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Automating the updated grade severity rating system (GSRS) using the Visual Basic.net programming language

Vincent-Michael Kwesi Ampadu *, Khaled Ksaibati **

* *Department of Civil & Architectural Engineering, University of Wyoming,*
1000 E University Avenue, Laramie, WY 82071, USA
Graduate Research Assistant
Tel: 307-761-1910
vampadu@uwyo.edu
** *Wyoming Technology Transfer Center, Department of Civil & Architectural Engineering, University of Wyoming,*
1000 E University Avenue, Laramie, WY 82071, USA
Ph.D., P.E., Director
Tel: 307-766-6230; Fax: 307-766-6784
khaled@uwyo.edu

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Abstract: Truck crashes on steep downgrades due to excessive brake heating, resulting from brake applications to control speeding, are a continuing cause of concern for the Wyoming Department of Transportation (WYDOT). In 2016, WYDOT funded a project to update the existing Grade Severity Rating System. Furthermore, in 2020, WYDOT commissioned a research project to automate the updated version of the mathematical model through an interactive, intuitive, aesthetically appealing and user-friendly Visual Basic.net objected-oriented software to simplify the computation of the maximum safe descent speed on these downgrades based on the truck weight. The software provides functionality for both the continuous Slope and separate downgrade methods. The primary beneficiaries of this software will be the highway agencies who will be able to estimate the maximum safe speed of descent for trucks with various weight categories and hence produce Weight Specific Speed (WSS) signs for each downgrade or a multigrade section.

Keywords: updated GSRS, longitudinal downgrades, object-oriented programming, Visual Basic.net programming language

1. Introduction

Highway safety on mountain passes is of significant concern to most highway agencies in the western parts of the United States. In comparison to other vehicle classes, large trucks are disproportionately affected by crashes on downgrades, and this may generally be attributed to their weight and size, although crash risks exist for buses, single-unit trucks, recreational vehicles, and

Corresponding author: *Vincent-Michael Kwesi Ampadu*
E-mail: vampadu@uwyo.edu

passenger vehicles as well (Moomen, Rezapour, Raja & Ksaibati, 2019). Most of all, the high cost of crashes to society resulting from road deaths, injuries, and property damage, especially on downgrades, places a huge burden on the economy of most nations (Moomen, Rezapour, Raja & Ksaibati, 2020).

Wyoming has one of the highest truck-related fatality rates amongst states in the U.S. Several factors account for this, but they are mostly related to the challenging mountainous terrain, placing an extra burden on truck drivers with respect to requiring a higher level of alertness and driving skill. Such impacts of dangerous terrain on Wyoming truck crashes were quite frequently reported by previous studies (Haq, Zlatkovic & Ksaibati, 2019, 2020a, 2020b, 2022). As part of the measures required to reduce the rate of truck-related crashes in mountainous areas, the Wyoming Department of Transportation (WYDOT) initiated a study to explore the causes of truck crashes in the downgrade areas of Wyoming. Several studies have investigated the contributory factors to severe injury crashes focused on level road sections. This study was therefore conducted to fill the research gap. It was discovered that downgrade length, shoulder width, horizontal curve length, number of lanes, number of access points, and truck traffic on the highway all influence truck-related crashes and injury frequencies on Wyoming downgrades (Moomen, Rezapour, Raja & Ksaibati, 2020). Other sophisticated techniques directed at the same question revealed driver gender, age, weather, lighting and road conditions, number of crest curves, crash type, number of driveways, day of the week, and posted speed limit as significant importance (Moomen, Rezapour & Ksaibati, 2019).

The combination of heavy loads, steep inclines, and long downgrade lengths raises the probability of brake failure resulting from brake heating. As trucks descend downgrades, large amounts of potential energy are generated and absorbed by the truck's service brakes. This potential energy is then converted to heat energy. This is then absorbed by the braking system, which increases the braking temperature. With increasing absorption of heat, braking efficiency begins to decrease, and a phenomenon referred to as "brake fade" (Moomen et al., 1990). If the brake system temperature continues to increase, the condition proceeds from brake fade to brake failure resulting in an out-of-control or runaway truck (Bowman & Coleman, 1990). Different factors lead to the occurrence of truck runaways and subsequent crashes on downgrades. These include; failure to downshift, defective brakes, inexperienced drivers, and inadequate signing for downgrades (Rezapour, Moomen & Ksaibati, 2019). Suggestions have been made to reduce the risk of downgrade crashes by improving the quality of information available to drivers. Such information would include downgrade length and percent, the requirement to use lower gears, the presence of truck turnouts, or the availability of brake check areas. Advance warning signs usually convey this type of critical information. Such advance signs notify drivers when upcoming steep grades and roadway geometry might have adverse impacts on driver capability and vehicular performance. Intelligent transportation systems (ITS) can also be used to convey this type of information to drivers. Examples of ITS include downhill truck warning systems, dynamic curve warning systems, and automatic truck rollover warning systems. The downhill warning system installed on the Eisenhower Tunnel on Interstate 70 in Colorado is a typical example of an ITS which has been found to be effective in reducing truck crashes (Moomen et al., 2019).

In Wyoming, some highways traverse over mountain passes featuring steep downgrades. The significant mountain passes in the state include US 14, US 16, Teton pass, South Pass, and US 14 Alternative. The trucks, which traverse these mountain passes, typically carry large truckloads and thus can be very dangerous. In fact, during specific periods of the year, some mountain passes only accommodate lower weight limits, whereas others are closed to all traffic completely (Moomen et al., 1990). Differences in the geometric characteristics of downgrades and the mechanics of vehicle operations per such sections imply that different factors influence crash-injury severity in contrast to straight and level roadway sections. Resulting from the ordered nature of the response variable, the ordered logit model was selected to explore the influencing factors of crash injury severity of downgrade crashes. The model was calibrated separately for single and multiple-vehicle crashes to be sure the different factors influencing both types of crashes were captured. The results of the ordered model for single-vehicle crashes indicated that alcohol, gender, road condition, vehicle type, point of impact, vehicle maneuver, safety equipment use, driver action, and annual average daily traffic (AADT) per lane all affected the injury severity of downgrade crashes. Lighting conditions posted speed limit, lane width, and the use of safety equipment were also determined to be significant factors influencing multiple-vehicle downgrade crashes (Rezapour, Moomen & Ksaibati, 2019).

The Manual on Uniform Traffic Control Devices (MUTCD) for streets and highways endorses hill signs placed ahead of the downgrade descent of mountain passes as an attempt to mitigate this concern. WYDOT, therefore, decided to install advance-warning signs before steep grades on mountain passes. Mountain passes exacerbate the risk of a truck runaway, and as a result, the presence of advance warning signs notifies the driver about specific precautions to take, inclusive of which are reducing speed and lowering gears during descent. Despite these interventions, there has still been growing concern for truck runaways. Therefore, a study was commissioned to evaluate the safety effectiveness of steep-grade advance warning signs for predicting truck crashes on mountain passes (Apronti et al., 2019). The research led to two models demonstrating high risks of runaway truck accidents at long and steep-graded locations or locations where grades were long and possessed multiple vertical curves. Furthermore, this analysis showed the current advance warning systems were not significant in influencing truck crash risks at high-risk locations. The study, therefore, recommended improving the current advanced warning signs, the Federal Highway Administration (FHWA) Grade Severity Rating System (GSRS) in order to significantly enhance truck safety at hazardous locations. It also informed policymakers, and other stakeholders about the safety issues on Wyoming mountain passes with respect to runaway trucks and recommended measures for mitigating the risk of crash runaways and associated crashes on mountain passes (Apronti et al., 2019).

Despite the fact that the Weight Specific Signs (WSS) convey explicit information concerning the appropriate speeds at which drivers can safely descend steep downgrades, changes in truck design and braking systems following the 1970's require a review and update of the current FHWA GSRS model for current trucks to continue to mitigate crashes. To counter such crashes, WYDOT initiated a research project in 2016 to update a previous GSRS model originally developed in 1981. This was based on the necessity of upgrading the previous GSRS models since they were no longer representative of current truck characteristics after undergoing significant changes over the decades, thus rendering descent speeds conservative and hence prone to trivialization. The research project entailed fully instrumenting a truck and subjecting it to several field tests. Software simulations were then used to complement the testing because of environmental and time constraints.

Additionally, a validation test was then conducted to assess the accuracy of the updated model by comparing field brake temperatures to the predicted temperatures. A close match between the predicted temperatures and field temperatures suggested that the updated GSRS model was accurate. This new model incorporated changes in truck characteristics, inclusive of which were new streamlined designs, reduced frontal areas, differences in tire types, and engine characteristics.

Computers are capable of assisting in a broad scope of activities in the planning, design, simulation, fabrication, and operation of engineering systems. Recent advances in artificial intelligence, for instance, as occurs in knowledge-based expert systems, have generated aids for planning and design, especially in the conceptual and preliminary phases. In contrast to that, evaluation is based on mathematical models of the system, which render algorithmic solutions generally appropriate. Solutions based on computing systems typically stress the problem-solving methodology, part and parcel of which includes numerical methods, inference strategies, or logic at the expense of data representation. Abstraction is significantly advocated as a technique for data representation development. It implies the separation of a concept from its implementation. It permits the development of data representations that stress important characteristics of a system while hiding the details of how the properties are stored in the computer system. This results in the development of software that is responsive to changing needs and requirements. Objects are a mechanism for representing data using abstraction. On the other hand, object-oriented languages are languages for writing programs to manipulate objects. Object-oriented program development leads to modular programs and reusable code (Fenves, 1990).

After developing the GSRS by the FHWA, Disc Operating System (DOS) was used to computerize it in 1990 to allow implementation. The program would request input parameters of truck weight, speed, and the physical characteristics of the downgrade, length, and Slope to be specific and use that information to compute maximum safe speeds, brake temperatures, and total travel time for different truck weights. This program was indispensable for multigrades 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?"

The GSRS program developed for IBM computers in 1989 estimated the maximum descent speeds for multigrades. Currently, automating the GSRS will entail the formulation of two types of analysis based on the physical characteristics of the multigrade downgrade. Multigrade hills are categorized into two; those containing non-braking intervals (upgrades and level sections) and those that do not. For multigrades having non-braking intervals, the separate downgrade method of analysis is utilized. This method is used to optimize travel time by analyzing a multigrade as a series of constant-speed braking downgrades separated by non-braking intervals. Brake temperature increases occur as energy is absorbed by the brake system, whereas brake cooling occurs on non-braking intervals where downshifting is allowed. Ideally, the separate grade 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.

Multigrade containing braking intervals only utilizes the continuous downgrade method. This method estimates one safe speed for each 5000 lb vehicle weight decrement and is maintained for the entire Slope. This technique is used when non-braking segments of sufficient length to permit downshifting do not exist within the downgrade. The program produces an output of one speed for each 5000 lb decrement from the maximum vehicle weight until the speed limit is reached (Moomen et al., 1990).

This study is intended to document the background, methodology, and implementation of the automation of the GSRS software so WYDOT and other highway agencies can use it to estimate the maximum safe speed of descent for various weight categories and hence produce Weight Specific Speed (WSS) signs for each downgrade or a multigrade section. The contribution of this research is an intersection between transportation and software engineering, where an interactive, intuitive, aesthetically appealing, and user-friendly application is developed using the Visual Basic.net objected-oriented programming language.

2. Literature review

The use of WSS signs generated from the GSRS developed by the 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 to say it computes the corresponding speeds for a given final brake temperature given a particular downgrade at a given weight. The implication is that provided a maximum safe final brake system temperature is defined that prevents brake fade; the corresponding maximum safe speed may be computed for that specific downgrade. Based on this, a WSS sign recommending maximum speeds that would be kept constant throughout the duration of the downgrade for several weights could be set up (Moomen et al., 1990).

Johnson et al. noted that it was relevant for sufficient braking to be available at any point along the downgrade to enable an emergency stop. Their argument 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 (Moomen et al., 1990).

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:

(a) "What precisely was your contribution?"
(b) "What is your new result?"
(c) "Why should the reader believe your result?"

There has been a growing emphasis on the need for reproducibility of software results by program co-chairs. For instance, should a paper contain a produced artifact often in the form of a procedure or technique and tool or notation categories, reviewers would prefer to see it as generally available to the general public in the form of open source (Theisen et al., 2017).

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

(a) Problem: What issue the paper would like to solve or the question the paper would like to answer. This includes "Type of Software engineering questions" of which five groups were identified; Development Method, Analysis method, Specific Instance, Generalization or characterization, Feasibility study or Exploration**.**
(b) Contribution: What is the main result presented in the paper? This encapsulates "Type of software engineering results," Type of article, Research approach, and Research Method. Finally, the four paper categories of ICSE call for papers: Theoretical, Technological, Empirical, and Perspectival.
(c) Validation: What evidence the paper shows that the contribution is valid: Analysis, Evaluation, Experience, Example, No-validation.
(d) Topic: What is the main topic the paper addresses?

Of the three types of categorizations, the researcher's choice of validation technique was found to be the most crucial factor determining whether a paper would be accepted or otherwise (Bertolino et al., 2017).

3. Research methodology

The purpose of the algorithm based on the updated GSRS model is to determine the maximum speed which a truck can descend the downgrade, without exceeding the speed limit or maximum limiting temperature of the braking system (which has been experimentally determined to be 500˚F or 530˚F depending on the lining material).

Equations (1) through (9) are the equations governing the updated GSRS.

$$T_f = T_o + [T_\infty - T_o + K_2 HP_B]\left[1 - e^{-K_1 L/V}\right] + T_E \quad (1)$$

$$T_E = 3.11\, x\, 10\hat{} - 7WV^2 \quad (2)$$

$$HP_B = \left(W\theta - F_{drag}\right)\frac{V}{375} - HP_{eng} \quad (3)$$

$$K_1 = 1.5x(1.1852 + 0.0331V \quad (4)$$

$$K_2 = (0.1602 + 0.0078V)^{-1} \quad (5)$$

$$F_{drag} = 459.35 + 0.132V^2 \quad (6)$$

$$HP_{eng} = 63.3 \quad (7)$$

$$T_\infty = 90 \quad (8)$$

$$T_o = 150 \quad (9)$$

Where,

T_f = the Final temperature at the bottom of the segment (˚F)

T_E = the Emergency stopping temperature (˚F)

HP_B = the Horsepower into the brakes (hp)

K_1 = the diffusivity constant (1/hr)

K_2 = the heat transfer parameter (˚F/hp)

F_{drag} = the drag forces (lb)

HP_{eng} = the engine brake force (hp), experimentally determined as 63.3 hp for brake systems of current truck models without retarders engaged

W = weight of truck (lb)

θ = Slope of segment (%)
V = Speed of Truck (miles per hour)
L = Length of segment (miles)
T_∞ = Ambient Temperature = 90˚F
T_o = Initial brake temperature = 150˚F
Time to descend downgrade (min) = (Total Length of segments in downgrade) x 60 /V

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

(A) Continuous slope method

This method works for downgrades, which have no upgrades or level segments interspersed with downgrade segments. Also, 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 to brake, the speeds cannot be controlled. Thus, when descending segments, downgrades are referred to as braking segments.

It works by taking in the following input parameters;

The grade (%) and corresponding length (miles) of each segment composing the downgrade, maximum truck weight (lb), speed limit (mph), maximum brake temperature (500˚F or 530˚F), initial brake temperature at top of first segment (˚F), and ambient temperature (˚F).

The algorithm does the following;

(1) Starting from the maximum truck weight,

Test speeds from 1 mph to Maximum speed (speed limit) in 1 mph increments.

Using the equations above (1-9),

At each speed, compute the temperature at the bottom of each successive segment starting from the first.

The final temperature at the bottom of the segment becomes the initial temperature for the next segment.

Repeat the process until the bottom of the last segment at the end of the downgrade.

Print out the results below based on equations (1-9) for each iteration of speed.

(a) Weight, Speed, Temperature at bottom of downgrade, Time to descend downgrade.

(2) Repeat the process in step (1) for each successive decrement in truck weight by 5000 lb until 0 lb.

Print out the results below based on equations (1-9) for each iteration of speed.

(a) Weight, Speed, Temperature at bottom of downgrade, Time to descend downgrade.

To determine maximum safe speeds for each truck weight (fastest speed, which the truck can descend the downgrade without exceeding maximum temperature limit or speed limit), 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.
(b) At each weight level, determine the row with maximum corresponding speed. Eliminate all others.
(c) As soon as the weight with a maximum allowable speed equal to speed limit, eliminate all rows beneath.

This last step is necessary because it can be assumed every lower weight category can travel at the speed limit and will be safe.

The algorithm also computes at 0.5-mile intervals along with downgrades, the weight, speed, 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.

(B) Separate slope/downgrade method

This method works for downgrades, which have upgrades or level segments longer than 0.5 miles interspersed with downgrade segments. This is referred to as a multigrade. Since the driver does not need to control the speed of the truck due to acceleration from gravity, he/she does not engage the braking system, and thus upgrades or level segments are referred to as non-braking segments. This is because it is the application of brakes that lead to temperature increases, brake fade, and ultimately truck runaway and crashes.

For this method, in addition to the input parameters requested in the continuous grade method, the algorithm requests for the number of grades in the multigrade as well.

The algorithm does the following;

First 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 does the following;

(1) Starting from the maximum truck weight,

Test speeds from maximum speed (speed limit) to 15 mph in 5 mph decrements.

Using the equations above (1-9),

At each speed, compute the temperature at the bottom of each successive segment, starting from the first.

The final temperature at the bottom of each segment becomes the initial temperature for the next segment.

Repeat the process until the bottom of the last segment at the end of the downgrade.

Print out the results below based on equations (1-9) for each iteration of speed.

(a) Weight, Speed, Temperature at bottom of downgrade, Time to descend downgrade.

The algorithm allows the results to be filtered to eliminate all rows with the associated temperature at the bottom of the downgrade exceeding the temperature limit (500˚F or 530˚F).

The next objective is to minimize travel time, so the algorithm further filters the above results for the row with the minimum time of descent and selects the associated temperature of descent. It then uses it as the initial temperature for the next group, provided the temperature is above 90˚F, or else it simply assigns 90˚F. This is due to technical reasons associated with the experiments performed to derive the equations.

Next, the group are upgrades; (0% grades with associated length)

The algorithm for this method is similar to that for the continuous grade method and does the following, which is similar to A (1);

(2) Starting from the maximum truck weight,

Test speeds from 1 mph to Maximum speed (speed limit) in 1 mph increments.

Using the equations above (1-9),

At each speed, compute the temperature at the bottom of each successive segment starting from the first.

The final temperature at the bottom of each segment becomes the initial temperature for the next segment.

Repeat the process until the bottom of the last segment at the end of the downgrade.

Print out the results below based on equations (1-9) for each iteration of speed.

(a) Weight, Speed, Temperature at end of upgrade/level section, Time of travel.

(3) Repeat the process in step (2) above for each successive decrement in truck weight by 5000 lb until you get to 0 lb.

Print out the results below based on equations (1-9) for each iteration of speed.

(a) Weight, Speed, Temperature at bottom of downgrade, Time to descend downgrade.

To determine maximum safe speeds for each truck weight, the algorithm filters the results through the following stages;

(a) Eliminate all rows with final temperatures greater than maximum specified temperature.

(b) At each weight level, determine the row with maximum corresponding speed. Eliminate all others.
(c) As soon as the weight with the maximum allowable speed equal to the speed limit, eliminate all rows beneath.

Thus, depending on when the maximum speed limit can be attained, a few to several weight categories and their respective parameters can be printed. Following this, the algorithm prompts for selection of the first row, which is the row, which prints out the maximum weight of the truck with associated maximum speed, the temperature at the end of the grade, and time of travel. Then the algorithm assigns the temperature at the end of the downgrade to the initial temperature for the next grade (provided temperature is above 90˚F, it assigns the full value, or else it simply assigns 90˚F for technical reasons). Next, it prompts one to enter segment lengths and grades for the upgrade (since the next grade is a non-braking segment) and performs calculations for the upgrade as illustrated in B (2)

Process continuously until the maximum number of grades in multigrade is exceeded, 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 Figure 1, Figure 2, and Figure 3.

Figure 1: Process flow chart for continuous slope method

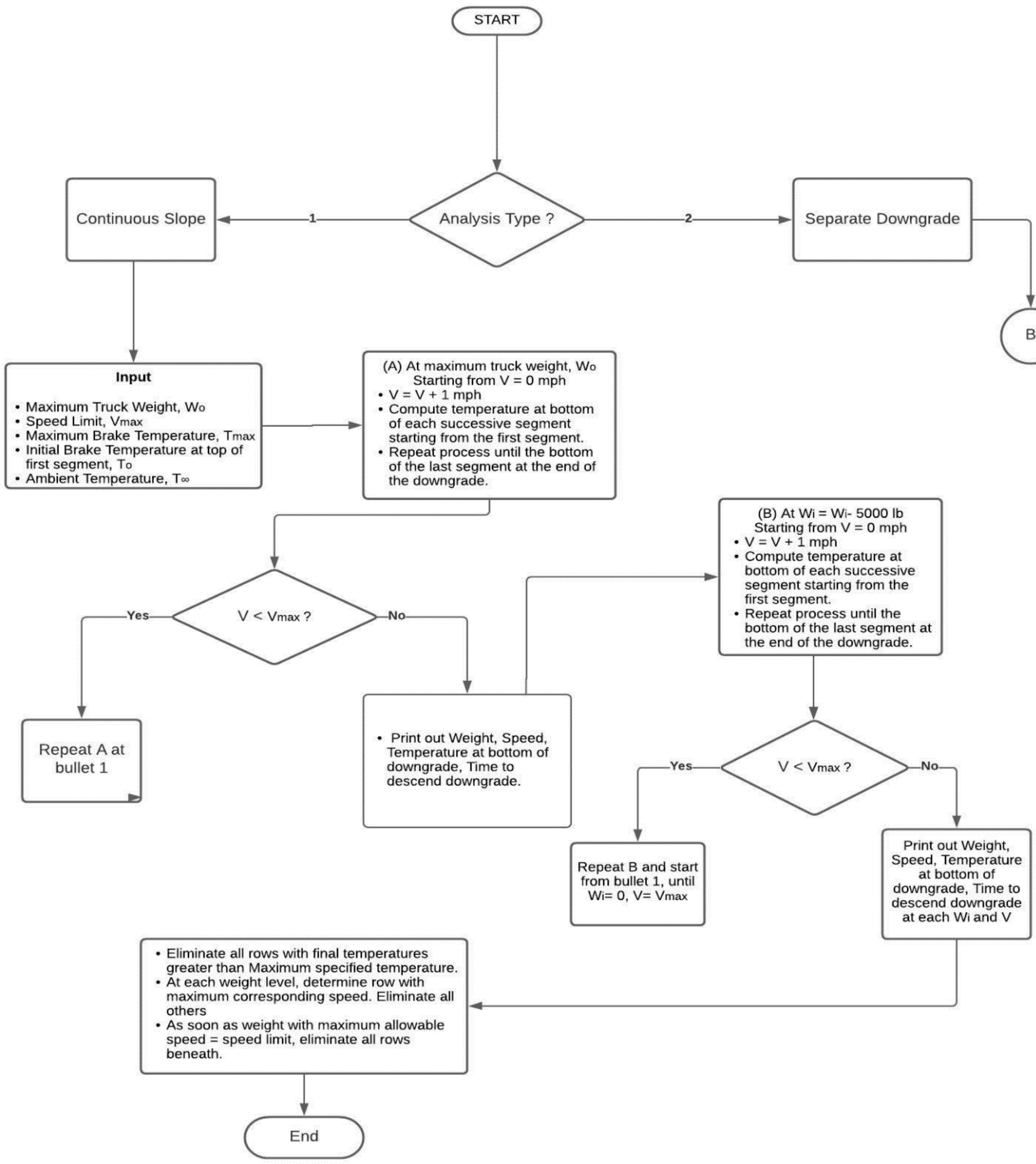


Figure 2: Process flow chart for braking group of segments for separate downgrade method

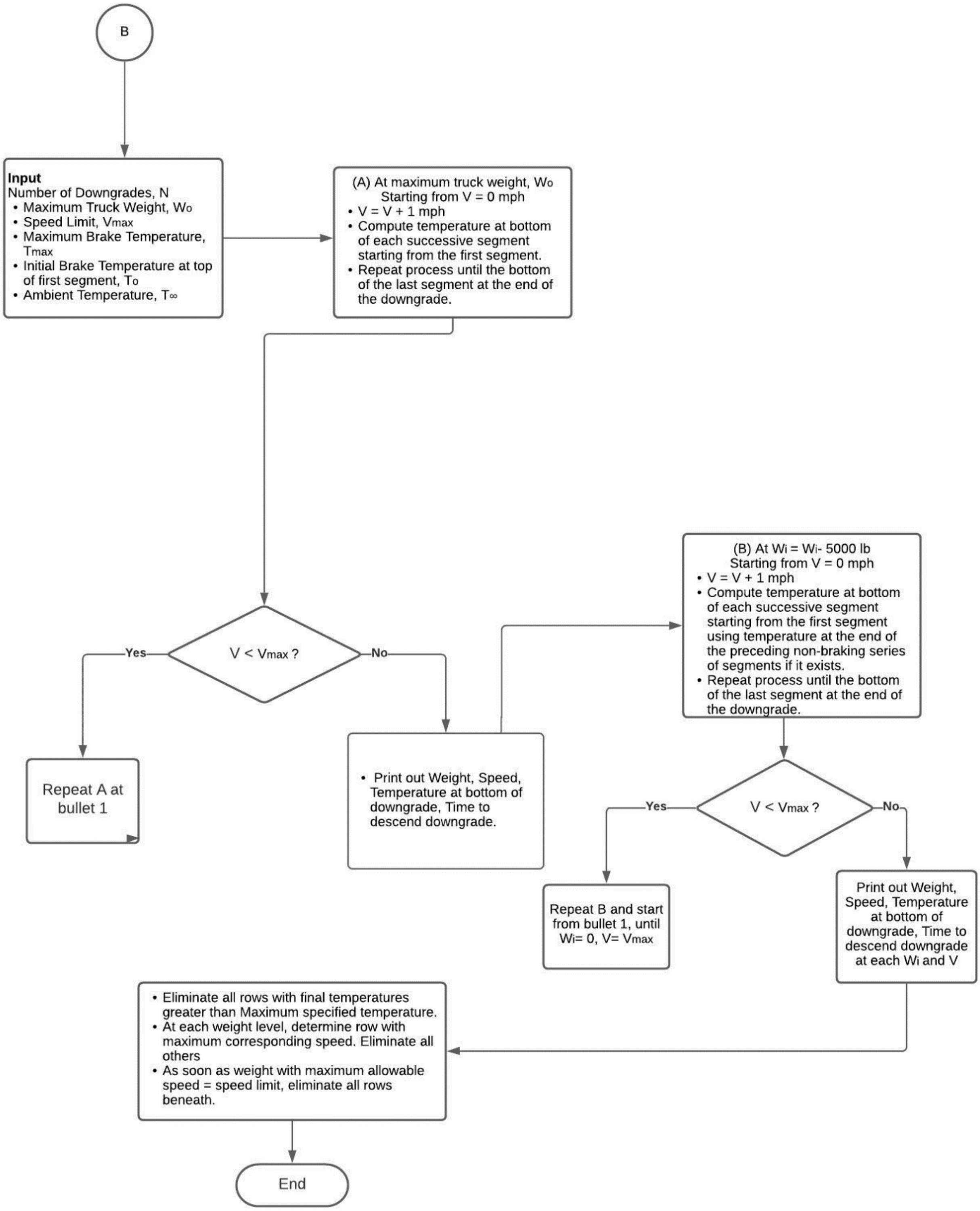
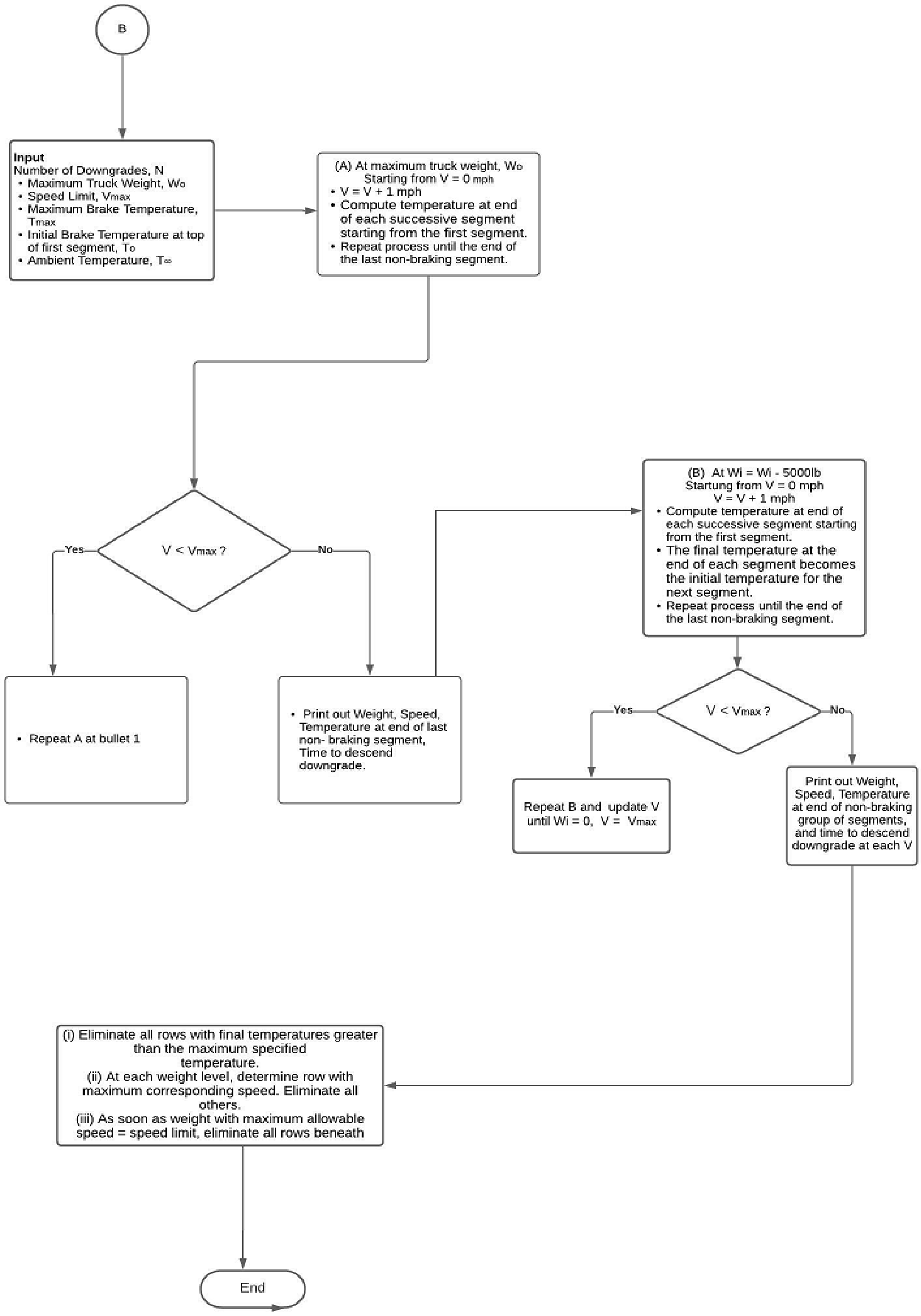


Figure 3: Process flow chart for a non-braking phase of separate downgrade method



4. Results and discussion

To proceed with the results and discussions, screenshots of various phases of the software execution are presented and discussed. The format for this discussion is patterned after similar software in various scientific fields (Di Nucci et al., 2017, Sharma & Khandait, 2016; Yang & Zhou, 2012).

Figure 4 shows the continuous slope analysis option of the GSRS software illustrating input parameters; the number of segments in the downgrade, maximum temperature, maximum weight of the truck, maximum descent speed (speed limit), initial temperature, ambient temperature, and the various grades and lengths of the segments comprising the downgrade. The output illustrates the maximum speed of descent and the final temperature at the bottom of the downgrade for various maximum weight categories.

Figure 4: Continuous slope analysis option of the GSRS

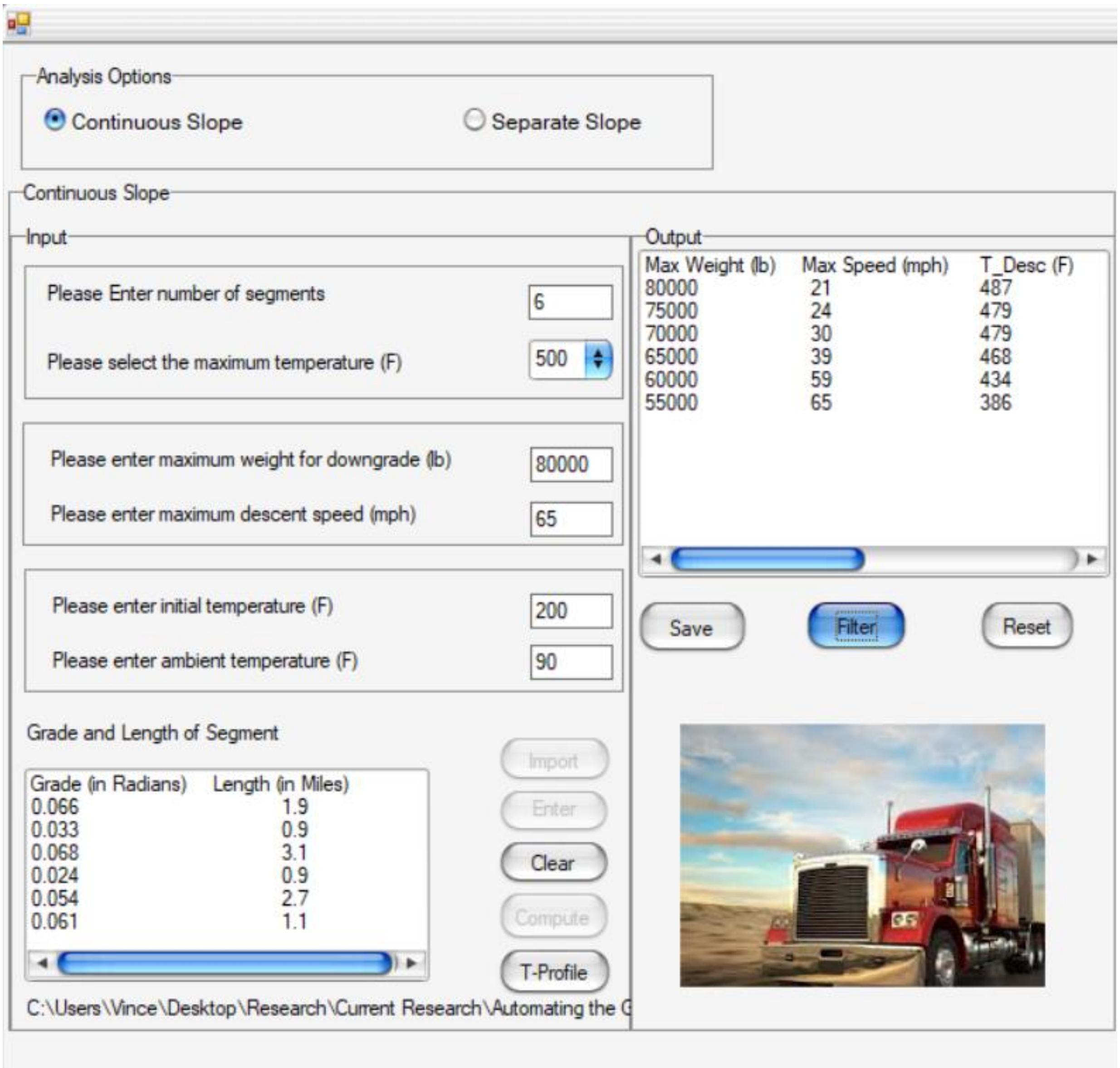


Figure 5 shows the temperature profile of the brake temperature at 0.5-mile intervals along with the downgrade as well as a plot of the results. The red line on the graph indicates the maximum brake temperature.

Figure 5: Temperature profile and plot along the downgrade

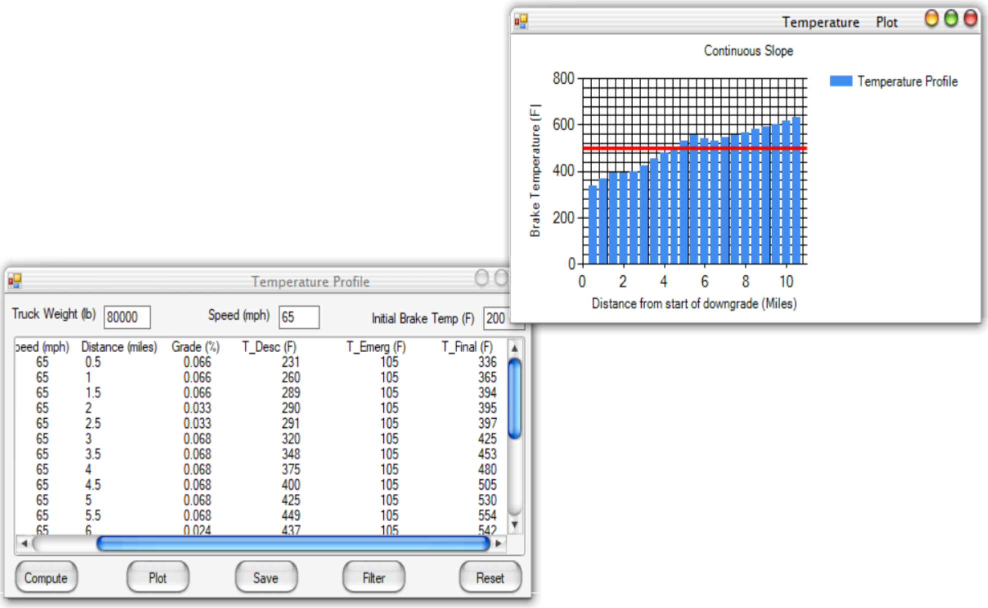


Figure 6 shows the input parameters for the separate downgrade method and outputs the maximum speed, temperatures, and time of travel for an 80,000 lb truck for a typical braking downgrade of the multigrade.

Figure 6: Separate downgrade analysis option: Braking phase

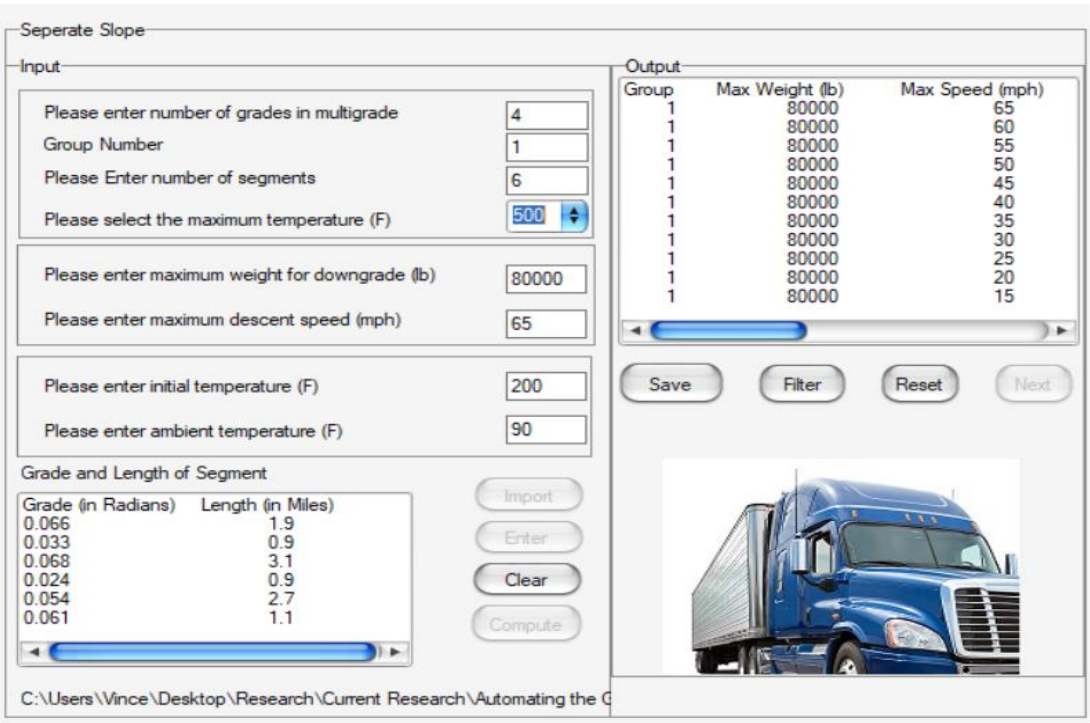
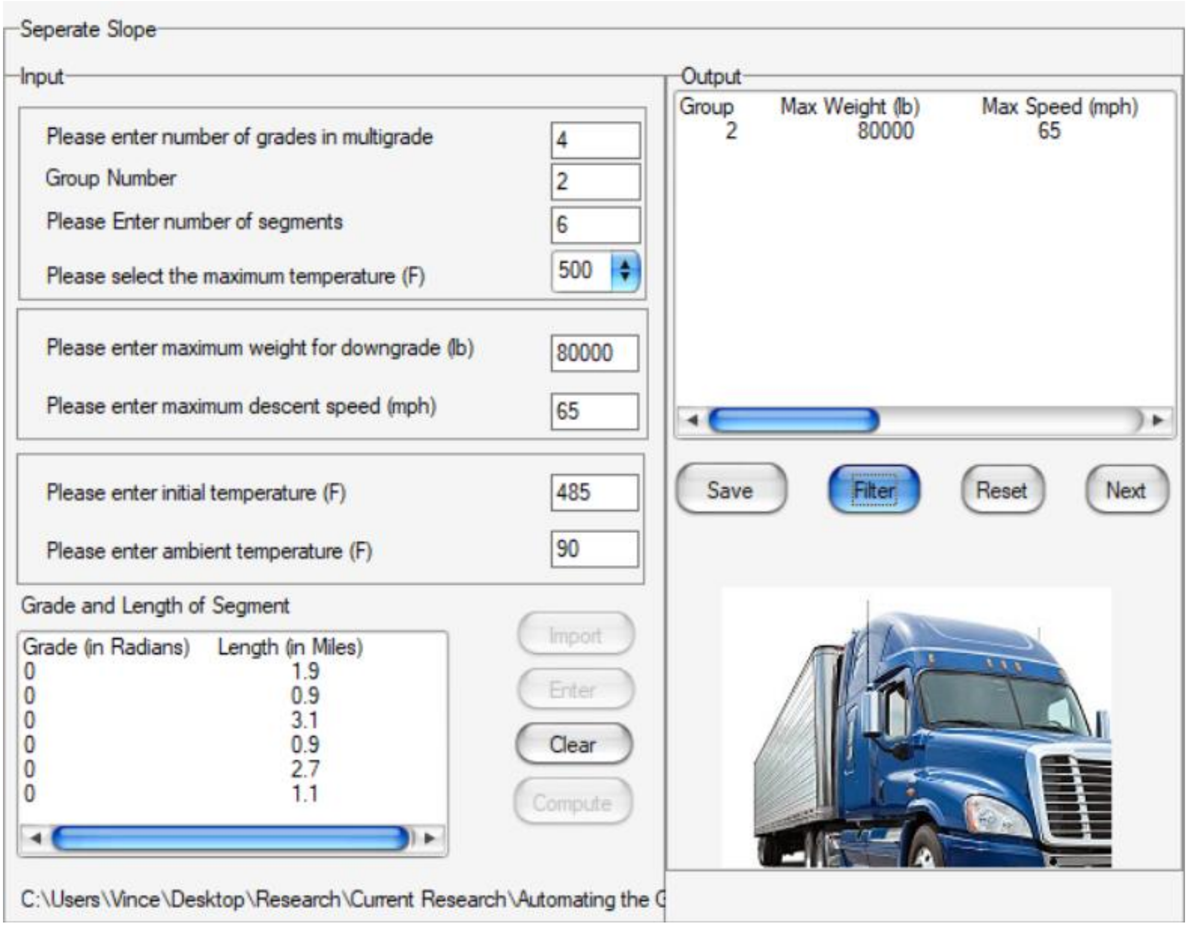


Figure 7 shows the input parameters for the separate downgrade method and outputs the maximum speed, temperatures, and time of travel for an 80,000 lb truck for a typical non-braking downgrade of the multigrade.

Figure 7: Separate downgrade analysis option: non-braking phase

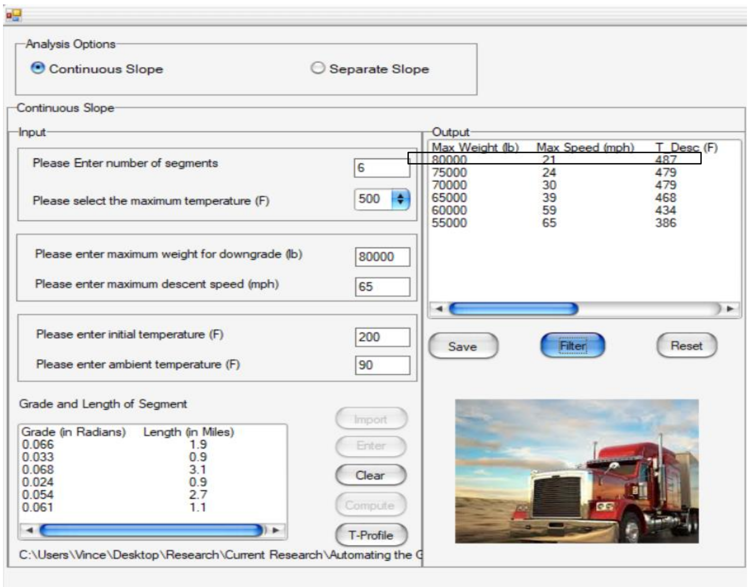


Based on recommendations from the literature review, validating the test results are essential. For validation, an excel sheet programmed with all the relevant equations is presented to output a single scenario of the relevant parameters of the continuous slope method with the input variables indicated in Figure 8. A screenshot of the output of the continuous slope method from the software showing both input and output confirming the results of the excel sheet is also included in Figure 9

Figure 8: Validation of temperature of descent for a scenario of the continuous downgrade method (Excel calculations)

W					80000	
T_o					200	
T_∞					90	
V					21	
HP_{eng}					63.3	
$F_{drag} = 459.35 + 0.132V^2$					517.562	
$K_1 = 1.5x(1.1852 + 0.0331V$					2.82045	
$K_2 = (0.1602 + 0.0078V)^{-1}$					3.08642	
$T_E = 3.11 x 10^{\wedge} - 7WV^2$					10.97208	
$\theta =$	0.066	0.033	0.068	0.024	0.054	0.061
$L =$	1.9	0.9	3.1	0.9	2.7	1.1
$HP_B = (W\theta - F_{drag})\frac{V}{375} - HP_{eng}$						
$HP_B =$	203.3965	55.5565	212.3565	15.23653	149.6365	180.9965
$T_f = T_o + [T_\infty - T_o + K_2 HP_B][1 - e^{-K_1 L/V}]$						
$T_f =$	316.6145	310.336	458.5052	421.9027	461.4242	487.1358

Figure 9: Output for continuous slope method of analysis highlighting maximum weight, maximum speed, and temperature of descent (validating Figure 8)



5. Conclusions

Steep downgrades present significant challenges to trucks because they often result in excessive brake heating, brake fade, and truck runaway. Crashes on downgrades not only lead to mortality, injury, and property damage, but seriously affect the GDP of the state and nation due to associated costs. A mathematical model was developed in the 1980's to determine maximum safe descent speeds, and an IBM console application was developed based on the model. In recent years, WYDOT funded research experiments to update the model to account for the new truck and environmental characteristics. Most recently, it commissioned a research project to automate this latest version of the mathematical model through an interactive, intuitive, aesthetically appealing, and user-friendly objected-oriented program to simplify the computation of the maximum safe descent speed on these downgrades based on the truck weight. The software provides functionality for the continuous slope method and the separate downgrade method. Practically, it will enable engineers at WYDOT and other highway agencies to easily estimate the maximum safe speed of descent for various weight categories and hence produce WSS signs for each downgrade or multigrade section.

6. Recommendation

Currently, the software does not account for the influence of horizontal curves along with the downgrade. The third phase of this research project is thus recommended to incorporate the influence of horizontal curvature and roadway geometry into the mathematical model and then into the automated GSRS. This will enable accounting for vehicle stability, rollovers, and skidding/side slip specifically on these combined downgrades.

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Author contributions

The authors confirm contribution to the paper as follows; Study conception and design: K. Ksaibati, Vincent Ampadu; Software development: Vincent Ampadu; Analysis and interpretation of results: Vincent Ampadu; Draft manuscript preparation: Vincent Ampadu, K. Ksaibati. All authors reviewed the results and approved the final version of the manuscript.

Declaration of interest statement

No potential conflict of interest is reported by the authors.

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