 5	Brake 6	Brake 7	Brake 8	Brake 9	Brake 10
HD - I 30 mph	HD 1-1											
	HD 1-2											
HD – I 40 mph	HD 1-1											
	HD 1-2											
HD – II 35 mph	HD 2-1											
	HD 2-2											
HD – II 45 mph	HD 2-1											
	HD 2-2											
HD – III 40 mph	HD 3-1											
	HD 3-2											
HD – III 50 mph	HD 3-1											
	HD 3-2											

Table B.2 Data collection form for validation tests

Segment	**Spot ID**	**Brake Temperature (˚F)**									
		Brake 1	Brake 2	Brake 3	Brake 4	Brake 5	Brake 6	Brake 7	Brake 8	Brake 9	Brake 10
1) V 1 – V 2 2) V 2 – V 3	V 1										
	V 2										
	V 3										

Figure B.8 Images taken during the test

Figure B.9 Image taken during presentation at Admiral Transport Corp

Figure B.10 Downgrade; road signage on Hill Descent segment

Figure B.11 Concluding remarks to team