The Capability and Enhancement of VDANL and TWOPAS for Analyzing Vehicle Performance on Upgrades and Downgrades Within IHSDM

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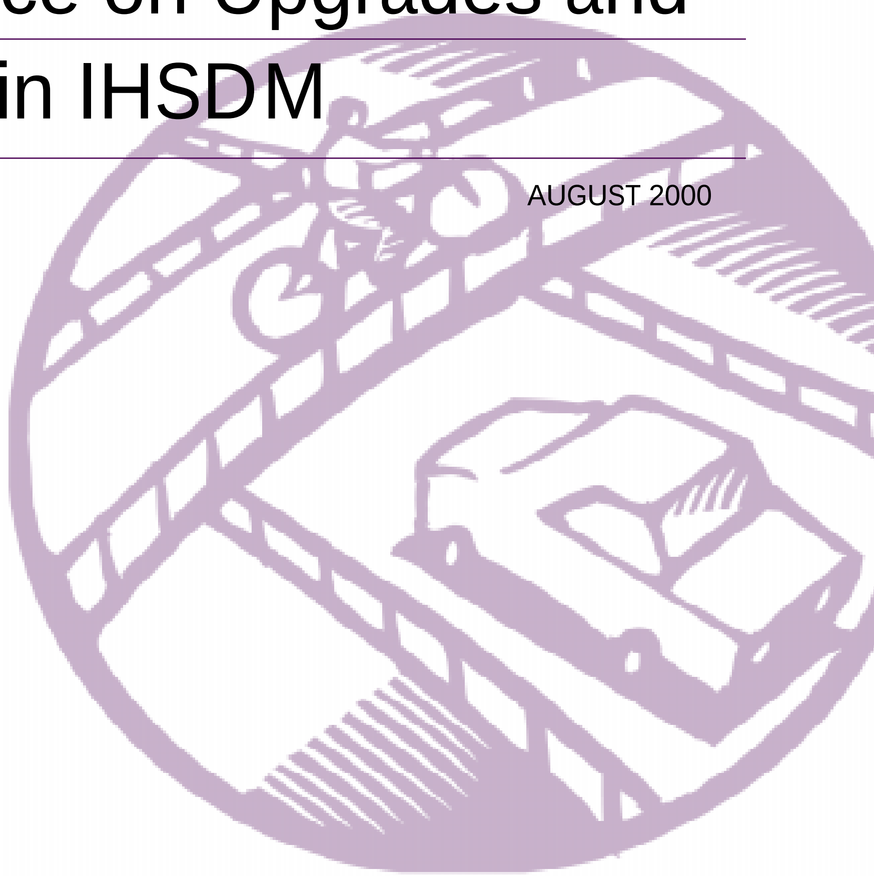

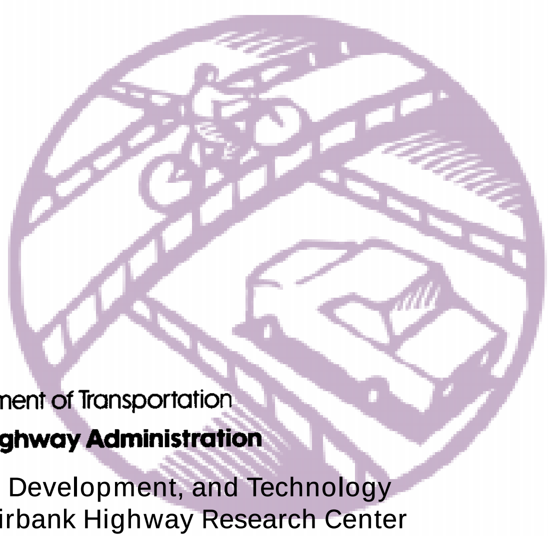

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FOREWARD

This report documents the results and recommendations for defining and analyzing "Vehicle Performance on Upgrades and Downgrades" on two lane rural roads. The contract objective was to develop functional requirements (and identify gaps) to enhance the capability of the Interactive Highway Safety Design Model (IHSDM) in evaluating vehicle operations on upgrades and downgrades, and to provide outputs useful for evaluating grade steepness and the location and design of climbing lanes and emergency escape ramps. The analysis procedures involve the use of two simulation programs: VDANL, a vehicle dynamics simulation; and TWOPAS, a traffic flow simulation. This report includes recommendations for the best approach for applying both VDANL and TWOPAS, the planned improvements to the programs, and data collection and research needed for software enhancement, calibration, verification and validation. Case studies of an example upgrade and downgrade are also included to help support the recommended enhancements.

This report gives a reasonably comprehensive review of the current capabilities of VDANL and TWOPAS, and discusses relevant literature that might have some impact on future upgrades. Upgrade and downgrade test cases are included that demonstrate the current capabilities of VDANL and TWOPAS, and also highlight areas that need upgrading in order to give a more comprehensive capability for evaluating upgrade and downgrade designs. Enhancements are recommended for VDANL and TWOPAS in order to allow a comprehensive evaluation of rural, two lane upgrades and downgrades. Research needs are also cited that will help to fill in current gaps in our modeling capability.

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16. Abstract **This report documents the results and recommendations for defining and analyzing "Vehicle Performance on Upgrades and Downgrades" on two lane rural roads. The contract objective was to develop functional requirements (and identify gaps) to enhance the capability of the Interactive Highway Safety Design Model (IHSDM) in evaluating vehicle operations on upgrades and downgrades, and to provide outputs useful for evaluating grade steepness and the location and design of climbing lanes and emergency escape ramps. The analysis procedures involve the use of two simulation programs: VDANL, a vehicle dynamics simulation; and TWOPAS, a traffic flow simulation. This report includes recommendations for the best approach for applying both VDANL and TWOPAS, the planned improvements to the programs, and data collection and research needed for software enhancement, calibration, verification and validation. Case studies of an example upgrade and downgrade are also included to help support the recommended enhancements.**		
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I. INTRODUCTION

This report documents the results and recommendations derived from our work on Tasks A-D of FHWA contract DTFH61-98-F-00364 “Vehicle Performance on Upgrades and Downgrades.” These tasks include: A – Critical Review of Literature; B – Review IHSDM Component Models (VDANL, TWOPAS); C – Develop Functional Requirements; D – Document Results. The contract objective was to develop functional requirements (and identify gaps) to enhance IHSDM’s capability in evaluating vehicle operations on upgrades and downgrades, and to provide outputs useful for evaluating grade steepness and the location and design of climbing lanes and emergency escape ramps. This report includes recommendations for the best approach for applying both VDANL and TWOPAS, the planned improvements to the programs, and data collection and research needed for software enhancement, calibration, verification and validation. Case studies of an example upgrade and downgrade are also included to help support the recommended enhancements.

This report summarizes a review and assessment of the state of knowledge of vehicle performance capabilities and techniques for modeling vehicle operations on upgrades and downgrades. The emphasis is on truck operations, but recreational vehicles and other vehicle types influenced by upgrades and downgrades are considered in the review and analysis. The applicability of the VDANL and TWOPAS models to evaluating vehicle performance on grades, and alternative road improvements, such as climbing lanes and emergency escape ramps, are assessed along with proposed needed enhancements. A key element of the research is in comparing how VDANL and TWOPAS model vehicle performance and recommending ways of bringing the representation of vehicle performance in the two models closer together. As will be developed herein, TWOPAS is recommended primarily for upgrade analysis where power and speed capability are limiting factors, while VDANL is recommended for downgrade analysis where runaway due to brake fade and rollover on horizontal curves are critical issues.

II. BACKGROUND AND OVERVIEW

The FHWA is currently developing a set of interactive computer tools for highway designers collectively known as the Interactive Highway Safety Design Model (IHSDM). IHSDM is intended to provide a means for highway designers to explicitly consider the safety consequences of highway design decisions [1]. The IHSDM consists of five modules: Design Consistency (DCM), Driver/Vehicle (D/VM), Accident Analysis (AAM), Policy Review (PRM), and Traffic Analysis (TAM). The first stage of IHSDM development is addressing rural two-lane highways.

This project concerns enhancement of the D/VM and TAM components to create a new analysis tool for upgrade and downgrade operations. The D/VM includes a vehicle dynamics module known as VDANL-IHSDM [2] that represents driver and vehicle performance for 12 AASHTO design vehicles. The TAM for rural two-lane highways is a microscopic simulation model of two-lane highway traffic known as TWOPAS [3]. Both VDANL and TWOPAS model vehicle operations on upgrades and downgrades, but do so in different fashions since the two models have been developed independently. The capabilities of both VDANL and TWOPAS will need improvement in order for the IHSDM to address all issues of interest. Also, for IHSDM to function as an integrated model it would be desirable for the vehicle performance concepts in VDANL and TWOPAS to be brought closer together. This can be accomplished by evaluating the capabilities of both models to evaluate features of upgrades and downgrades including grade steepness, downgrade crawl regions, climbing lanes, and emergency escape ramp location and length, and recommending the best methods for applying the models and common modeling approaches that can be incorporated in each.

The next section (III) gives a review of highway design for upgrades and downgrades. This discussion sets the context for the need to improve the VDANL and TWOPAS simulation models so as to increase the functionality of the IHSDM. This section also presents recommended methodologies for upgrade and downgrade analysis. Section IV reviews the capabilities of the VDANL and TWOPAS models and the potential needs for improvements. Additional capabilities are also reviewed in Appendices A and B. Section V presents case studies that reveal the current capability of VDANL and TWOPAS. Section VI then proposes future enhancements to VDANL and TWOPAS that will allow the complete upgrade and downgrade analysis discussed in Section III. Functional specification for software enhancements to allow the upgrade analysis discussed here is given in Appendix C, while functional specification for software enhancements to allow the downgrade analysis discussed here is presented in Appendix D. Research requirements due to the suggested model enhancements are then reviewed in

Section VII. Finally, in Appendix E a model is summarized that is critical for gear and speed selection in heavy truck downgrade operations.

III. HIGHWAY DESIGN FOR UPGRADES AND DOWNGRADES

A. OVERVIEW

This section summarizes current highway design procedures and considerations for upgrades and downgrades. The section also includes a discussion of potential methodologies for improving the design process for upgrades and downgrades. An analysis methodology upgrades is researched based on established AASHTO criteria. A largely new analysis methodology for downgrades is based on the analysis presented in Refs. [4]-[6] and in Appendix E, and the analysis capability of VDANL to model brake fade and rollover on horizontal curves.

B. MAXIMUM AND MINIMUM GRADES

The steepness of grades used in the design of vertical alignment is strongly influenced by the topography being traversed. Grades are likely to be progressively steeper in level, rolling, and mountainous terrain, respectively. Maximum grades have been established by design policies for various design situations, but the actual grades may exceed these maximums based on constraints of topography and cost.

Unlike other geometric features, the maximum grade on a roadway is not strongly related to the roadway design speed. While design speed is a consideration, the functional classification and desired operating conditions for the roadway also play a role. There are not separate criteria for maximum grades of upgrades and downgrades because, on an undivided highway, where traffic in one direction of travel experiences an upgrade, traffic in the other direction of travel experiences a downgrade of the same length and percent grade. On divided highways, the roadways in opposite directions of travel may have independent alignments, but the net change in elevation for both roadways between given points must be the same, so both roadways are likely to have similar grades.

Design guidelines for the Interstate highway system generally set a maximum grade of 3 percent, with grades up to 6 percent permitted in rugged terrain. The AASHTO *Policy on Geometric Design for Highways and Streets* [7], known as the Green Book, specifies a maximum grade of 5 percent for roadways with a design speed of (113 km/h). For a design speed of (48 km/h), the Green Book states that maximum grades are generally in the range from 7 to 12 percent, with an average of about 8 percent.

Control grades for roadways with 40-, 50-, and 60-mph design speeds would be between the values quoted above.

In general, very steep grades are rare on the U.S. highway system and occur only where topography dictates. A recent analysis of the FHWA Highway Performance Monitoring System (HPMS) data base found that grades steeper than 6.4 percent constitute only 1.4 percent of the total mileage of rural two-lane highways, 1.4 percent of rural multilane highway mileage, 0.8 percent of urban arterial mileage, 0.2 percent of rural freeway mileage, and 0.2 percent of urban freeway mileage.

The AASHTO Green Book also establishes minimum grades for use in roadway design. These minimum grades are needed for drainage reasons (i.e., to promote the flow of water off the pavement and to reduce the potential for ponding of water in flat spots on the roadway). These minimum grade criteria are generally irrelevant to traffic operations and safety of the roadway except as they pertain to the drainage issue discussed above.

C. DESIGN CONSIDERATIONS FOR UPGRADES

Beyond the maximum grade criteria presented above, design considerations for upgrade focus on the effect of the grade on the speed of heavy trucks and the effect of reduced truck speeds on the rest of the traffic stream. Figure III-25 (A) of the AASHTO Green Book [7], presented here as Figure 1, shows speed profile curves for a 180-kg/kW (300-lb/hp) truck ascending upgrades of various specified percent grades. A designer can use data of this sort to assess the speeds at which trucks will operate on various grades. The figure shows that if a grade is long and steep enough a truck will reach a crawl speed from which it cannot accelerate, but from which it will no longer decelerate. Beyond this point, unless the grade steepens, the truck will be able to continue up the grade at constant speed.

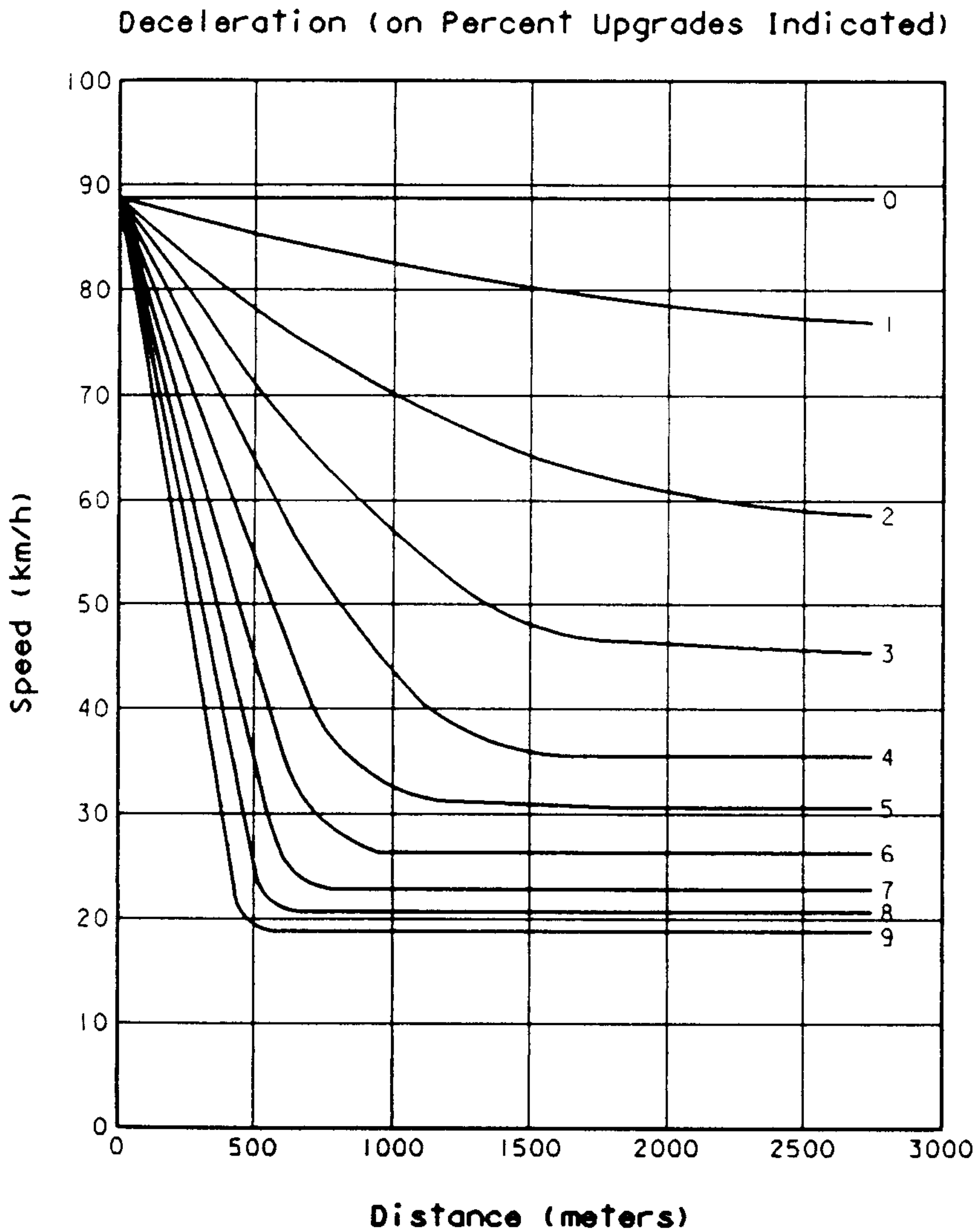


Figure 1. Speed Profile Curves for a 180-kg/kW (300-lb/hp) Truck Ascending a Grade as a Function of Length and Steepness of Grade

The AASHTO Green Book [7] states that maximum grade alone is not a complete design control and that a critical length of grade based on truck operations should be considered as well. The length of a grade to be analyzed is generally the length of the tangent grade (i.e., the portion of the grade with constant percent grade). However, when vertical curves with large algebraic differences in grade are present, about one-quarter of the length of each vertical curve may be included in the length of the grade. The Green Book [7] defines the critical length of grade as that length which will result in the speed of a truck being reduced by 15 km/h below the average running speed of all traffic. It is generally assumed that the average speed of all traffic on the grade is equal to the speed of the truck at the foot of the grade. Figures III-29 from the AASHTO Green Book [7], presented here as Figure 2, shows the maximum speed reduction of a 180-kg/kW (300-lb/hp) truck as a function of the length and steepness of the grade Figure 3, based on Green Book Figure III-30, shows comparable data for a recreational vehicle.

The procedures of Chapter 8 of the Highway Capacity Manual (HCM) [8] provide a means for assessing the traffic operational impact of the presence of trucks on a steep two-lane highway grades on the other traffic on the grade. From parameters including the percent grade, the length of the grade, and the mix of vehicle types on the grade, the HCM Chapter 8 procedures predict can predict the average upgrade speed for the mixed traffic stream. Similar operational analysis procedures for specific upgrades appear in HCM Chapter 3 for basic freeway segments and in HCM Chapter 7 for rural and suburban multilane highways. A new HCM edition will be published in the year 2000. The two-lane highway procedures are expected to change substantially in the new HCM, while the freeway and multilane highway procedures will not.

D. DESIGN CONSIDERATIONS FOR CLIMBING LANES ON UPGRADES

The AASHTO Green Book [7] states that three conditions and criteria, reflecting economic considerations, should be satisfied to justify a climbing lane:

1. Upgrade traffic flow rate in excess of 200 veh/hr for the peak 15-min of the design hour
2. Upgrade truck flow rate in excess of 20 veh/hr for the peak 15-min of the design hour
3. One of the following exists:
    - A speed reduction of 15 km/h or greater is expected for a typical heavy truck (i.e., the critical length of grade, as defined above, is exceeded).
    - Level-of-service E or F exists on the grade.
    - A reduction of two or more levels of service is experienced when moving from the approach segment to the grade.

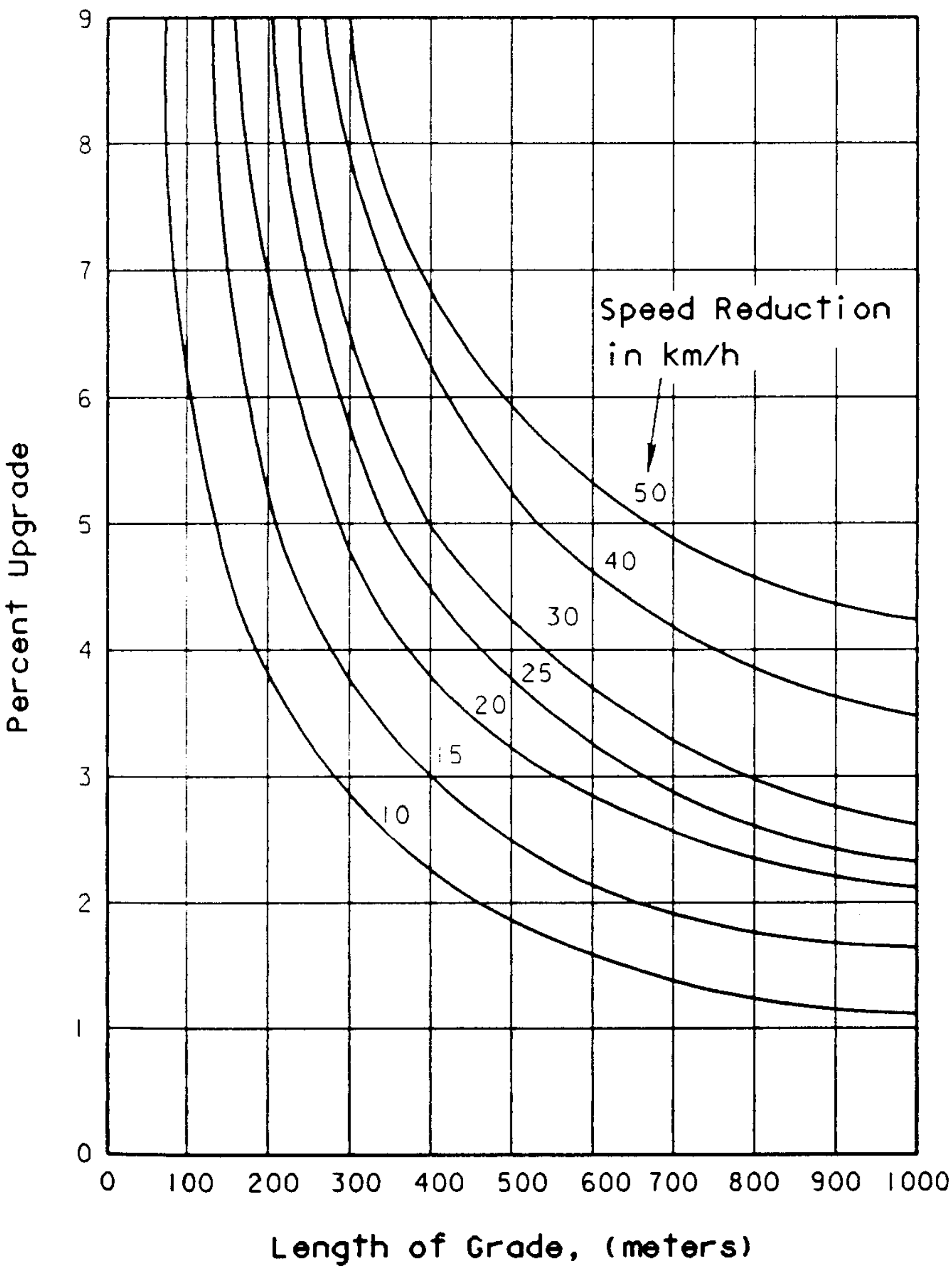


Figure 2. Maximum Speed Reduction of a 180-kg/kW (300-lb/hp) Truck as a Function of Length and Steepness of Grade

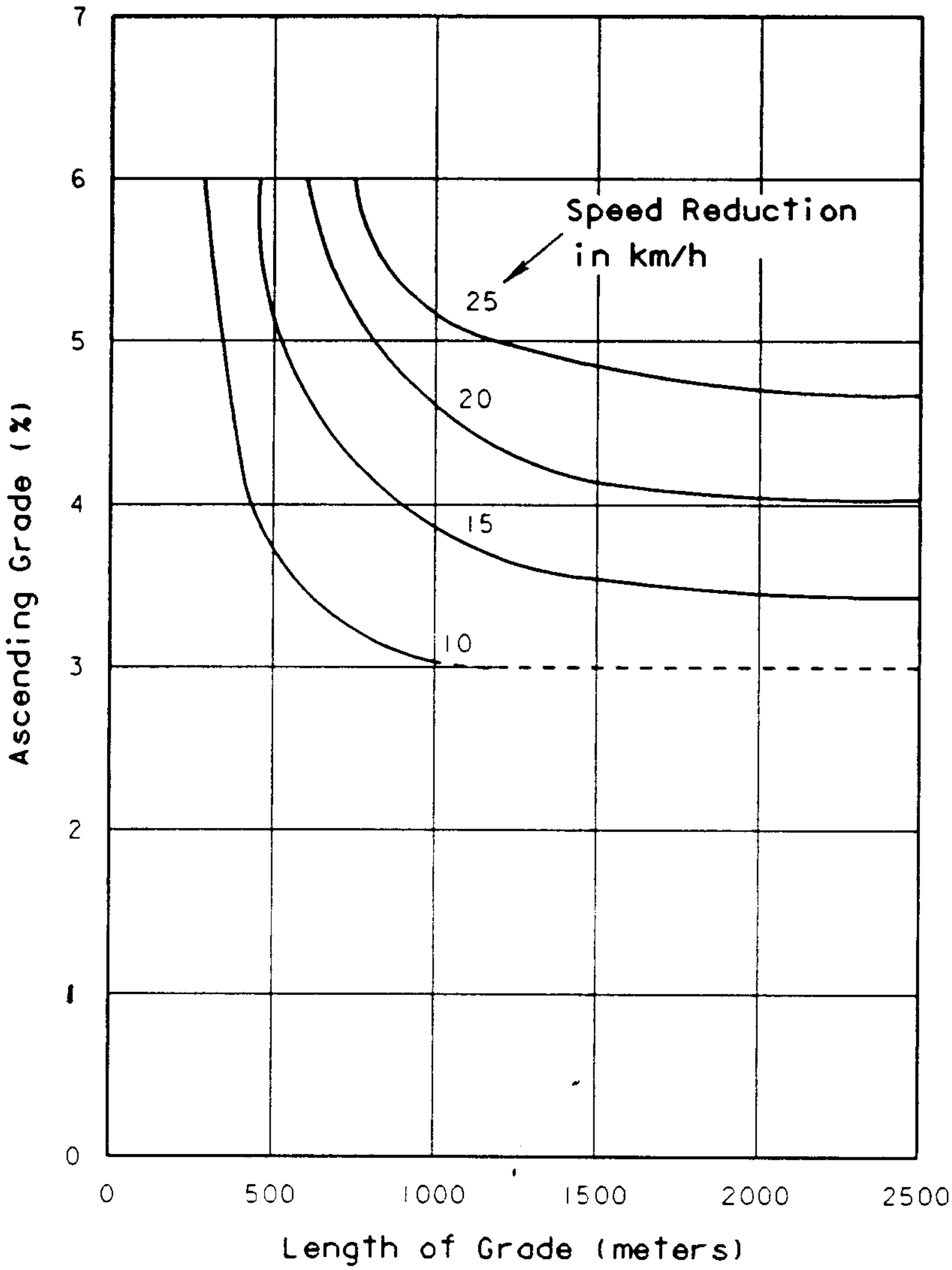


Figure 3. Maximum Speed Reduction of A Recreational Vehicle as a Function of Length And Steepness of Grade

E. POTENTIAL NEEDS FOR IMPROVEMENTS TO THE DESIGN OF UPGRADES AND CLIMBING LANES

There is a clear need for several improvements to the procedures for design of upgrades and climbing lanes. Potential problems or inconsistencies in the current procedures are as follows:

- The AASHTO Green Book [7] criteria for critical length of grade are extremely conservative, because they are based on the 180-kg/kW (300-lb/hp) truck used to derive Figure 1 and Figure 2. There was a time prior to 1960 when 180-kg/kW (300-lb/hp) trucks were very common on U.S. highways, but truck engine horsepower's have increased dramatically. The Green Book states that the average weight-to-power ratio of trucks on U.S. highways had fallen to about 80-kg/kW (130-lb/hp) by 1985. Trucks with weight-to-power ratios over 120 kg/kW (200 lb/hp) have become rare except for transportation of raw materials over short distances. Still further power improvements may have occurred since 1985. It would be desirable to base the determination of critical length of grade, and the warrants for climbing lanes, on a current truck population.

- Truck populations vary substantially from one road to another. There are some roads -- for example sites with coal trucks -- where use of a truck with a weight-to-power ratio of 180 kg/kW (300 lb/hp), or even higher, is needed. Thus, it would be desirable to be able to use a site-specific truck population for the design of upgrades and climbing lanes.

- The HCM [8] operational analysis procedures for two-lane highways are based on average upgrade speed as the level-of-service criterion, while the procedures for general terrain segments is based on percent time spent following. Consequently, it is possible for the level of service on an extended upgrade to be better than a preceding general terrain segment carrying the same traffic. This makes it difficult to apply the AASHTO Green Book criterion concerning a reduction of two or more levels of service when moving from the approach segment to the grade. This problem can be fixed by using the same level-of-service criteria for both general terrain segments and upgrades. This change is expected to be made in the new edition of the HCM to be published in the year 2000.

- The current HCM [8] does not contain operational analysis procedures for assessing the level of service of an upgrade on a two-lane highway with a climbing lane in place. This problem is expected to be addressed in the new edition of the HCM to be published in the year 2000. The chapter should include procedures to assess the effect of a climbing lane on both percent time spent following and average travel speeds.

F. PROPOSED METHODOLOGY FOR ANALYSIS OF UPGRADES IN IHSDM

This section presents a methodology for the analysis of upgrades in IHSDM. The methodology is largely based on the climbing lane criteria presented in the AASHTO Green Book (see Items 1 through 3 above in Section D). These criteria seem satisfactory and incorporate the key variables that define the traffic operational performance of a grade: the volumes of traffic and heavy vehicles (particularly trucks), the speed reduction for a typical heavy truck, and the level of service of the approach roadway and the grade. However, the methodology as implemented in IHSDM will be much more flexible than is possible with the current manual procedure based on graphs presented in the Green Book. The key elements of flexibility that will be provided in the IHSDM methodology are:

- the IHSDM user will be able to select the typical heavy truck that is suitable for analysis of particular grades and will not be constrained to use the 180-kg/kW (300-lb/hp) truck which forms the basis for the charts in the AASHTO Green Book. Today's truck fleet generally has weight-to-power ratios much lower than 180 kg/kW (300 lb/hp), although weight-to-power ratios of 180 kg/kW (300 lb/hp) or greater may be suitable for some specific sites, such as those used predominantly for bulk-haul trucks (e.g., coal trucks).

- the IHSDM user will be able to specify the approach speed of the truck (i.e., the speed at which the truck will enter the bottom of the grade). Thus, the methodology will not be constrained to the 89-km/h (55-mi/h) entry speed assumed in the charts in the AASHTO Green Book.

- the analysis will be conducted for the actual alignment of the upgrade roadway (vertical *and* horizontal), not merely for an upgrade specified by given percent grade and length of grade. In other words, there will be no need to approximate the actual alignment (or proposed alignment) by a single equivalent grade.

The upgrade analysis methodology will be implemented as follows:

Step 1 - Select a suitable truck for use as the design vehicle for upgrade analysis.

Step 2 - Determine the speed profile for the selected truck on the actual upgrade alignment and calculate the speed reduction of the truck as the difference between the truck entry speed at the foot of the grade and the minimum truck speed at any point on the grade.

Step 3- Assess the level of service on the approach to the upgrade.

Step 4 - Assess the level of service on the upgrade.

Step 5 - Apply the AASHTO criteria (see Items 1 through 3 in Section D above) and determine whether the addition of a climbing lane is warranted.

Step 6 - At the IHSDM user's option, reassess the level of service on the upgrade with a climbing lane in place at a location specified by the user.

Appendix C of this report provides a functional program specification for implementing the upgrade analysis methodology in IHSDM. It is recommended that an upgrade analysis software package be developed to implement the recommended methodology. This software package would serve as a user interface to request needed information from the user and present output reports to the user. The upgrade analysis software package would use the truck performance equations from TWOPAS to determine the truck speed profile on the upgrade. Both the VDANL model and the full TWOPAS model are more complex than is needed for this application. The TWOPAS truck performance equations provide a desirable approach because of their simplicity and because the primary parameter on which they are based is the truck weight-to-power ratio, which is the quantity that highway engineers have historically used to describe truck performance capabilities. The level-of-service assessments for the approach to the upgrade and to the upgrade itself, with and without climbing lanes, would be performed by using the TWOPAS model to assess percent time spent following and average travel speed and then applying the *Highway Capacity Manual* level-of-service definitions. It is recommended that the level-of-service definitions from Chapter 20 of the forthcoming Year 2000 edition of the *Highway Capacity Manual* be applied for this purpose.

G. DESIGN CONSIDERATIONS FOR DOWNGRADES

There are no formal design criteria for downgrades beyond the maximum grade criteria presented above. The major design considerations for long, steep downgrades deal with truck operations. On long, steep downgrades, truck drivers must descend the grade slowly to maintain control of their vehicle. If a speed that is too fast is chosen, the driver will need to apply the truck brakes frequently during the descent. This may lead to overheating of the brakes. Once the brakes become overheated, they are no longer effective in slowing the truck, so the truck may begin to gain speed and run away on the downgrade, out of the driver's control.

Two important design considerations for downgrades arise from the potential for runaway trucks. First, the use of slower speeds by trucks to descend a grade may delay other vehicles. Passing lanes can be provided on the downgrade to allow passenger cars and other vehicles whose speed is not constrained by the grade to pass the slow-moving trucks. Second, emergency escape ramps can be provided on the downgrade to provide a safe stopping place for runaway trucks. The truck driver can choose to steer into the emergency escape ramp, which is designed to bring their vehicle to a safe stop, rather than continuing down the grade with the potential to run off the road or collide with another vehicle. The design considerations are discussed below.

H. DOWNGRADE PASSING LANES

Upgrade highway design procedures are mature, and warrants for added climbing lanes are clearly stated and well known. Climbing lanes are used to reduce traffic delays that would otherwise occur if some trucks were slowed by the upgrade, and traffic volumes are sufficiently large.

If downgrades are steep enough and long enough, heavy trucks are advised to use a lower gear and use a crawl speed in order to maintain speed control without relying solely on the foundation brakes. Indeed, for 36,000 kg (80,000 lb) trucks, crawl speeds of 48kg/h (30 mph) and lower are recommended for many U.S. downgrades [4]-[6]. If traffic volumes were sufficiently large, vehicles trapped behind those using slow crawl speeds would experience significant delays. These delays could be greatly reduced if a downgrade-passing lane was added.

The AASHTO Green Book [7] addresses added passing lanes in general, but not specifically for downgrade crawl regions. It is recognized that conducting passing maneuvers on a downgrade is easier than on upgrades or on level terrain because gravity can assist the passing vehicle to accelerate. It is also true that many states permit downgrade vehicles to pass using the closest of the two upgrade lanes (where an upgrade climbing lane has been added) when no upgrade vehicles are present. Many other states do not allow this, however.

I. EMERGENCY ESCAPE RAMPS

The following discussion presents the need for and placement of emergency escape ramps and the design of the escape ramp itself.

Need for and Placement of Emergency Escape Ramps

There is relatively little available in the way of design guidelines for determining the need for and the placement of emergency escape ramps. Accident experience may provide some indication of the necessity of providing an escape ramp, but that is a corrective measure. Designing escape ramps during highway design is not routine. The Green Book [7] provides little guidance in this regard, other than to suggest that "an escape ramp should be provided as soon as a need is established. Unnecessary escape ramps should be avoided. For example, if an escape ramp is provided just before a sharp horizontal curve, a second ramp would not be required just beyond the curve that created the need for the initial ramp."

Probably the best analysis for determining when and where an escape ramp is needed is provided in the report of Abdelwahab and Morrall [9]. They go beyond the work on grade severity warning systems [4]-[6], which consider the length and steepness of the grade, and the weight of the truck. Abdelwahab and Morrall also include considerations of horizontal curves. They developed a model to simulate truck downhill speed and brake temperature. The model begins with specifying the vertical and horizontal alignments of the roadway to be examined. Two alternative scenarios are postulated: one, that the driver stops at the top of the grade at a brake test area, then begins the descent from zero speed; and two, that the driver does not stop but enters the beginning of the downgrade travelling at the truck speed limit. It is implied that for both cases the driver does not select the proper low gear but descends in high gear, and uses the brakes as the only means of controlling speed. (Later case example show that, for sufficiently long grades, the initial speed has little importance.)

The downgrade speed in [9] is calculated using a model developed by Stanley [10]. An equation is given that determines the truck speed as a function of distance from the top of the grade in terms of the initial speed, truck weight, frontal area, and slope of grade. It incorporates aerodynamic and friction losses, but assumes no braking. As the truck approaches a horizontal curve, the model determines the safe cornering speed for the truck on that horizontal curve. Braking is then initiated if necessary to reduce speed to the curve-limiting speed, and the brake temperature is determined based on research published by Bowman [11]. It is noted that an alternative would be to have the driver apply the brakes continuously on the downgrade, rather than coasting and then braking heavily on the final approach to the curve, but the work of Fancher et al. [12] shows that the choice of strategies makes little difference in the final brake temperature.

On the approach to each curve three conditions are evaluated:

1. Is the speed too high to allow safe cornering, so the truck must slow down (V)?
2. Is the brake temperature too high, indicating a loss in braking ability (T)?
3. Is there a fixed object, such as a house, that could be hit (J)?

Eight combinations of these three conditions, each being either no or yes, are tabulated:

Case	Escape Ramp Needed	Priority
All No	No	N/A
(V)	No	N/A
(T)	No	N/A
(J)	No	N/A
(V,J)	Yes	Low
(V,T)	Yes	Moderate
(T,J)	Yes	Moderate
(V,T,J)	Yes	High

Our opinion is that we agree, generally, with the authors' conclusions [9], but would suggest certain modifications. The (V J) case is rated low in priority for an escape ramp, with which we agree, but we would go further and say that under these conditions an escape ramp would not be needed at all because the truck brakes still would enable it to slow to a safe speed. On the other hand, we believe that the case (T) warrants an escape ramp, even if the truck's speed is low enough to enable traversing of the horizontal curve, because the truck is still vulnerable to overtaking and hitting slower vehicles. In fact, to generalize on the model, it might be appropriate to have the driver brake continuously as needed to maintain the speed of other traffic, and declare that an escape ramp is warranted when condition (T) is approached. The authors imply early in their paper that if the truck at any time can not come to a complete stop an accident might occur, but they do not carry this thought through in their modeling.

Design of Emergency Escape Ramps

Emergency escape ramps are provided as a means of slowing and stopping vehicles that have "run away" on long or steep downgrades. Run away occurs when its foundation brakes can no longer control a truck's speed and/or its engine drag. In normal circumstances it should not occur if the driver selects an appropriate lower gear so that engine braking may be employed along with the foundation brakes to control the speed of the truck. If a lower gear is not selected, or if the brakes are defective, truck run away may occur. If the driver is lucky, he will reach the bottom of the grade without incident, but running into a slower vehicle or rolling over on a horizontal curve could be possible outcomes of run away. Therefore, escape ramps are desirable.

The Green Book [7] provides much material on the design of these escape ramps, as does the paper of Ballard [13]. Emergency escape ramps should be designed to stop a truck travelling at its aerodynamics-limited speed of about 130 to 140 km/h, and assuming the truck has no brakes and is not in gear. The most common type of escape ramp is a bed of arresting material such as sand or pea gravel, to a depth of about 0.6

m or more. It should be wide enough to accommodate two runaway vehicles, as once a truck enters the bed of arresting material it normally can not exit without the assistance of a tow truck. Its length is dependent on the grade of the escape ramp, with a longer ramp being required if it is on a downgrade, rather than level or on an upgrade, where gravity can assist in slowing the truck.

Other types of escape ramps include sand piles, which have the disadvantage of providing too much deceleration, and gravity ramps, which are hard surfaced ramps on an upgrade. These use just the deceleration effects of gravity, but have the disadvantages of requiring a very long length, and also may result in the truck rolling backwards after it stops, since it has no brakes, and probably jack-knifing.

Escape ramps can be located on either side of the roadway, but the right side is preferred, and is the case for nearly all escape ramps in the U.S.

Potential Needs for Improvements to the Design of Downgrades

Potential needs for the improvement of procedures for the design of downgrades are as follows:

- There are currently no available guidelines for the design of passing lanes on downgrades and no analytical tools for assessing the improvement in traffic operations performance on a downgrade are in routine use. HCM [8] Chapter 8 does not address the traffic operational effects of passing lanes on downgrades, nor will its successor being prepared for the new version of the HCM to be published in the Year 2000.
- There currently is no reliable tool for evaluating the speeds of trucks on downgrades for use in evaluating the placement and design of emergency escape ramps.

Role of VDANL and TWOPAS in Design of Highway Upgrades and Downgrades

The VDANL and TWOPAS models both have potentially important roles in the design of highway upgrades and downgrades. These roles are discussed in this section of the report. The remainder of the report addresses the capabilities of these models in detail and the need for improvement of the models to better serve as highway design tools.

VDANL has the capability to simulate the speed profile of a single truck on a grade. Thus, VDANL could be used to determine whether a truck is slowed sufficiently to warrant provision of a climbing lane. However, VDANL has no capability to simulate climbing lane operations or compare levels of service on two-lane roadway upgrades with and without climbing lanes.

On downgrades, VDANL has the ability, with some extension, to simulate a truck speed profile and assess the effects of brake applications on brake temperature and potential runaway. This capability is essential to evaluating the need for trucks to slow to a crawl speed in advance of particular downgrades.

TWOPAS can simulate speed profiles of isolated trucks on upgrades, as well as the operational effects of trucks in mixed traffic. Thus, TWOPAS can be used to establish the extent to which any particular truck is slowed by the grade and to evaluate the level of service for upgrades with and without climbing lanes. Thus, TWOPAS has both of the capabilities required to apply the AASHTO Green Book criteria for climbing lane warrants.

TWOPAS has only limited capabilities to simulate truck operations on downgrades. Trucks on downgrades in TWOPAS normally travel at their driver's desired speed unless they are slowed by other traffic or by restricted horizontal curves. The TWOPAS user can force trucks to slow to a particular crawl speed on downgrades, but the user must specify crawl zones and the truck crawl speed, as opposed to being determined automatically from truck characteristics. Furthermore, TWOPAS has no capability to vary the specified crawl speed between truck types.

Neither VDANL nor TWOPAS has much current capability for application to the design of emergency escape ramps. However, VDANL could be modified to become a useful tool for evaluating the speed profile of a runaway truck on a downgrade. This would require VDANL to simulate either (1) a truck descending a grade in a gear that is too high to prevent a runaway or (2) a truck descending a grade out of gear (an even more critical situation since no engine braking is available).

J. PROPOSED METHODOLOGY FOR ANALYSIS OF DOWNGRADES IN IHSDM

This subsection presents a methodology for the analysis of downgrades in IHSDM. The methodology is largely new; the only similar methodology was that developed by Systems Technology, Inc. (STI) for FHWA in *The Development and Evaluation of a Proposed Grade Severity Rating System* [4] which is summarized in Appendix E, but that earlier effort could not take advantage of the automated models that are available today.

The methodology will be applied in the IHSDM to the geometry of a particular downgrade, either an existing grade or a grade being designed. It is assumed that the horizontal and vertical alignment of the grade will be available in IHDSM either from a CAD file or from data entered in a non-CAD environment. The analysis will use a particular truck selected for the analysis by the user.

It is recommended that the design of downgrades be based on the answers to four key questions. These are:

1. What is the maximum speed at which the specified truck can descend the specified grade without losing braking ability?
2. What is the maximum speed at which the specified truck can descend the specified grade without rolling over on a horizontal curve?
3. What is the maximum speed at which the specified truck can descend the specified grade without losing the ability to brake safely to a stop using a deceleration rate of 3.4 m/sec^2 or more?
4. What is the maximum speed at which the specific truck can descend the specified grade without losing the ability to slow to the appropriate desired for any horizontal curve?

Criteria 1 and 2 are safety criteria that represent the thresholds at which accidents are expected. Speeds higher than the speed for Criterion 1 would be expected to result in loss of braking control (i.e., a "runaway" truck). Speeds higher than Criterion 2 would be expected to result in a truck roll over.

Criteria 3 and 4 are more conservative and represent thresholds for good design that do not approach impending loss of control. Criterion 3 assures that a truck will be able to brake to a stop using a deceleration rate of at least 3.4 m/sec^2, the deceleration rate assumed in the proposed new criteria for stopping sight distance design [14]. Criterion 4 assures that the truck will not only not roll over on a horizontal curve, but also will be able to traverse each curve on the grade at the speed that drivers normally select for such curves when they are not on a downgrade.

The *recommended truck operating speed* for the grade is the lesser of the speeds determined for Criteria 3 and 4. The appropriateness of the recommended truck operating speed can also be judged by the magnitude of its margin of safety with respect to the *loss-of-control speed* (i.e., the lower of the speeds determined with Criteria 1 and 2). To judge the acceptability of the downgrade design, the IHSDM user must assess whether, with appropriate warning signs, it is reasonable to expect truckers to slow to the recommended truck operating speed before reaching the top of the grade. The proposed methodology can also provide output data to indicate:

- the location at which loss of safety margin, based on Criterion 3 or 4, would be expected for various entering truck speeds
- the maximum percentage of brake fade temperature reached as a function of entering speed

- the location at which loss of control, based on Criterion 1 or 2, would be expected for various entering truck speeds
- the speed profile of the truck following loss of braking ability, if Criterion 1 is, in fact, more critical than Criterion 2.

The recommended methodology for downgrade analysis is as follows:

Step 1 - Select a suitable truck for use the design vehicle for downgrade analysis. If recreational vehicles are present in substantial numbers on the downgrade (e.g., 5% of the traffic stream or more), a suitable recreational vehicle should also be selected for analysis.

Step 2 - Determine the speeds designated by Criteria 1 through 4. Determine the recommended truck operating speed and the margin of safety to the loss-of-control speed.

Step 3 - Assess whether the recommended truck operating speed will be maintained by the vast majority of truck drivers. This assessment could be made with formal risk assessment logic based on further research, or it could be left to the judgement of the IHSDM user.

Step 4 - Modify the geometrics of the downgrade if necessary and feasible. This could involve using less steep slopes, flattening horizontal curves, or both.

Step 5 - If the recommended truck operating speed is deemed too low and it is physically or economically infeasible to modify the geometrics of the downgrade, the IHDSM outputs, specifically, the loss-of-control locations and the speed profiles following loss of control can be used to identify potential sites for emergency escape ramps. The speed profile data can also be used to anticipate potential truck entry speeds to the emergency escape ramp. The truck entry speed is an important design parameter in determining the required length of the ramp.

Step 6 - A traffic operational assessment, patterned after the assessment procedure used for upgrades, should be made to determine whether the provision of a passing lane on the downgrade is warranted to reduce the delays to other traffic by trucks operating at crawl speeds. The warrants for downgrade passing lanes should be analogous to those used for climbing lanes:

- Downgrade traffic flow rate in excess of 200 veh/hr for the peak 15-min of the design hour
- Downgrade truck flow rate in excess of 20 veh/hr for the peak 15-min of the design hour
- One of the following exists:
  - a speed reduction of 15 km/h or greater is expected for a typical heavy truck
  - level-of-service E or F exists on the downgrade
  - a reduction of two or more levels of service is experienced when moving from the approach segment to the downgrade

Appendix D of this report provides a functional program specification for implementing the downgrade analysis methodology in IHSDM. It is recommended that a downgrade analysis software package be developed to implement the recommended methodology. This software package would serve as a user interface to request needed input data from the user and present output reports to the user. The downgrade analysis software package would call VDANL and TWOPAS as necessary to complete the analysis in a manner that would be transparent to the user. The basic downgrade analyses to determine the maximum safe speeds would be performed with VDANL. VDANL would need to be modified for this purpose to fully account for downgrade considerations including the gear and speed selection discussed in Appendix E. TWOPAS would be used only for level of service analysis in assessing the warrants for downgrade passing lanes.

IV. COMPARISON OF KEY VDANL AND TWOPAS MODEL FEATURES

A. OVERVIEW

The following paragraphs provide a brief overview of the VDANL and TWOPAS models that are the primary subjects of this report and their potential ability to contribute to the upgrade and downgrade design issues discussed above.

VDANL – This vehicle dynamics model (VDM) has recently been selected as a component within the IHSDM. The model has a long history of development for the NHTSA [15]-[17], and based on recent developments for FHWA [1] is currently able to represent 12 AASHTO design vehicles including passenger cars, single unit trucks and busses, articulated trucks and busses, and cars and motor homes pulling travel trailers. VDANL has a driver model that will follow horizontal roadway alignment, and will control speed to safely negotiate horizontal curvature. VDANL has an automatic transmission for gear selection, but the driver model is not currently setup for speed and gear selection on upgrades and downgrades. The VDANL tire model has been expanded under FHWA sponsorship to accommodate a full range of paved and off-road surfaces [18]. This tire model has the capability of producing the high rolling drag associated with gravel beds in truck escape ramps.

The vehicle dynamics in VDANL have no intelligence for invoking steering and/or speed control actions. Control actions come from the driver model component of VDANL that can exert closed loop control over the vehicle dynamics to maintain lateral lane position and, under some conditions, maintain desired speeds. The driver model looks ahead in the roadway design horizontal alignment to determine upcoming curvature and predicted lateral alignment. A steering control law produces steering commands to minimize lateral lane tracking error. Speed control is generally accomplished by the driver model under three conditions. First, VDANL has a speed limit, and deceleration can be triggered on downgrades to maintain speed at this limit. Second, during cornering the driver model is set to maintain lateral acceleration below a specified level. The driver model looks ahead at horizontal curvature in the roadway file and begins deceleration when current speed would cause lateral acceleration to exceed a specified level. Third, VDANL can follow a speed profile that is defined in an external input file. Speed selection for downgrades to eliminate brake overheating and runaway is not currently incorporated in VDANL. Appendix E summarizes the requirements for such a model that would also benefit TWOPAS.

A suitably enhanced VDANL can provide highway designers with a unique capability for evaluating highway designs that include a combination of downgrades and horizontal curvature as will be discussed subsequently. The VDANL dynamics model correctly represents the braking and cornering performance of heavy vehicles, and so can determine the points where brake overheating and excessive speeds on curves might become a problem. This analysis can be used to evaluate alternate routes, and/or the best location for escape ramps.

TWOPAS – This microscopic computer simulation model of traffic operations on two-lane highways can be used to evaluate traffic performance on any two-lane highway alignment including both upgrades and downgrades. TWOPAS models the performance of 13 vehicle types (five passenger car types, four truck types, and four recreational vehicle types) whose performance characteristics can be specified by the user. The user can also specify any traffic demand and vehicle mix and any highway alignment, including tangents, horizontal curves, upgrades, downgrades, and vertical curves. TWOPAS can model not only the effects of upgrades and downgrades on vehicle performance, but also driver restraints on and preferences in the use of vehicle performance capabilities, effects of horizontal curves on driver speed, effects of added passing and climbing lanes, and effects on traffic operations of reduced speeds by drivers of heavy vehicles in downgrade crawl regions.

B. NORMAL DESIRED SPEED

VDANL

VDANL handles normal desired speeds in two ways: 1) with a speed profile assigned to the driver model. The driver model follows this speed profile throughout a given run. The profile is designated as a function of distance traveled; 2) with a speed limit and desired cornering acceleration. The driver maintains the speed limit on straight sections, and when necessary, reduces speed to obtain the desired cornering acceleration for a given horizontal curve of radius R:

$$\text{Cornering Acceleration} = (R)^{-1}(\text{Speed})^2 \tag{1}$$

TWOPAS

The key variable that governs vehicle speeds in TWOPAS is the driver's normal desired speed. The desired speed is the speed at which an individual driver would choose to travel when his/her speed is not constrained by roadway geometrics, vehicle performance limitations, or other traffic. The desired speed is a concept commonly used in traffic modeling to represent the driver's approach to speed selection. Obviously, driver speed selection behavior, even for a single individual, is more complex than can be represented by a single number. The speeds at which drivers wish to travel are undoubtedly influenced by a wide variety of factors. TWOPAS makes no attempt to model these factors that influence the speed preferences of individual drivers. Rather, TWOPAS chooses individual desired speeds from a distribution of desired speeds whose mean and standard deviation are specified by the user. Realistic values of the mean and standard deviation of the desired speed distribution can be estimated from field studies typically on low-volume roadways under ideal or nearly ideal conditions.

In TWOPAS, a vehicle traveling on a level roadway with no other traffic present will travel at its driver's desired speed as long as the vehicle has sufficient performance capability to maintain that speed. However, the presence of upgrades, downgrades with crawl regions, sharp horizontal curves, and other traffic on the roadway may force vehicles to slow to speeds less than the driver's desired speed. Normally, drivers will never exceed their desired speeds; in other words, the desired speed sets an upper bound on vehicle speed. However, drivers are permitted to exceed their desired speeds during passing maneuvers that involve use of the lane normally reserved for opposing traffic.

Each vehicle on the simulated roadway is assigned a desired speed selected stochastically from a truncated normal distribution (mean ± 3 standard deviations). The mean desired speed and the standard deviation of desired speeds are part of the mandatory input data for TWOPAS. The assignments of desired speeds for the individual vehicles are made in the preprocessing stage of TWOPAS based on a random number between zero and one generated within the program. The desired speed for an individual vehicle is determined with the following equation:

$$V_d = \overline{V}_d + r\sigma_v \tag{2}$$

where:

V_d = normal desired speed (ft/sec) for a particular vehicle

$\overline{V}_d$ = mean desired speed (ft/sec) for all vehicles in the same vehicle category

r = number of standard deviations above or below the mean desired speed; determined from the value of a random number between 0.001349898 and 0.998650102

σ_v = standard deviation of desired speed (ft/sec) for all vehicles in the same vehicle category

A random number is converted into a desired speed by linear interpolation within Table 1. If the random number generated is less than 0.001349898 or greater than 0.998650102, then another random number is generated and used.

Table 1. Determination of Desired Speed Based on a Random Number

Random number	Desired speed (standard deviations from the mean)
0.001349898	–3.0
0.006209665	–2.5
0.022750132	–2.0
0.066807201	–1.5
0.158655254	–1.0
0.308537539	–0.5
0.500000000	0
0.691462461	0.5
0.841344746	1.0
0.933192799	1.5
0.977249868	2.0
0.993790335	2.5
0.998650102	3.0

TWOPAS allows the user to specify a "bias" in desired speeds by vehicle category, so that recreational vehicles (RVs) and/or trucks can be assigned desired speeds from a distribution with a mean that is less than the mean desired speed for passenger cars. The bias is simply a value that is subtracted from the mean desired speed of passenger cars to get the mean desired speed for another vehicle category. However, in the current version of TWOPAS, all vehicle types within a category have the same mean desired speed. That is, all passenger vehicles and light trucks have the same value, etc.

TWOPAS does not currently permit a bias by vehicle category to be assigned to the standard deviation of desired speeds. In other words, the standard deviation of desired speeds is the same for passenger cars, RVS, and trucks. TWOPAS also assumes that the distribution of desired speeds is the same for both directions of travel. However, NCHRP Project 3-55(3) is adding the capability to vary both the mean and standard deviation of desired speeds by vehicle category and direction of travel.

Comparison of VDANL and TWOPAS

Both models use a similar approach to determining a driver's desired speed. VDANL requires either 1) a speed limit and desired cornering acceleration, or 2) desired speed as user-supplied input data specifying a speed profile for the simulated highway. It then allows the actual speed to be modified by speed limits, desired cornering acceleration, and grades. TWOPAS requires a single desired speed for each vehicle for the entire simulated highway, but the actual speed will also be affected by speed limits, horizontal curves, grades, other traffic, and roadway cross-section. Further, all TWOPAS vehicles do not have the same desired speed; a mean and standard deviation are input, and individual vehicles are given random desired speeds based on these input data. Also, trucks and/or RVs may be biased to have lower mean speeds.

C. SPEEDS ON UPGRADES

VDANL

The VDANL drive train has an automatic transmission. The transmission will gear down to reach an achievable constant speed as described in Appendix A of [1] depending on vehicle performance capability. This vehicle behavior is considered to be a reasonable approximation to driver gear selection behavior on upgrades. VDANL_IHSDM allows for the selection of any of 12 AASHTO vehicles with given performance capability [1]

TWOPAS

The modeling of speeds on upgrades in TWOPAS varies with the vehicle type being modeled. Drivers of all vehicles attempt to maintain their desired speed, but may be limited from doing so by the performance capabilities of their vehicle on upgrades. The following discussion presents the modeling of vehicle performance on grades for automobiles and light trucks, recreational vehicles, and trucks.

a. Automobile and Light Truck Performance Characteristics

This section describes the form of modeling the performance (acceleration versus speed) for cars and light trucks used in TWOPAS, and the values of the performance variables recommended in 1998 as part of the research performed in NCHRP Project 3-55(3), “Capacity and Level of Service Procedures for Two-Lane Highways” [19].

Form of Acceleration Versus Speed Relationships: A data base consisting of the acceleration performance characteristics of 92 vehicles reported in 1994 by Car & Driver magazine was recently assembled. This data base was selected because it had fairly detailed acceleration data. Typically, the reported data consisted of vehicle characteristics along with performance results as follows: time to accelerate from 0 to 30 mph; times to accelerate from 0 to 40, 50, 60, 70, etc. mph; time to accelerate from a stop to a quarter mile; the speed reached at that point; and (often) the vehicle's top speed. From the series of times at 10-mph intervals, the average accelerations from 30 to 40 mph, 40 to 50 mph, etc. can be calculated. Figure 4 shows the data for one of these vehicles, a Dodge Avenger ES with automatic transmission.

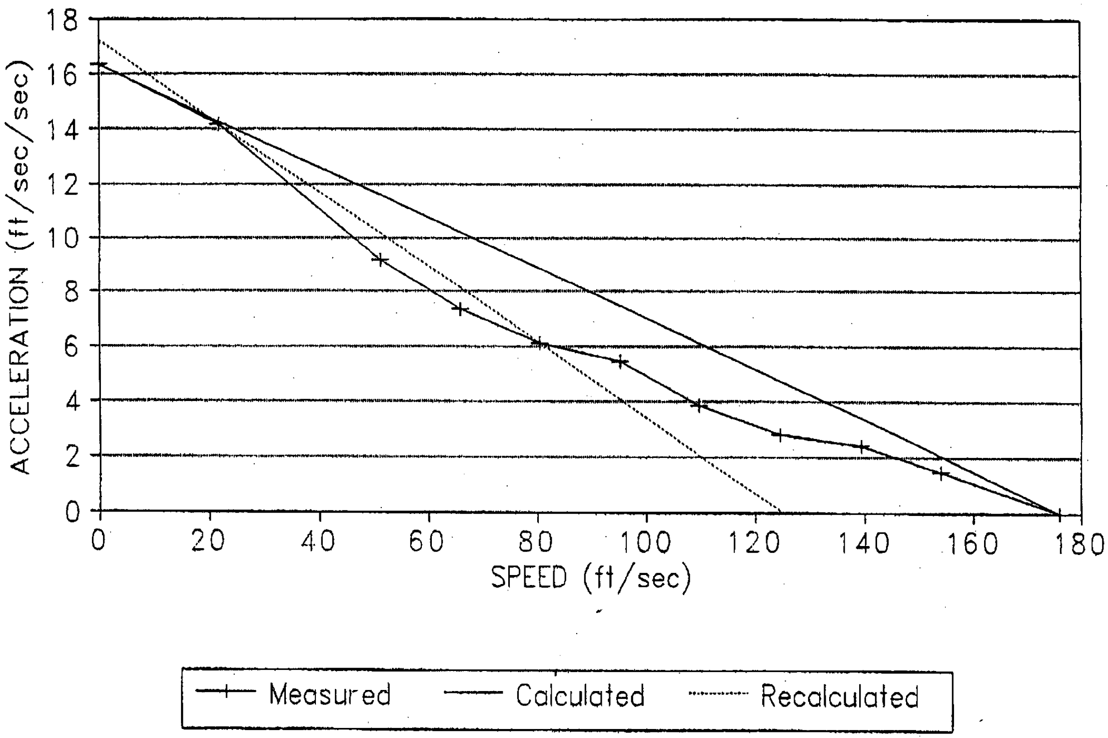


Figure 4. Acceleration *vs.* Speed Relationships for a Representative Passenger Car

Also shown in Figure 4 is a straight line calculated to pass through the 0 to 30 mph average acceleration and the reported maximum speed. It suggests that a straight line assumption, simple mathematically, may not be too unrealistic of representing actual performance. Note, however, that the actual performance falls consistently below this straight-line approximation. This phenomenon is typical of all car performances examined in detail. Thus, it illustrates that one should not use the actual top speed to determine the parameters defining the straight line: rather, a pseudo top speed (and maximum acceleration) should be used that produce a straight line that more closely fits the test data in the range of speeds of interest. One example is shown by the dotted line in Figure 4, which was constructed by passing a line between the average acceleration between 0 and 30 mph, plotted at 15 mph or 22 ft/sec, and the average acceleration between 50 and 60 mph, plotted at 55 mph or 81 ft/sec. This fit matches the test data fairly well from 0 to 75 mph, although it may overestimate the zero-speed acceleration and underestimate the very high speed accelerations.

Basic Equations: The simulation program uses logic that assumes that the performance characteristics of all vehicles except heavy trucks (GVW > 10,000 lbs) can be modeled by a straight line as:

$$a = A + Bv \tag{3}$$

where

a = vehicle acceleration (f/s^2)

v = vehicle speed (fps)

and A and B are coefficients to be determined.

Simple algebra shows that $A = a_o$, where a_o is the zero-speed acceleration, and B is determined as- $\left(a_o / v_m\right)$, where v_m is the vehicle's maximum speed. As stated above, these are not selected to be the actual maximum acceleration and speed, but are such that the straight line resulting from their definition provides a reasonable fit to the actual performance in the range of speeds of most interest. Thus, the performance equation can be written as:

$$a = a_o \cdot \left(1 - v / v_m\right) \tag{4}$$

This is the form of the acceleration/speed relationship used on level terrain. On a grade the term, "-gG" is added, where g is the acceleration of gravity (32.17 ft/sec^2) and G is the local grade expressed as a decimal (eg., G is +0.05 for a five-percent upgrade).

For future use, it is convenient to integrate equation (4) twice. Replacing a with dv/dt and integrating from time t_1 to time t, to determine the change in speed from v_1 to v, we obtain:

$$\left(t - t_1\right) = \left(v_{m/a_o}\right) \cdot \left[\ln\left(v_m - v_1\right) - l_n\left(v_m - v\right)\right] \tag{5}$$

Setting $v = dx/dt$, we can integrate equation (5) to obtain a relationship between distance traveled, x, and time:

$$\left(x - x_1\right) = v_m \cdot \left(t - t_1\right) + \left(v_m / a_o\right) \cdot \left(v_m - v_1\right) \cdot \left[\exp\left(-a_o / v_m \cdot t\right) - \exp\left(-a_o / v_m \cdot t_1\right)\right] \tag{6}$$

The application for Equation (6) in this document is to compute the time required to accelerate from a stop to the distance of 1/4 mile, which is a commonly available piece of experimental data. Writing the special case of Equation (4) for this situation yields:

$$1320 = v_m \cdot t + \left(v_m^2 / a_o\right) \cdot \left[\exp\left(-a_o / v_m \cdot t\right) - 1\right] \tag{7}$$

which is a transcendental equation in t, but it can be readily solved numerically. Then, knowing the time to reach 1/4 mile (1320 ft), the speed at 1/4 mile can be obtained from Equation (5).

Selection of a Vehicle Data Base: The use of the Car & Driver data base to document the performance of vehicles on the road in the U.S. presents some problems. The database consists mostly of cars. It does include some utility vehicles and a few vans, but it contains 7 station wagons among the 92 vehicles, over-representing that class of vehicles, and no pick-up trucks.

The vehicles tested by them tended to be high-performance vehicles, with 25 of the 92 vehicles having top speeds of over 130 mph. Indeed, the database includes the vehicles depicted in Table 2.

Table 2. Non-Representative Vehicles

Vehicle	Top Speed, mph
Volvo 850 Turbo	150
BMW 850 Csi	> 158
Porsche Carrera 4	161
Porsche 911 Carrera	162
Acura NSX	162

Another non-representative aspect of the data base is that nearly half (43 of 92) of the vehicles tested had manual transmissions, 5- or 6-speed. Of the vehicles on the road in the United States, only about 10 percent have manual transmissions.

Given the shortcomings of using this specialized data base to approximate the performance of vehicles on the road in the U.S., another source was examined. Consumer's Reports tests and reports on about four vehicles per month. They cover a wide range of vehicles, including small, medium, and large cars, luxury and sporty vehicles, sports utility vehicles, minivans, and pick-up trucks (standard and compact). Thus, it appears that a data base from these data would be more representative of the vehicles on the roads in the U.S.

A disadvantage of this data base is that the reported data from the testing are not nearly as extensive as those from Car & Driver. The data reported consist of the following:

- Time from 0 to 30 mph
- Time from 0 to 60 mph (from which the time from 30 to 60 mph can be determined)
- Time from 45 to 65 mph
- Time to cover 1/4 mile from standing start.

Our initial attempts to use these data lead to unacceptable results. We used the average accelerations from 0 to 30 mph, and 45 to 65 mph, to determine a_o and v_m. We then realized that using average accelerations was inconsistent with the form of the relationship in Equation (4). An improvement was then made by using the integral of Equation (4), shown as Equation (5), twice to satisfy the two conditions, and solving the transcendental equations numerically for the two unknowns.

Better results were obtained, but they were still not satisfying. The maximum speeds determined thus were felt to be unrealistically low. These determinations also produced 0 to 60 mph and 1/4-mile times that were consistently slower than the test data.

We examined the results obtained when other combinations of the reported data were used to determine a_o and v_m. The best results were consistently obtained using the 0 to 30 and 30 to 60 mph data. The results from the Consumer's Reports data from 1996 and 1997 were obtained for the 81 vehicles they tested during those two years. Because the general intent was to obtain performance estimates for representative vehicles on the road, similar calculations were performed for the 69 vehicles they tested during the years 1990 and 1991.

Oak Ridge National Laboratory Data: Oak Ridge National Laboratories (ORNL) publishes yearly statistics on vehicle data, primarily focused on fuel economy [20]. They break down their data for automobiles based on EPA "size" categories, where the interior volume is taken as the measure of size. Although this is not the most convenient parameter for the present study, it was used because of the extensive amount of data available relative to this parameter.

ORNL classifies passenger vehicles into six categories: 2-seaters, minicompacts, subcompacts, compacts, midsized, and large vehicles. Table 3 provides selected data relative to these classifications. (These data were obtained by ORNL from R.L. Polk files and are reported in ORNL's Tables 3.2, 3.12, and 3.13.)

Table 3. ORNL Passenger Vehicle Size Data for the 1995 Calendar Year

Parameter	2-Seater	Mini compact	Sub-compact	Compact	Mid-Sized	Large
Vol. (ft^3)	N/A	77	95	103	114	128
"Stock" (millions)	2.4	1.9	30.3	36.0	35.5	17.2
Engine Size (l's)	3.7	2.6	2.2	2.2	3.0	4.1
Weight (1000 lbs)	3.0	3.0	2.5	2.7	3.2	3.7

“Stock” is defined in Table 3 as the set of vehicles still registered and presumed to be on the road. It was determined by summing the yearly sales data over each prior year, diminished by scrappage rates. Lacking more definitive data, ORNL assumed that scrappage rates were independent of vehicle size class.

In addition to automobiles, ORNL also reports data on light trucks. This category of vehicles generally includes standard and small pick-ups, standard and small sport utility vehicles (SUVs), and minivans.

In comparing the EPA passenger vehicle size categories with the Consumer's Reports data, it is clear that we have little if any information about the performance of the vehicle classes called 2-Seater and Mini-compact, which tend to be sports cars. For that reason, plus the fact that there are relatively few of them in the mix of vehicles, those categories were eliminated from any further analyses, leaving five categories (four for cars plus one for light trucks).

Although we were not able to make an absolute determination of the EPA category for each Consumer's Report vehicle, reasonable assignments could be made based on the average engine size and curb weight shown in Table 3.

The ORNL report enables one to estimate the mix of these categories of vehicles on the road in 1995. This was done using ORNL-reported annual sales data, annual scrappage rates, and average annual vehicle-miles of travel, by year. Our goal was to estimate the performance of the mix of vehicles on the road in 1998. To this end, for simplicity we used the 1996/1997 Consumer's Reports data to represent the years from 1993 through 1998, and the 1990/1991 data to represent the years 1992 and earlier.

The Consumer's Reports vehicles were rank ordered by performance. Because the performance is determined in terms of two parameters, a_o and v_m, the ranking was performed using the calculated acceleration at a speed of 50 mph, considered a representative speed that would be common in the simulations. Then, using vehicle miles of travel as a weighting function, the percentiles of performance from this tabulation were determined.

The computer model, TWOPAS, presently includes the capability of modeling the performance of five passenger cars (including light trucks), denoted as vehicle types 9 through 13. The performance of these five types varies from lowest (type 9) to highest (type 13). The percentages of each type presently in the model are 10, 15, 20, 25, and 30, respectively, for types 9 through 13.

The data from the weighted rankings were divided into the corresponding percentages, and the values of v_m and a_o for all of the vehicles in each division were averaged to obtain a “representative” set of vehicles. The results are given in Table 4.

Table 4. Recommended Passenger Car Performance Characteristics for Use in TWOPAS

TWOPAS Vehicle Type	Percent of Passenger Car Population	Maximum Acceleration (ft/sec^2)	Maximum Speed (ft/sec)	Comments
9	10.0	11.17	112.8	Lowest performance car
10	15.0	11.99	117.8	
11	20.0	12.77	121.1	
12	25.0	13.22	127.0	
13	30.0	14.10	142.7	Highest performance car

A final comment is made concerning the maximum accelerations in Table 4. Up to this point in the discussion the (derived) maximum accelerations were based on the test data in the Consumer's Reports. These data were obtained with the vehicle relatively unloaded, containing only the test driver and some test equipment. More representative results for vehicles on the road would probably be obtained with greater loads, say two persons and some luggage. Additional load would not appreciably affect the maximum speed, but acceleration at any speed is inversely proportional to the mass. To include this effect, we assumed that the vehicle weight on the road would average about 10 percent more than as tested, or about 250 lbs for subcompacts and 370 lbs for large cars. Thus, the values of a_o in Table 4 are only 90 percent of the averages calculated from the rank-ordered tabulations.

b. <u>Recreational Vehicle Performance Characteristics</u>

This section describes the form of modeling the performance (acceleration versus speed) for recreational vehicles (RVs) used in TWOPAS, the values of the actual performance variables used in the past by TWOPAS, and recent values recommended in 1998 as part of the research performed in NCHRP Project 3-55(3), "Capacity and Level of Service Procedures for Two-Lane Highways" [19].

The model uses logic that assumes that the performance of RVs satisfies the same form of equation as do passenger cars and light trucks, namely:

$$a = a_o \cdot \left(1 - v / v_m\right) \tag{8}$$

where a_o and v_m are the "maximum" acceleration and speed values determined by curve fitting actual acceleration versus speed data, emphasizing the range of speeds of interest in a highway environment.

That is, actual top speed of a vehicle is not of particular interest, nor is the actual maximum possible acceleration at essentially zero speed, as these extremes will rarely, if ever, be encountered in the modeling. As with automobiles and light trucks, this equation applies on level terrain. To account for a grade the term "- gG" is added, where g is the acceleration of gravity (32.17 ft/sec^2) and G is the local grade expressed as a decimal (eg., G is 0.05 for a five-percent grade).

Very little data exist on the performance characteristics of RVs. This is due, in part, to the fact that their performance is so variable. A given RV could be operated essentially empty, or with a very heavy load, thereby exhibiting greatly different performance characteristics. Also, there are many types of vehicles that could be classified as RVs, including a car pulling a small camper trailer, a pickup with a camper shell, a vehicle pulling a large camping trailer, a motor home, a motor home pulling a car, etc.

The only extensive data of which we are aware are those of Werner [21], reported in 1974. Those data are heavily relied on here, despite their age.

To establish a framework for the incorporation of RVs in the model, it is instructive to inquire about their prevalence in the traffic stream. In another early report [22], it is stated that (in the early 70's) RVs made up between 4 and 7 percent of the total vehicles in the traffic stream, although in recreational areas the percentage may be observed to be as high as 36. We do not know how these percentages have changed over the past 25 years, but are inclined to think they have decreased.

Some applicable data are presented in Table 5. Here are shown sales data of RVs, from industry reports, and car and light truck sales from R. L. Polk files. The RV data are rather skimpy and lacking good definitions. For example, it is unclear whether "park trailers" are all RV trailers, or just small camper-type trailers. Polk could define an RV as a self-propelled recreational vehicle, thus excluding all trailer combinations. Further, beginning in 1994, the RV industry began classifying conversions (eg., an SUV converted for recreational use by installing swivel chairs, a table, cup holders, etc.) as RVs. However, the automotive industry includes them in the count of light trucks produced.

Despite all these data difficulties, it is seen that RV sales, as a percentage of car and light truck sales, is a very small fraction. If their scrappage rate is similar to that of cars and light trucks and they accumulate similar mileage, then their presence in the traffic stream will be small. The impact of this finding is that it is probably not too important that their performance characteristics be determined with great accuracy. Their performance will be somewhere between that of cars/light trucks and heavy trucks, and their actual performance will not appreciably affect the results of running the simulation model. The exception would be if the model were applied specifically to study traffic in recreational areas or on recreational routes. If such applications are intended, then more accurate modeling of RVs would be advised.

Table 5. RV and Car/Light Truck Sales (Thousands)

Year	RVs[1]	Cars	Light Trucks	Cars + Light Trucks	RVs / Cars + Lt Trucks
1987	400.2	10278	4610	14888	0.0269
1988	427.3	10626	4800	15426	0.0277
1989	388.3	9898	4610	14508	0.0268
1990	347.3	9301	4548	13849	0.0251
1991	293.7	8175	4123	12298	0.0239
1992	382.7	8213	4629	12842	0.0298
1993	420.2	8518	5351	13869	0.0303
1994	518.8[2]	8990	6033	15023	0.0345
1995	475.2[2]	8635	6053	14688	0.0324
Ave.	406.0	9182	4973	14155	0.0287

[1]Excludes "Park Trailers."[2] Some double counting started in 1994 when pickup and SUV conversions were counted as RVs.

Early Data: The St. John report [22], includes presentations of the data from Werner, mentioned earlier. Some of that data is summarized here.

Ranges for vehicles pulling travel trailers:

Top 10%: v_m = 114 ft/sec, a_o = 12 - 18 ft/sec^2

Median: v_m = 100 - 110 ft/sec, a_o = 8 - 10+ ft/sec^2

Low 5%: v_m = 90 ft/sec, a_o = 4 - 6 ft/sec^2

Selected representative travel trailer combinations:

Top 10%: v_m = 110 ft/sec, a_o = 12 ft/sec^2

Mid 80%: v_m = 104 ft/sec, a_o = 9.2 ft/sec^2

Low 10%: v_m = 104 ft/sec, a_o = 6.2 ft/sec^2

Campers:

Top 34%: use performance of medium to high performance cars

Mid 56%: v_m = 100 ft/sec, a_o = 10 ft/sec^2

Low 10%: v_m = 91 ft/sec, a_o = 7.6 ft/sec^2

Motor homes:

Top 85%: v_m = 100 ft/sec, a_o = 10.4 ft/sec^2

Low 15%: v_m = 100 ft/sec, a_o = 7.0 ft/sec^2

Degradation in performance when pulling a trailer:

Car - compared to not pulling a trailer, degradation in performance is in the range of 15 - 20 ft/sec for v_0 and 2 - 4 ft/sec^2 for a_o, depending on the particular trailer.

Pickup - compared to not pulling a trailer, degradation in performance is in the range of 5 - 10 ft/sec for v_0 and 2.5 - 4.5 ft/sec^2 for a_o, depending on the particular trailer.

Recent Field Data: In the summer of 1997 MRI collected data on speeds of trucks at crawl speeds on a long (4-mile) upgrade averaging 4.37 percent. Amongst the truck data were data on 11 RVs. Their speeds ranged from 21 to 53 mph. The vehicle at 21 mph seemed to be an outlier, as the next slowest was traveling at 34 mph. Examining just those between 34 and 53 mph, and adjusting vehicle performance for altitude and the fact that drivers of cars, light trucks, and RVs do not use maximum performance capabilities for extended periods (unlike heavy truck diesel engines, RV engines are not intended to be operated in such a fashion), the sea level performance on zero grade was estimated. Assuming a maximum speed of v_m = 110 fps, calculated a_0 values range from 6.23 to 13.71. Modifying the assumption about v_m by ± 10 fps does not greatly change the calculated a_o values.

Performance characteristics based on data on pickup trucks reported by Consumer's Reports in recent years are as follows:

1990 full-sized pickups: v_m = 115 - 130 ft/sec; a_o = 13 - 14 ft/sec^2

1996 full-sized pickups: v_m = 120 - 130 ft/sec; a_o = 14.5 - 16.5 ft/sec^2

1997 small pickup: v_m = 120 ft/sec; a_o= 14 ft/sec^2

These data may be compared to the 1971 Chevrolet pickup used in the St. John [22], study:

$$v_m = 115 \text{ ft/sec}; a_o = 17 \text{ ft/sec}^2$$

The maximum speed seems reasonable, but the maximum acceleration probably should not be compared with the more recent vehicles because, we suspect, a different estimation procedure was used. A maximum acceleration value of 17 ft/sec^2 using the method applied in the current studies is attained only by sports cars and luxury sedans.

Recommended Performance Characteristics: Based on all the foregoing, and assuming some improvement in top speed today compared with 25 years ago, leads to the recommended design RVs given in Table 6. These recommendations, if used, would lead to a set of vehicles whose poorest performers are slightly poorer than the poorest performing cars and whose best performers are about equal to the average car.

Table 6. Recommended Recreational Vehicle Performance Characteristics for Use in TWOPAS

TWOPAS Vehicle Type	Percent of RV Population	Maximum Acceleration (ft/sec^2)	Maximum Speed (ft/sec)
5	10	9.0	110
6	40	11.0	115
7	40	12.5	120
8	10	14.0	125

c. Heavy Truck Performance Characteristics

This section describes the modeling approach for heavy truck performance used in the computer program, TWOPAS. It also presents values of the performance variables used most recently, along with values recommended in 1998 as part of the research performed in NCHRP Project 3-55(3) [19]. The development here is taken from the work of St. John and Kobett [22], that was conducted in the early to mid 1970's.

Basic Equations: The horsepower-limited acceleration, a_p, in ft/sec^2, can be stated as:

$$a_p = \left[a_c + 15368\, C_{pe} / \left(\left(W / NHP \right) V \right) \right] / \left[1 + 14080 / \left(\left(W / NHP \right) V^2 \right) \right] \tag{9}$$

where:

a_c = coasting acceleration (ft/sec^2) during gear shifts

C_{pe} = altitude correction factor for converting sea-level net horsepower to local elevation, taken by the authors as 1 - 0.00004 E for gasoline engines, where E is the local elevation (ft)

W = gross vehicle weight (lb

NHP = net horsepower, and

V = truck speed, ft/sec.

The coasting acceleration is given by:

$$\begin{aligned} a_c &= -0.2445 - 0.0004\,V - 0.021\,C_{de}\,V^2 / \left(W / A\right) \\ &\quad - 222.6\,C_{pe} / \left(\left(W / NHP\right)V\right) - gG \end{aligned} \tag{10}$$

where:

C_{de} = correction factor for converting sea-level aerodynamic drag to local elevation, given by $(1\text{-}0.00000688\ \text{E})^{4.255}$

A = projected vehicle frontal area (ft^2)

g = acceleration of gravity, 32.17 ft/sec^2, and

G = local grade, expressed as a decimal.

When a heavy truck ascends a long and steep grade, it will gradually slow to a steady crawl speed, beyond which it lacks the power to accelerate. An expression relating this speed and the truck characteristics can be obtained by substituting a_c from equation (4) into equation (1) and setting a_p equal to zero. The result is:

$$\begin{aligned} \left(W / NHP\right)\left[0.2445 + 0.0004\,V + 0.021\,C_{de}\,V^2 / \left(W / A\right) + g\,G\right] \\ = 15145\,C_{pe} / V \end{aligned} \tag{11}$$

which, if V, G, and W/A are known, can be solved for W/NHP.

Earlier Data: As noted, the original work on TWOPAS was conducted, and the data used, were from the early to mid 1970's. Since that time there have been many major changes in truck characteristics. The Federal weight limit for heavy trucks was raised from 73,280 lbs to 80,000 lbs, a nine percent increase. Truck engines have become more powerful, with several manufacturers now offering engines of over 500 horsepower, and one (Cummins) began marketing a 600-horsepower engine in the spring of 1998.

Trucks are now wider (102 inches versus the older 96 inches) and longer (45-ft and shorter semitrailers were the standard; the Surface Transportation Assistance Act of 1982 (STAA) mandated that all states must allow 48-ft semitrailers on the "designated system"). Semitrailers of 53 feet in length are now commonplace, and some states allow 58-ft semitrailers. The STAA also mandated that all states must allow trucks with twin trailers, each up to 28.5 feet in length, on the designated system. Many states, especially in the western U.S., allow even heavier and longer trucks, so-called Longer Combination Vehicles (LCVs).

Thus, the use of data largely obtained in the early 1970s on truck performance is unlikely to produce results representative of today's fleet.

Newer data developed in the mid-1980s for use in TWOPAS are shown in Table 7 [3]. They determine the acceleration performance of the four truck types modeled by TWOPAS, ranging from the lowest performance type (Type 1) to the highest (Type 4). (These data are quite similar to those collected by Gillespie in 1984 [23] and subsequently reanalyzed and reported by Harwood, et al in 1990 [24]. The latter reported an 87.5 percentile weight-to-horsepower ratio of 250 lb/hp and a median of about 175 lb/hp.) Even newer data were obtained and analyzed in 1997/1998 as part of the research for NCHRP Project 3-55(3) [19].

Table 7. Truck Performance Characteristics in the mid-1980s.

TWOPAS Vehicle Type	Percent of Truck Population	Weight to Net Horsepower (lb/hp)	Weight to Projected Frontal Area (lb/ft^2)
1	12.0	266	620
2	25.6	196	420
3	34.0	128	284
4	28.4	72	158

Recent Field Data: Truck speeds were measured during two days in the summer of 1997 approximately 4 miles up a grade that averaged 4.37 percent, at which location most trucks were presumed to be at their crawl speeds. The grade was on Route 97 in Siskiyou County, California. A total of 262 trucks were observed during this study.

The speed of each heavy truck was obtained, along with brief descriptive information. Based on these descriptions, a few were eliminated from further analysis (e.g., a pick-up truck pulling a travel trailer, a motor home pulling a car, etc.).

Data Analysis: The speeds of each truck were loaded into a spreadsheet, and then sorted from slowest to fastest. Next, it was desired to obtain the weight-to-horsepower ratio for each truck, using equation (3), but the weight-to-projected-vehicle-frontal-area ratios were not known.

The reported weight-to-frontal-area values from Table 7 could have been used for the corresponding percentiles of the new data. However, trucks were probably heavier in 1997 than they were 13 years earlier, so it was decided to increase the tabulated values by 10 percent. It is noted that the aerodynamic term in equation (3), of which W/A is a part, is of essentially no significance for the lower speed trucks, and is relatively unimportant for even the fastest trucks, compared with the other terms.

The grade in question is at an altitude of approximately 5000 ft above sea level where the data were collected, so altitude was used in the calculations for the terms that are altitude dependent, i.e., C_{pe} and C_{de} in equations (9) – (11).

Averaging the calculated weight-to-horsepower ratios for the sets of trucks in each of the previous four categories produced the values in Table 8. Note the significant improvement in the performance of the heaviest trucks (types 1 and 2) compared with those of the early to mid 1980's. Note, also, the apparent slight degradation in the performance of the lighter trucks (types 3 and 4) compared with earlier. In summary, the truck fleet in the (late) 1990's appears to possess a more homogeneous set of performance characteristics than those of 10 to 15 years ago.

Table 8. Recommended Truck Performance Characteristics for Use in TWOPAS

TWOPAS Vehicle Type	Percent of Truck Population	Weight to Net Horsepower (lb/hp)	Weight to Projected Frontal Area (lb/ft^2)
1	12.0	228	682
2	25.6	176	462
3	34.0	140	312
4	28.4	76	174

Comparison of VDANL and TWOPAS

VDANL uses microscopic modeling of vehicle acceleration performance in that it includes such factors as vehicle weight, throttle position, engine RPM, engine torque and horsepower curves, gear selection, drive train parameters, and losses. It includes the effects of aerodynamic drag and rolling drag, the latter being dependent on the surface condition which could include the pea gravel in arrestor beds of escape ramps. TWOPAS, on the other hand, uses a more macroscopic approach. Equations were developed that include the effects of vehicle weight, (net) horsepower, frontal area, losses due to aerodynamic drag and rolling drag, and gear shift delays. TWOPAS does not explicitly deal with gear selection and shifting, engine speed, or drive train losses. The equations are intended to reflect observed acceleration behavior rather than how that acceleration is obtained. TWOPAS also includes a representation of how the drivers utilize the available horsepower (car and RV drivers do not use maximum available horsepower except for short, limited periods). The surface condition is not modeled.

D. DESIRED SPEEDS IN HORIZONTAL CURVES

1. VDANL

The VDANL driver model will reduce speed to achieve a designated lateral acceleration on horizontal curves. A look-ahead function allows the driver model to anticipate upcoming horizontal curvature (radius R) and reduce speed (V) according to the relationship:

$$\text{Desired Lateral Acceleration} = (R)^{-1}(V)^{2} \tag{12}$$

TWOPAS

One of the driver performance characteristics that is modeled in TWOPAS is the effect of horizontal curves on driver desired speeds. Speed transitions for vehicles entering and leaving horizontal curves are also modeled but this aspect of driver speed behavior is discussed in a later section of this report.

The geometrics of horizontal curves are specified by the user as input data to TWOPAS. The input variables that describe the geometrics of an individual horizontal curves, referenced to the user-preferred direction of travel (called direction 1 in the program) are as follows:

XCVN = Position coordinate (ft) of the beginning of the curve on Direction 1

RCUR = Radius of curve (ft)

SCUR = Superelevation of curve (ft/ft)

ACUR = Angular change in alignment in the curve (degrees); ACUR is specified as a positive number for a curve that turns to the right and as a negative number for a curve that turns to the left

The length of the curve and the position coordinate of the curve end are not entered explicitly by the user, but can be computed from the above data.

The speed distribution for a specific horizontal curve is based on an estimated maximum speed and an estimated minimum speed for that curve. These maximum and minimum speeds, designated U_{max} and U_{min}, are computed with the following equation:

$$U = -\frac{184321 a_1}{2d + 1.6} + \left[\left(\frac{184321 a_1}{2d + 1.6} \right)^2 + \frac{184321 (a_o + e)}{d + 0.8} \right]^{1/2} \tag{13}$$

where: d = degree of curvature (degrees/hundred feet)

e = superelevation (ft/ft)

a_o, a_1 = coefficients for U_{max} and U_{min} (see Table 9 and Table 10)

The values of the a_o and a_1 coefficients used to determine the maximum curve speed, U_{max}, are given in Table 9. Comparable values used in determining the minimum speed, U_{min} are given in Table 10. Equation (1) and its accompanying coefficient values were developed for TWOPAS from field data on speeds and lateral accelerations reported in the literature for horizontal curves, particularly the work of Glennon [25].

Table 9. Coefficients a_o and a_1 Used in Determining the Value of U_{max}

Speed range (ft/sec)	a_o	a_1
0 – 100	0.5	0
100 –135	1.857143	0.013571
> 135	0.025	0

Table 10. Coefficients a_o and a_1 Used in Determining the Value of U_{min}

Speed range (ft/sec)	a_o	a_1
0 – 55	0.29	0.0048182
> 55	0.025	0

In the solution for U_{max}, the coefficients for the lowest speed range (0 to 100 ft/sec) are used first. If the calculated value of U_{max} exceeds the top of the range (100 ft/sec), then higher speed ranges are tried in succession. The same procedure is used in a separate procedure to determine the value of U_{min}.

If the maximum speed on the curve, U_{max}, is greater than the mean desired speed plus three standard deviations then a flag is set so that the curve will have no effect on vehicle speeds.

The desired speed of a vehicle in the curve, V_c, is determined with a variation of Equation 1 (the normal desired speed):

$$V_c = \overline{V}_c + r\sigma_c \tag{14}$$

$$\overline{V}_c = \left(U_{\max} +_{\min}\right)/2 \tag{15}$$

where: V_c = desired speed (ft/sec) on a particular curve for a particular vehicle

$\overline{V}_c$ = mean desired speed (ft/sec) on that particular curve for vehicles in the same vehicle category

$$\sigma_c = \left(U_{\max} - U_{\min}\right)/6 \tag{16}$$

σ_c = standard deviation of desired speed (ft/sec) for vehicles in the same vehicle category

The curve-desired speed, V_c, influences the speed behavior of a vehicle in a horizontal curve only if $V_c < V_d$.

During extensive computer runs undertaken as part of NCHRP Project 3-55(3), it was noted that vehicle speeds on some simulated horizontal curves were higher than expected. It was found in the TWOPAS source code that when the maximum predicted speed on a horizontal curve was greater than the maximum predicted speed on a tangent, no correction was made to the speed of any vehicle on the horizontal curve. NCHRP Project 3-55(3) will make a change to TWOPAS to place a limit so that the maximum speed on the horizontal curve will always be less than or equal to the maximum speed on the tangent.

Equation (13) is being reevaluated in NCHRP Project 3-55(3) and may be replaced with a relationship currently being developed for FHWA by Texas A&M University [26].

Speed transitions at each end of a horizontal curve are handled in a manner similar to speed transitions at downgrade crawl regions, which are described below in the section on crawl regions.

Comparison of VDANL and TWOPAS

There is a similarity in how the two models allow lower speeds to be selected in horizontal curves. The VDANL model uses a designated lateral acceleration for a vehicle on a horizontal curve to determine its speed. TWOPAS uses empirical formulas based on field data of actual vehicle speeds in horizontal curves, based on their radius and superelevation.

E. SPEEDS ON DOWNGRADES

1. VDANL

The VDANL driver model currently only responds to either a speed limit and desired lateral acceleration on horizontal curves, or a speed profile. A low speed profile can be assigned for a downgrade that would be consistent with avoiding brake overheating and fade. Avoiding brake fade under critical conditions (i.e. heavy vehicles on long and steep downgrades) also requires that a gear ratio be selected to maximize engine drag at the desired downgrade speed. This strategy requires a special speed/gear selection algorithm as discussed elsewhere [4] and [5] and summarized in Appendix E. This speed/gear selection algorithm for downgrades is a critical enhancement for VDANL. The speed selection algorithm, as discussed subsequently, is also appropriate for TWOPAS.

2. TWOPAS

In TWOPAS, vehicle speeds on downgrades are generally not limited by driver preferences other than the driver's normal desired speed. Thus, unless other traffic or a horizontal curve is present, a driver would proceed at his/her normal desired speed.

On steep downgrades, there is a risk that the driver of a heavy vehicle may lose control of the vehicle due to overheating of the brakes if the brakes are applied too long or too often. Therefore, drivers of heavy vehicles on steep downgrades often slow their vehicle substantially, shift to a lower gear, and choose a crawl speed to proceed down the grade so that the need to apply their brakes is lessened.

Simulation of downgrade crawl speeds is implemented in TWOPAS by allowing the user to specify portions of the roadway, known as crawl regions, where heavy vehicles will use crawl speeds. Within any crawl region specified by the user, as TWOPAS is presently written, all trucks of types selected by the user will automatically slow to a single user-specified crawl speed. The user has the option to require some or all RVs to use crawl speeds as well. The program logic adds an approach region to each user-specified crawl region (see subsequent discussion of desired speeds in approaches to horizontal curves and crawl regions). A maximum of 12 crawl regions may be specified in input. Crawl regions are directional in nature; each crawl region affects vehicles in only one direction.

TWOPAS does not attempt to model the driver's process of deciding whether to slow to a crawl speed on a downgrade and, if so, what crawl speed to use. Rather, these values are supplied as input data by the user. The variables whose values are specified by the user to define each crawl region are as follows:

JD Direction of travel in which this crawl region is located

XCWN Position coordinate (ft) for the beginning of the crawl region; the beginning is defined as the first portion of the crawl region encountered in its particular direction of travel

CW2 Position coordinate (ft) for the end of the crawl region

CW0 Mean crawl speed in this region (ft/sec)

SCWL Standard deviation of crawl speeds (ft/sec)

Presently, the mean and standard deviations of crawl speed apply to all vehicle types that are to use crawl speeds. That is, TWOPAS currently does not enable the heaviest trucks to use lower crawl speeds than, say, RVs.

The actual crawl speed that will be used by an individual driver is computed with the values of CW0 and SCWL in a manner analogous to Equation (3) that is used for horizontal curve speeds:

$$V_{cr} = \overline{V}_{cr} + r \qquad (17)$$

where: V_{cr} = desired speed (ft/sec) in a particular crawl region for a particular vehicle

$\overline{V}_{cr}$ = mean desired speed (ft/sec) in a particular crawl region for all vehicles in a particular vehicle category, identified above as CW0

σ = standard deviation of desired speed (ft/sec) for vehicles in the same vehicle category [identified above as SCWL]

The crawl region desired speed, V_{cr}, influences the speed behavior of a driver in a horizontal curve only if $V_{cr} < V_d$. If both horizontal curves and crawl regions constrain driver speed choices, then the lower desired speed, V_c or V_{cr}, will govern.

There are no plans to modify the crawl region logic in NCHRP Project 3-55(3). No decision has yet been made as to whether crawl regions will be incorporated in the UCBRURAL interface, in which it is not yet implemented.

TWOPAS provides a transition region on the approach to each horizontal curve or crawl region specified by the user in input data. The length of the transition region and the mean desired speed within that region is computed within TWOPAS and, thus, is not specified by the user. The transition region comes into effect for any vehicle that is found to have a lower desired speed within the curve or crawl region than on the normal roadway. The transition region supplies a nearly constant deceleration from the normal desired speed to the curve or crawl region desired speed.

TWOPAS assumes that the approach region starts at a specified distance, z_o, upstream of the beginning of the beginning of the curve or crawl region. The value of z_o is determined as:

$$z_o = \frac{\left(\overline{V}_d^2 - \overline{V}_c^2\right)}{2A_a} \tag{18}$$

where: z_o = distance (ft) upstream from beginning of curve or crawl region to start of approach region

$\overline{V}_d$ = mean of normal desired speeds (ft/sec)

$\overline{V}_c$ = mean of desired speeds (ft/sec) in curve or crawl region

A_a = average deceleration in approach (assumed value of A_a = 3.5 ft/sec^2)

The mean desired speed at any point in the transition region is determined as:

$$\begin{aligned}\overline{V}_a &= \overline{V}_d\Big[\left(1 - c_1 x_o\right) + c_2 x_o^2 \\ &\quad + \left(c_1 - 2c_2 x_o\right)x + c_2 x^2\Big]\end{aligned} \tag{19}$$

where:

$\overline{V}_a$ = mean desired speed as a function of location in the approach region

x_o = position (ft) where the approach region begins $= x_c - z_o,\ x_o \le x_o \le x_c$

x_c = position where the actual curve or crawl region begins

and c_1 and c_2 are given by:

$$c_1 = -A_a / \overline{V}_d^2 \tag{20}$$

and

$$c_2 = -2\left(\frac{\bar{v}_c}{\bar{v}_d} - 1\right)\left(\frac{A_o}{\bar{v}_d^2 - \bar{v}_c^2}\right)^2 \tag{21}$$

The standard deviation of desired speeds in the transition region is assumed to be equal to the standard deviation of desired speed within the curve or crawl region. Equation (19) is employed in Subroutine SPDN to determine the mean desired speed at any point in an approach region. The actual desired speed of any particular vehicle at that point is determined by using the value of the mean desired speed from Equation (19) as the mean desired horizontal curve speed in Equation (3) and/or as the mean desired crawl speed in Equation (6).

There is no explicit transition region for vehicles leaving a horizontal curve or crawl region. Drivers will seek to resume their normal desired speeds subject to the limitations of driver acceleration preferences (see below), vehicle performance limitations, local alignment, and the presence of other traffic.

3. Comparison of VDANL and TWOPAS

VDANL can control downgrade speeds through its means of defining desired speed profiles on the highway being simulated. Having done that, it models the brake temperature that would result from using the foundation brakes to control the speed. Using a lower gear would relieve some of the brake heating, but in its current form VDANL does not have a speed or gear selection logic to accomplish this. TWOPAS allows the user to specify crawl speeds for trucks at specified locations on downgrades, but its flexibility in its current form is limited, e.g., all vehicles that are specified to use a crawl speed will use the same (mean) crawl speed.

F. DECELERATION/BRAKING

1. VDANL

VDANL has the drive train and brake system capability for realistic deceleration and braking performance. In addition, the STIREMOD tire model [18] gives realistic limit performance under combined cornering and braking conditions, and the model for articulated vehicles can also simulate jackknifing under limit performance braking. VDANL lacks additional retarding devices that are used to help in downgrade descents. VDANL also uses a simple, linear weight dependent rolling drag effect. A more complex model is required for accurate modeling of downgrade performance as discussed further on.

The vehicle dynamics in VDANL have no intelligence for invoking speed changes. VDANL deceleration and/or braking is generally accomplished by the driver model under three conditions. First, VDANL has a speed limit, and braking can be triggered on downgrades to maintain speed at this limit. Second, during cornering the driver model is set to maintain lateral acceleration below a specified level. The driver model looks ahead at horizontal curvature in the roadway file and begins deceleration when current speed would cause lateral acceleration to exceed a specified level. Third, VDANL can follow a speed profile that is defined in an external input file. VDANL will decelerate to follow this externally defined speed profile.

2. TWOPAS

TWOPAS does not model braking, but allows decelerations to be used. For example, very simple logic is employed as vehicles approach crawl-speed zones or horizontal curves where reduced speeds will be used. The model looks ahead and causes the vehicles to decelerate moderately (e.g., 3.5 ft/sec^2) on their approach. Its car-following logic allows for decelerations in response to the speed and relative location of the vehicle ahead. The magnitudes of the decelerations used has varied as different versions of the logic were implemented; one version caused fairly large and unreasonable decelerations but that version has been replaced. Decelerations of a modest magnitude may also be used by vehicles seeking to find a gap in the adjacent lane of traffic, either to reenter that lane after completing a passing maneuver or upon the approach to the end of a climbing or passing lane. The highest accelerations allowed are for passing vehicles that decide to abort the passing maneuver because of oncoming traffic.

3. Comparison of VDANL and TWOPAS

VDANL has a very sophisticated model of the braking process, including the combined effects of braking and cornering on vehicle stability. Heating of the brakes by braking is modeled, as is cooling by air flow over the brakes. In contrast, TWOPAS does not model the braking process as such, but simply allows deceleration levels believed to be in line with observed driver behavior.

G. OTHER MODEL FEATURES

Appendix A discusses other features of VDANL that are potentially relevant to evaluation of upgrades and downgrades but do not have directly corresponding features in TWOPAS. These include brake systems, engine and drive train retarders, heavy vehicle engine modeling, and speed control and gear selection driver model for downgrades,.

Appendix B discusses other features of TWOPAS that are potentially relevant to evaluation of upgrades and downgrades but do not have directly corresponding features in VDANL. These include desired speeds in horizontal curves, desired speeds in downgrade crawl regions, desired speeds in approaches to horizontal curves and crawl regions, driver lane choice at the beginning of a passing or climbing lane section, and driver lane changing behavior in passing and climbing lane sections.

V. CASE STUDIES

A. OVERVIEW

Two case studies were analyzed by both VDANL and TWOPAS. One case study was to analyze truck performance on an upgrade, to illustrate how the need for a climbing lane might be determined. The other was truck crawl performance on a downgrade, with a horizontal curve near the foot of the grade, to illustrate how the need for an emergency escape ramp might be determined.

In addition to the two case studies analyzed by both VDANL and TWOPAS, two additional case studies were completed by TWOPAS to illustrate the effects on traffic of an added climbing lane and, on a downgrade, of an added passing lane.

The upgrade is illustrated in Figure 5a. It consists of a 5% grade that is 14,665 ft (4470 meters) in length. The grade is preceded by a 2240-ft (683-meter) section that is level and an 800-ft (244-meter) vertical curve. At the top of the grade is a 1550-ft (472-meter) vertical curve and a 4505-ft (1373-meter) level section.

The downgrade is illustrated in Figure 5b. It is essentially the reverse of the upgrade, except that it has a 90-degree horizontal curve just preceding the final vertical curve. The horizontal curve has a radius of 273 ft (83 meters). (This radius is the maximum radius recommended by the Green Book for a design speed of 30 mph and a superelevation of 0.06, on rural highways.)

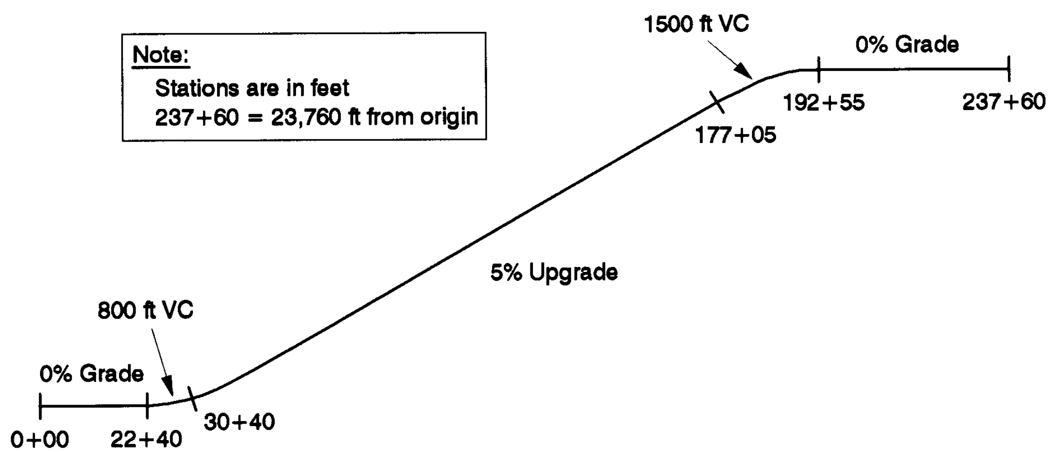
B. VDANL

Two case studies have been developed to demonstrate how VDANL_IHSDM can be used in the analysis of upgrade and downgrade alignments. The data set for the AASHTO WB-67 vehicle is used as an example with some parameter modifications. The upgrade case study examines the drive train modeling along with the transmission shifting logic. The downgrade case study examines the brake system modeling and gear selection logic along with the driver steering model and prediction of vehicle roll over.

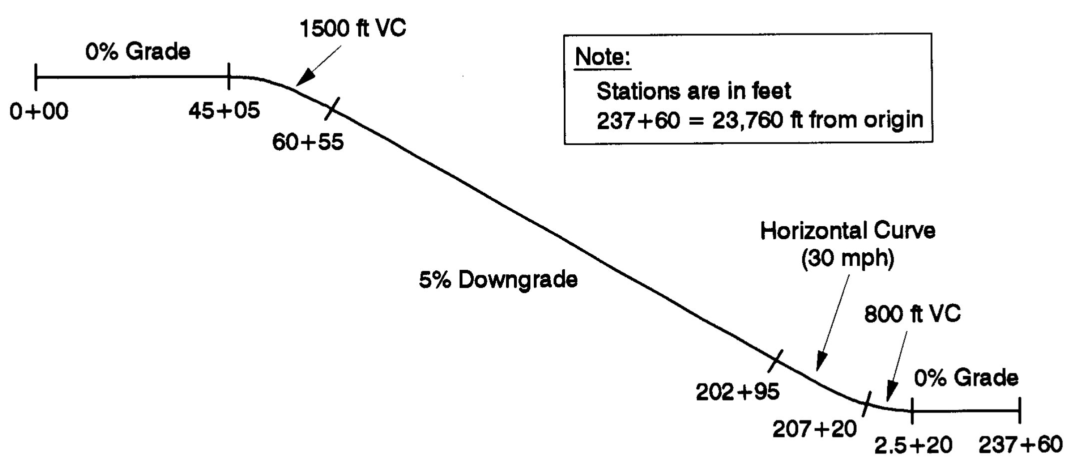
1. VDANL Case Study 1: Downshifting on an Upgrade

Three configurations of the AASHTO WB-67 vehicle are examined, roughly corresponding to the loading conditions: empty, medium load and full load. The total vehicle weights for the three loads are 36,500 pounds, 54,550 pounds, and 80,000 pounds. The engine torque model has a peak torque of approximately 1440 ft-lbs at 1100 rpm and a peak power of 388 hp at 1600 RPM. The ten speed transmission has equal gear spacing with a top speed of 130 km/h at 2000 RPM in tenth gear.

The upgrade case study demonstrates how the IHSDM vehicle dynamics model can be used to determine if a truck climbing lane is necessary for a proposed roadway alignment. For each vehicle configuration, the commanded speed was 105 km/h for the entire run. Figure 6 shows the speeds attained for each configuration (in meters per second, which is the output of VDANL IHSDM). Figure 7 shows



a) Upgrade Alignment



b) Downgrade Alignment

Figure 5. Case Study Grade Profiles

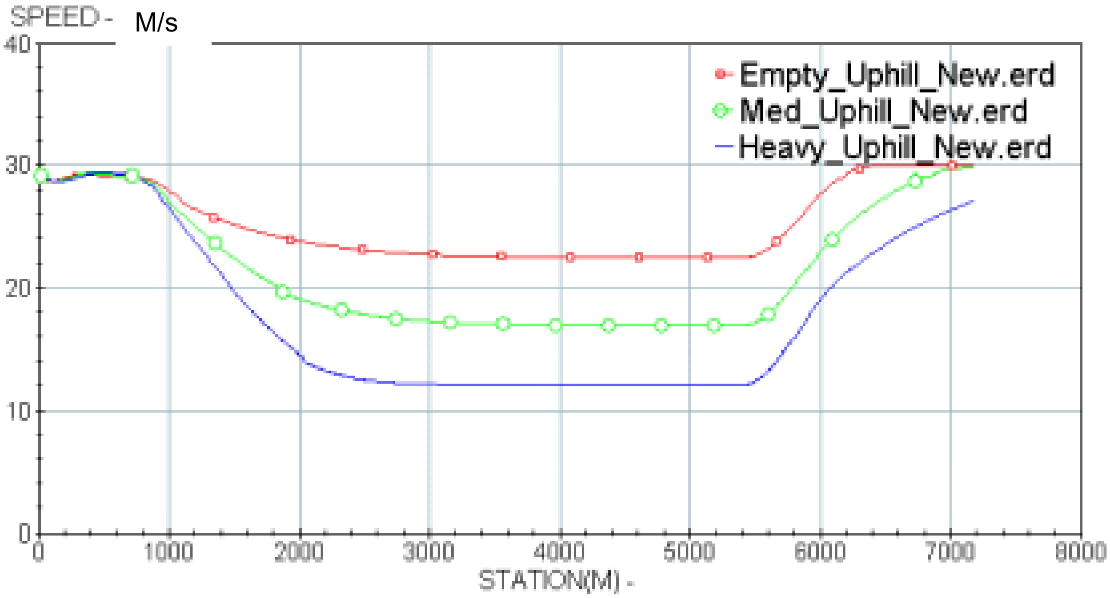


Figure 6. Upgrade Vehicle Speed in meters per second

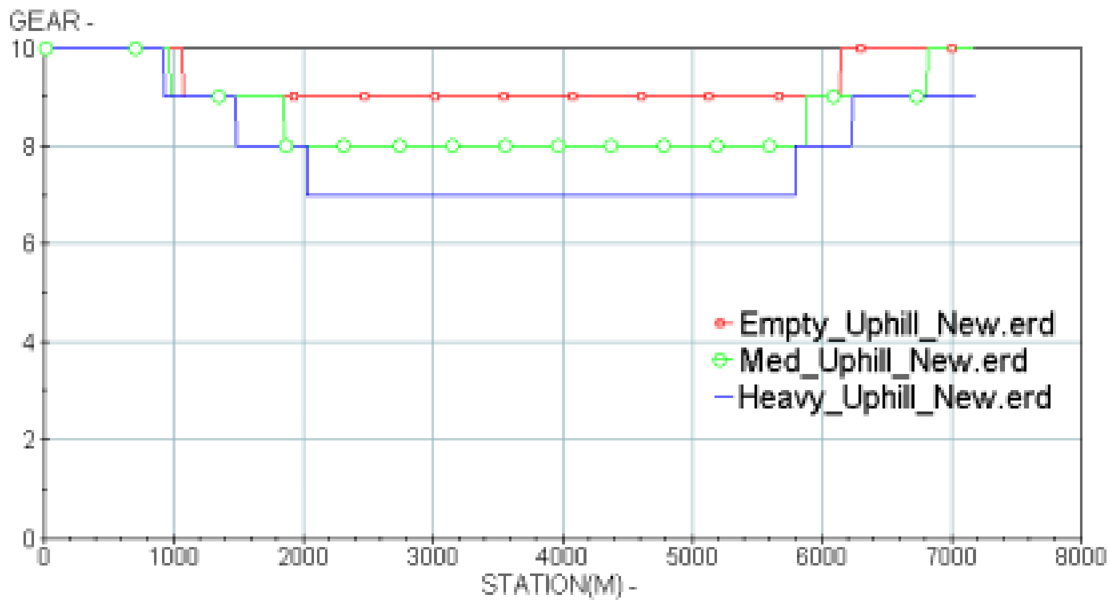


Figure 7. Upgrade Gear Selection

the gear selection for each run. The empty vehicle is shown by the line with the square symbol, the medium load by the circle symbol, and the full load by the line with no symbol. All three vehicle combinations slowed somewhat during the climb of the 5% grade. In all three cases, 100% throttle is applied during the climb. In the empty load case, the steady state speed is 80.6 km/h, and the transmission downshifts to 9th gear. The medium load vehicle can drops down to 61 km/h, and downshifts to 8th gear in an attempt to maintain the desired speed. The fully loaded vehicle speed drops to 44 km/h and the gear selection algorithm downshifts to 7th gear. The gear selection and throttle control show that the VDANL_IHSDM drivetrain, gear selection, and speed control algorithms are appropriate for upgrade performance predictions. Full engine power is used, and the correct gear is selected. Parameters for these models can be adjusted by the user to simulate a wide variety of vehicles.

This case study indicates the need for a truck climbing lane. The simulations show that with all three loads, the vehicle speed drops well below the commanded speed.

2. VDANL Case Study 2: Brake Heating on a Downgrade

While the upgrade case study tested VDANL_IHSDM engine, drivetrain, gear selection, and speed control algorithms at or near full engine power, the downgrade tests them at zero or negative engine power. In addition, the brake system and it's thermal model are tested along with the driver models ability to negotiate a curve. The downgrade alignment is the vertical curvature of the upgrade alignment driven backwards but with the addition of a horizontal curve as illustrated in Figure 5b. This curve is designed to require 0.5 g (4.9 m/sec^2) lateral acceleration at 73 km/h. The same three vehicle configurations are used as the upgrade case study. Each vehicle is commanded to maintain a speed of 60 km/h on the alignment and to slow down for the curve so that the lateral acceleration through the curve is 0.2 g.

During the initial checkout runs it was discovered that during brake application, the brake temperatures were decreasing rather than increasing. A review of the code revealed the the equations for computing the power input to the brakes, HP_{Bj} (equation A-85 in reference 2) was programmed incorrectly, with a negative sign added. This is a coding error, not a modeling error. This was corrected and a new version of VDANL_IHSDM was compiled and used for the downgrade case studies

Figure 8 through Figure 13 show the results from the downgrade case study. Figure 8 shows the vehicle speed in meters per second. The empty and medium load cases are able to maintain the 60 km/h (16.5 m/sec) speed throught out the downgrade, and only slow down for the curve. To maintain 0.2 g's lateral acceleration through the curve, the vehicle slows to approximately 46 km/h (12.7 m/sec). For the

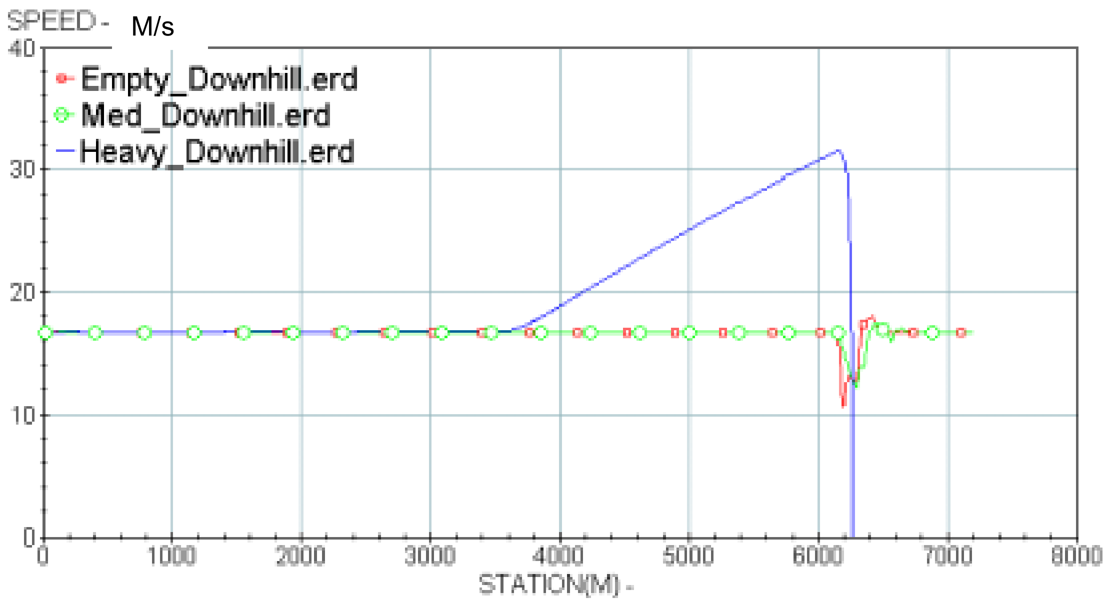


Figure 8. Downgrade Vehicle Speed in meters per second

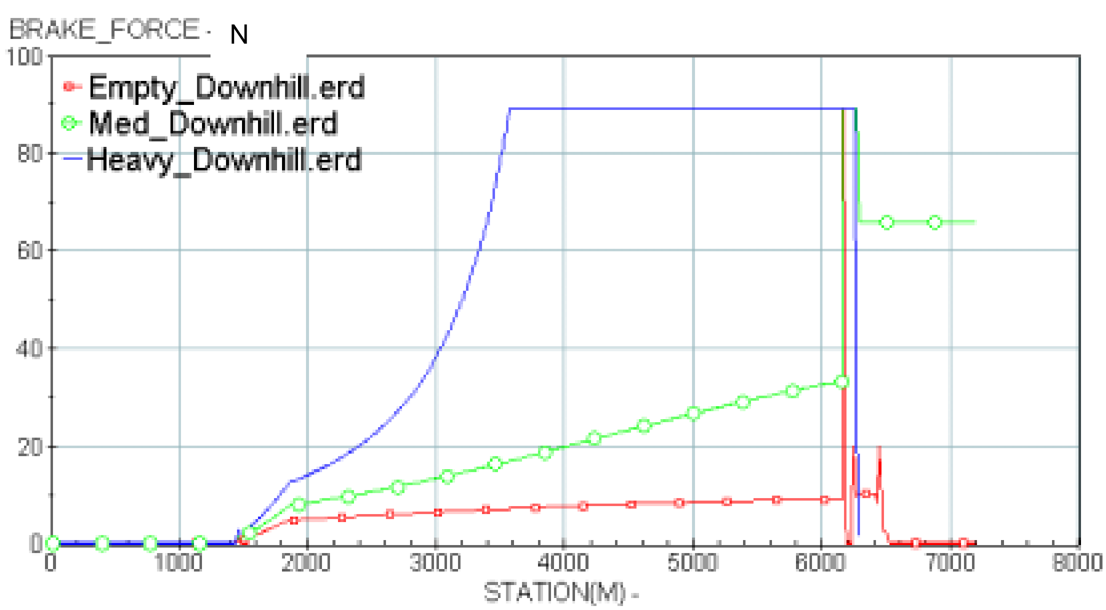


Figure 9. Downgrade Brake Pedal Force in Newton's

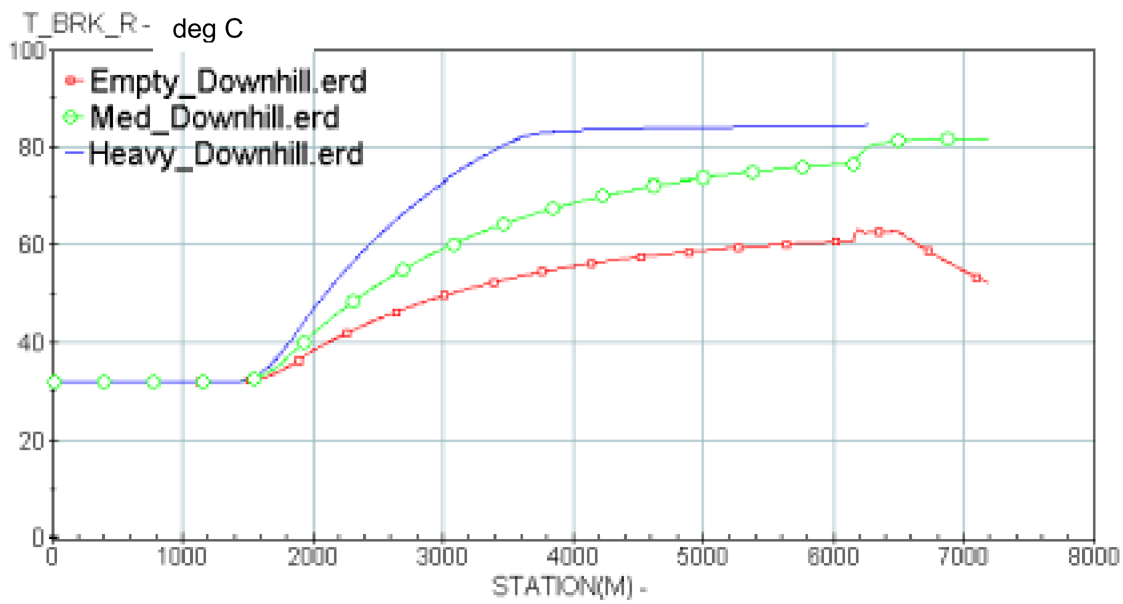


Figure 10. Downgrade Drive and Trailer Axle Brake Temperature in °C

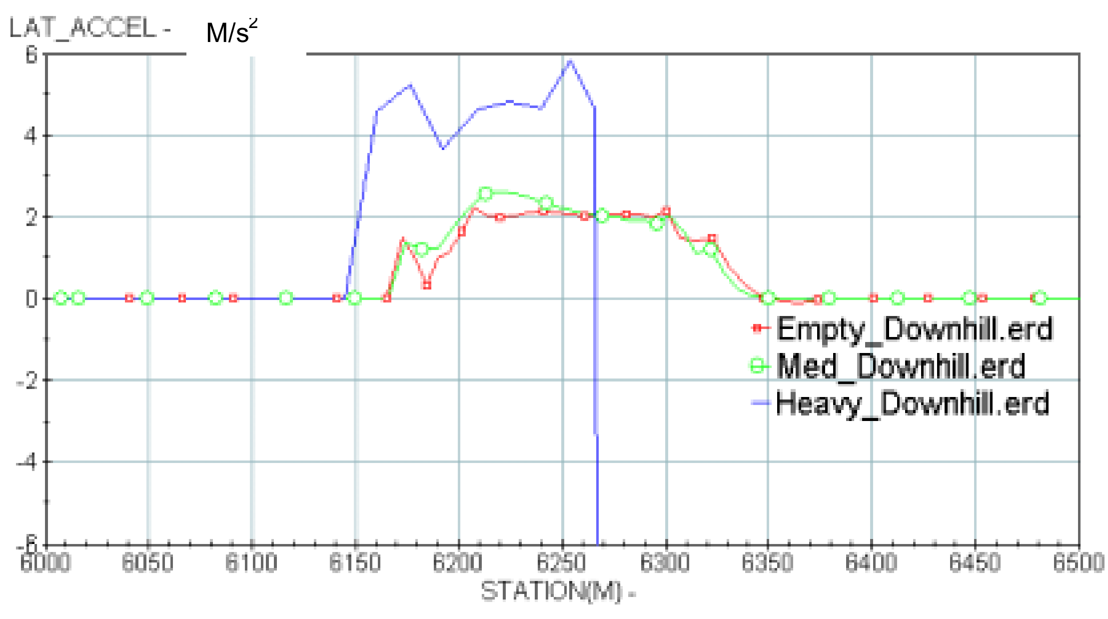


Figure 11. Downgrade Tractor Lateral Acceleration in meters per second^2

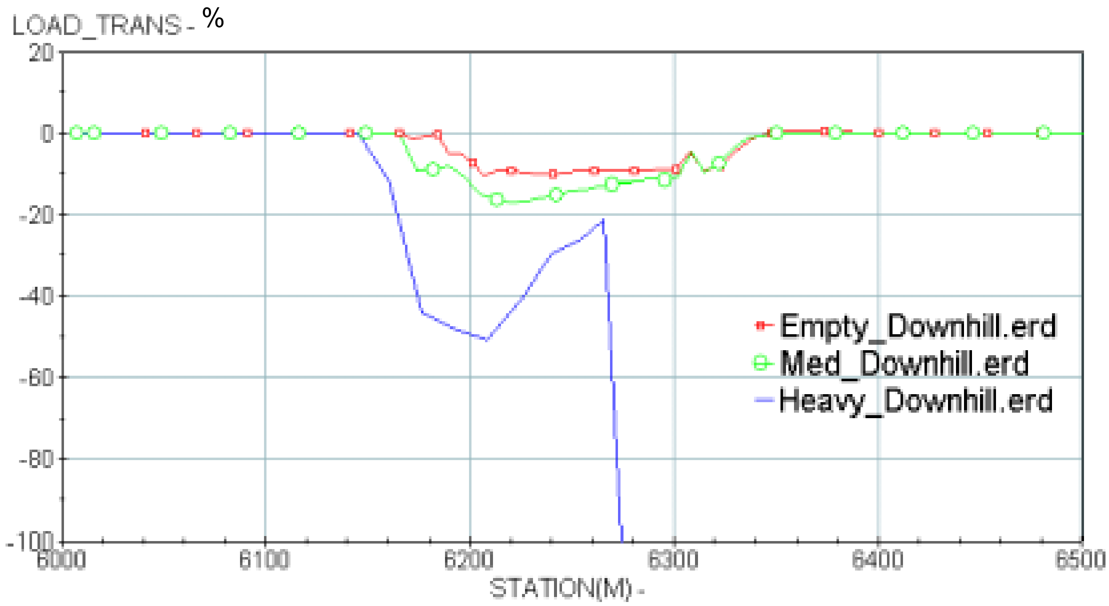


Figure 12. Downgrade Tractor Lateral Load Transfer in Percent

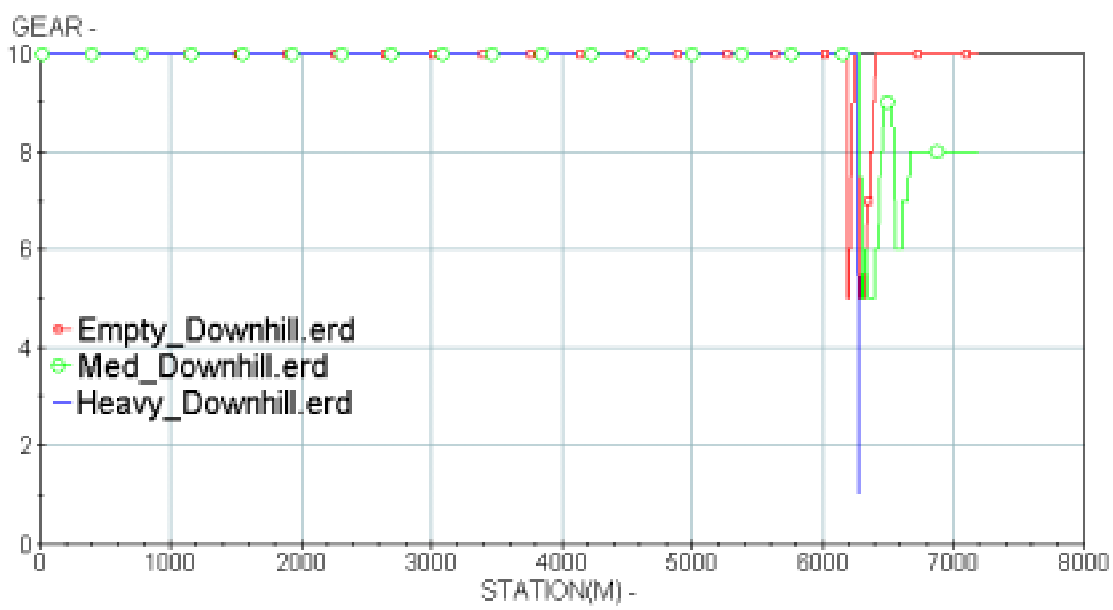


Figure 13. Downgrade Gear Selection

heavy load case, the vehicle speed of 60 km/h is not maintained throughout the grade and increases up to approximately 115 km/h (32 m/sec) by the beginning of the curve. At this speed, the truck can not negotiate the curve and rolls over.

The Figure 8 speed profile can be used to determine speeds that need to be arrested by an escape ramp depending on its location. Clearly, the escape ramp should be located prior to the horizontal curve. The ramp for this location should be designed to arrest vehicles with speeds on the order of 120 km/h.

Figure 9 shows the brake pedal force for the three runs, and Figure 10 shows the temperature of the drive and trailer axle brakes. For the lower load cases, the pedal force increases linearly throughout the run due to brake fade. The heavy load case had a exponentially increasing brake pedal force until the maximum allowable pedal force is reached. The brake torque in not sufficient to maintian the commanded vehicle speed and at this point the vehicle is in essence out of control.

Figure 11 and Figure 12 show the tractor lateral acceleration and lateral load transfer in the the vacinity of the curve. The lower load cases negotiated the curve nominally at 0.2 g, while the out of control heavy vehicle required on the order of 0.5 g, which is above its rollover threshold. The lateral load transfer for the lower load was below twenty percent, while the heavy load eventually to negative one hundred percent meaning that all of its right side tires have lifted off the road.

Figure 13shows the gear selection for the downgrade run. For all three vehicle confiurations, the gear selection algorithm keeps the transmission in its highest gear during the downgrade. Only engine braking at low engine speed is used, which puts more load on the brakes. As discussed in the *Speed Control and Gear Selection Driver Model* section, this is an area where improvement is needed. The brake parameters are set to demonstrate the run-away scenario, however, they are not realistic of an actual truck. The brake fade parameter is set very high so the brakes would fade at low temperatures. Because the brake thermal characteristics are hard coded in the current version of VDANL_IHSDM, it is not possible to setup a scenario were a vehicle has marginal or poorly adjusted brakes. Enhancements to the brake model to allow relistic downgrade simulations are discussed in the *Wheel Brake Model* section.

C. TWOPAS

The trucks simulated were those described earlier with the description of modeling of truck performance by TWOPAS. Their characteristics are repeated here in Table 11.

Table 11. Truck Characteristics Used in the Case Studies.

TWOPAS Vehicle Type	Percent of Truck Population	Weight to Net Horsepower (lb/hp)	Weight to Projected Frontal Area (lb/ft^2)
1	12.0	228	682
2	25.6	176	462
3	34.0	140	312
4	28.4	76	174

1. TWOPAS Case Study 1: Truck Speeds on Upgrades

Four simulation runs of trucks on upgrades were conducted for this study, each for a simulated run time of 1 hour. Each run consisted of only one type of truck, 1 through 4; a volume of 10 vph; and no other vehicles. The TWOPAS simulation model inserts a "warm-up" zone prior to the simulated roadway, to stabilize incoming traffic. This zone was 1-mile in length; no output data are presented for this zone. Also, a warm-up time of 18 minutes was used for the same purpose, and no data from that time period were used. All trucks were given a mean desired speed of 60 mph with a standard deviation of 0.1 mph, so all trucks would enter the grade at essentially the same speed.

Figure 14 presents the results of these simulations, depicting the average speed versus distance along the roadway for all the trucks of a specific type. Truck type 4, the most highly powered of the four, was reduced to a crawl speed of 53 mph. The others were reduced to 37, 30, and 24 mph, respectively. At the beginning of the final vertical curve all four truck types were able to accelerate, with truck type 4 being able to resume its desired speed by the end of that vertical curve and the others requiring more distance. Indeed, at the end of the simulated roadway, 4505 ft of level roadway after the end of the vertical curve, truck type 1 was still not back up to its desired speed.

2. TWOPAS Case Study 2: Truck Speeds on Downgrades

The conditions described above for the upgrade simulations were repeated on the downgrade. For this case study the trucks were not required to use crawl speeds. As can be seen from the results plotted in Figure 15, all of the trucks did, indeed, continue down the grade at their desired speed of

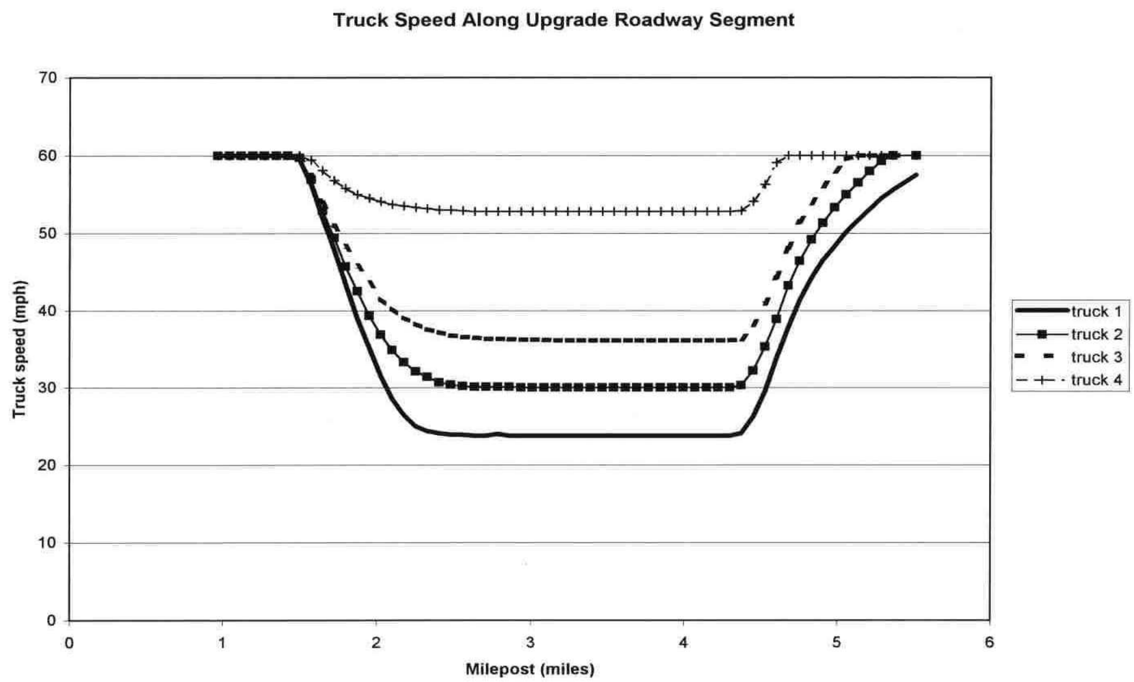


Figure 14. Average Speed *vs.* Distance Along an Upgrade for all Trucks of a Specific Type

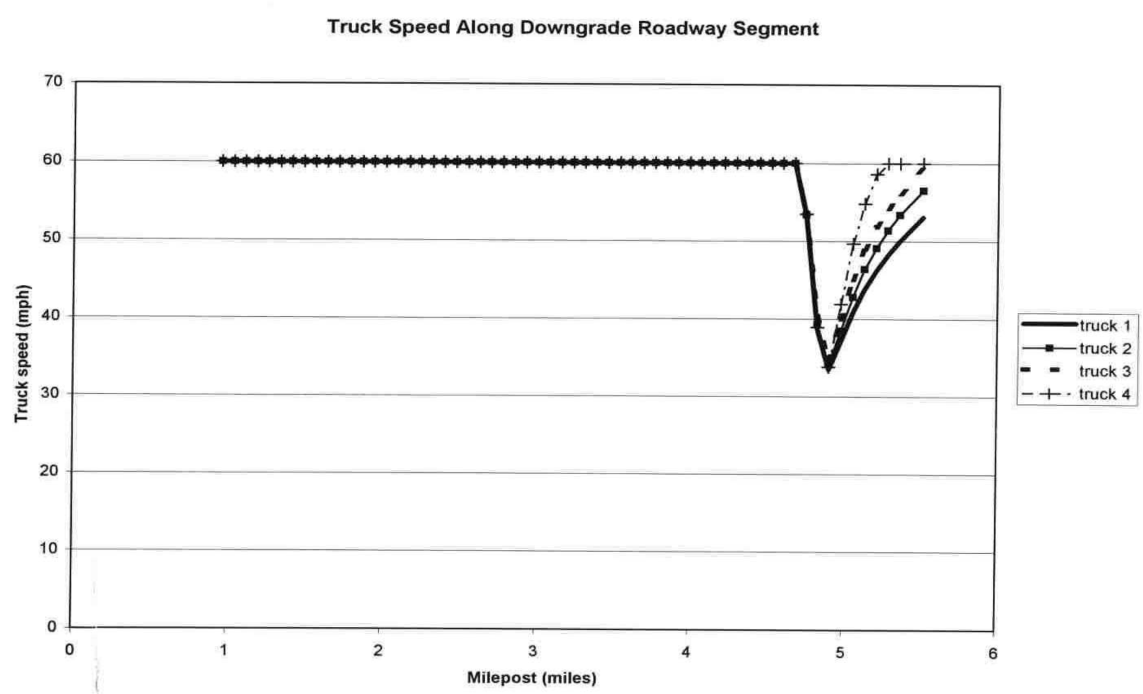


Figure 15. Average Speed *vs*. Distance Along a Downgrade for all Trucks of a Specific Type

about 60 mph. At mile post 4.68, about 800 ft before the beginning of the horizontal curve, all the trucks began to decelerate. They reached a minimum speed of about 34 mph in the curve, then accelerated again coming out of the curve.

TWOPAS does not have the capability of modelling brake heating. The fact that a truck might have to brake steadily on the downgrade to maintain a speed of 60 mph is not modelled. TWOPAS assumes that as the truck approaches the horizontal curve it is perfectly capable of braking to a lower speed (in this case, about 34 mph) with a deceleration independent of brake condition. Thus, the model is probably not realistic, especially for the heaviest truck(s).

3. TWOPAS Case Study 3: Traffic Speeds on a Grade with a Climbing Lane

If the trucks were part of a stream of mixed traffic, then by the time the traffic reached the top of the grade, all vehicles in the vicinity of a truck of type 1 would be slowed to its speed of 24 mph if there were no passing lane and no passing opportunities. To examine how this would be influenced by the presence of a passing lane, this case study added one and examined various traffic volumes.

The climbing lane began at station 30 + 40, at the end of the initial vertical curve, and ended at station 192 + 55, at the end of the final vertical curve. Trucks were directed into the climbing lane, although faster moving trucks were allowed to pass those travelling slower, using the through lane.

Traffic volumes of 200, 400, 800, and 1200 vph (one way) were simulated, all with 10% trucks distributed in accordance with Table 11. All vehicles had mean desired speeds of 60 mph with a standard deviation of 0.1 mph. The actual desired speeds, traffic volumes, and mix of vehicles were not exactly equal to those specified due to the stochastic nature of the simulation and its use of random numbers to simulate a traffic mix and speeds with "expected values" equal to the specified input data. The simulation results are shown in Figure 16.

It can be readily seen that the average speed for all vehicles on the upgrade is far greater than the 24 mph of the slowest trucks. The fact that the averages are not equal for all four traffic volumes, and that they do not reflect higher or lower values as a monotonic function of traffic volume is possibly a result of the stochastic nature of the model. One feature that is explainable, however, is the drop in average speeds at mile post 4.65, which is at the end of the climbing lane. This drop is most pronounced for the 1200 vph volume, but is also noticeable for the 800 vph volume. It is due to the need for merging at the end of the climbing lane by the slower vehicles, which would slow down faster vehicles in the through lane, at least least for a modest distance. The model allows passing using the oncoming lane in these simulation runs

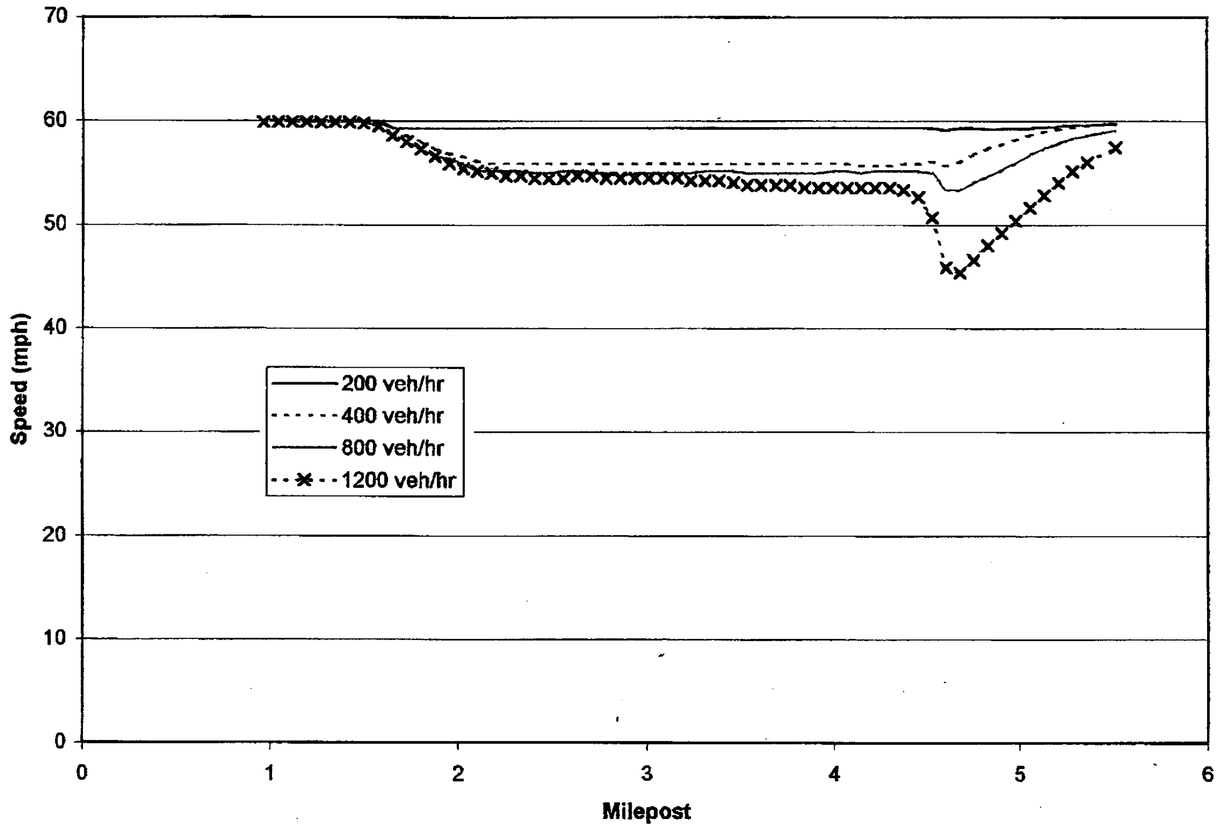


Figure 16. Simulated Upgrade Speed *vs.* Location on Grade for Mixed Traffic with 10% Trucks

where there is not a climbing lane. Because the oncoming traffic was modelled to be very light, it is likely that the simulated vehicles (cars, especially) found it easy to pass the slower trucks after the lane drop, so the average speed of all vehicles was not depressed as much as it would have been if passing were not permitted at that point.

4. TWOPAS Case Study 4: Traffic Flow on a Downgrade Where Trucks Use Crawl Speeds

Downgrade speeds of passenger cars with a desired speed of 60 mph, as simulated by TWOPAS, are shown in Figure 17. Since they do not use crawl speeds, they have a constant speed of 60 mph until near the foot of the grade, approaching the horizontal curve, where they reduce speed to traverse the curve.

Figure 18 shows the speed profiles of trucks of TWOPAS Truck Types 1, 2, and 3, for which crawl speeds of 30, 40, and 50 mph, respectively, were assigned on the downgrade. It can be seen that they

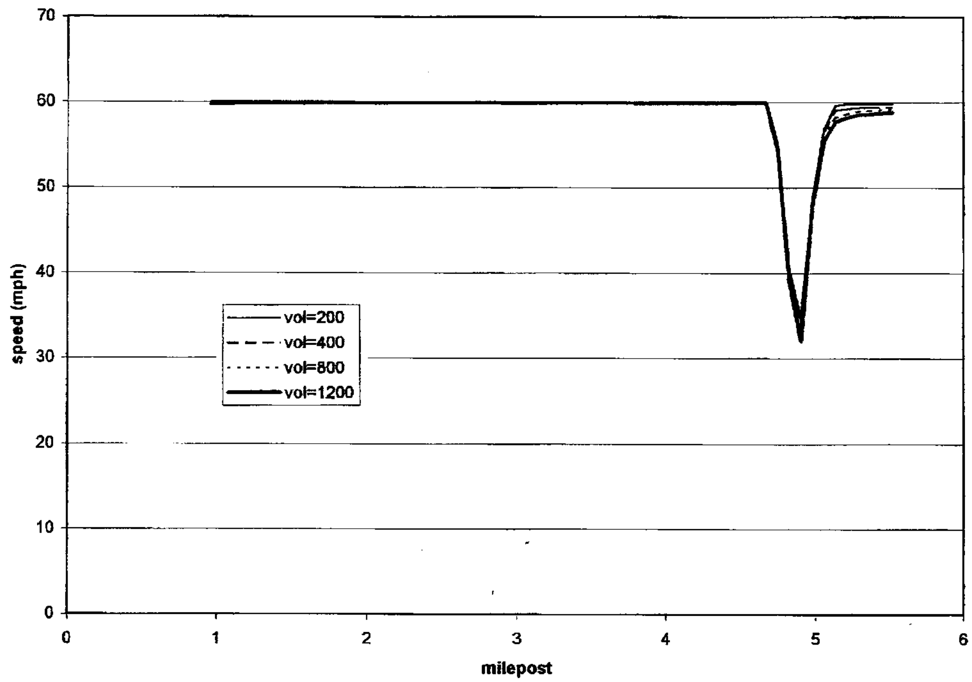


Figure 17. Simulated Downgrade Speed for Passenger Cars

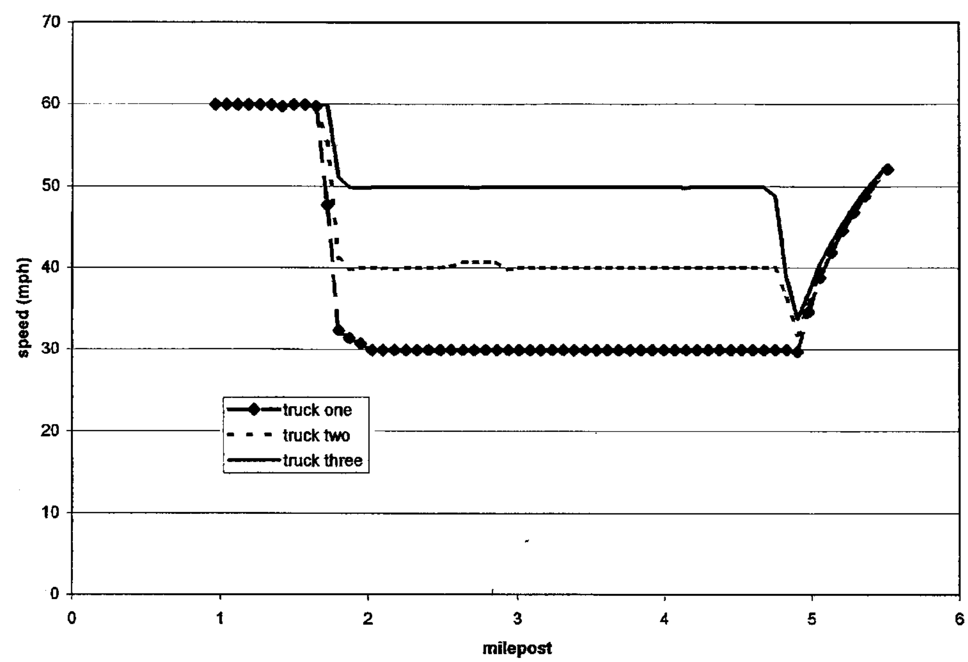


Figure 18. Simulated Downgrade Speeds for Trucks with Crawl Speeds of 30, 40, and 50 mph

reduce speed to the assigned crawl speed when they reach the specified crawl zone which begins at the vertical curve at the top of the grade. Also, Truck Types 2 and 3 slow further on the approach to the horizontal curve; the crawl speed for Truck Type 1 is already sufficiently slow to negotiate this curve without further slowing.

Figure 19 illustrates the affect of truck crawl speeds on traffic, in general. Here, several traffic volume levels are shown, with 10 percent trucks in each case, all with a crawl speed of 30 mph. There is no passing lane, and vehicles are not allowed to use the oncoming lane to pass. Thus, for example, with 1200 vph, all vehicle speeds are reduced to the truck crawl speed within slightly over a mile down the grade, being forced to slow because of the slow trucks ahead. At 800 vph, some passenger vehicles are able to maintain desired speed until the very end of the downgrade, because of the lesser volumes of slow trucks. At 400 and 200 vph, many passenger vehicles are not slowed at all because they do not catch up with a truck. Again, however, all slow on the approach to the horizontal curve.

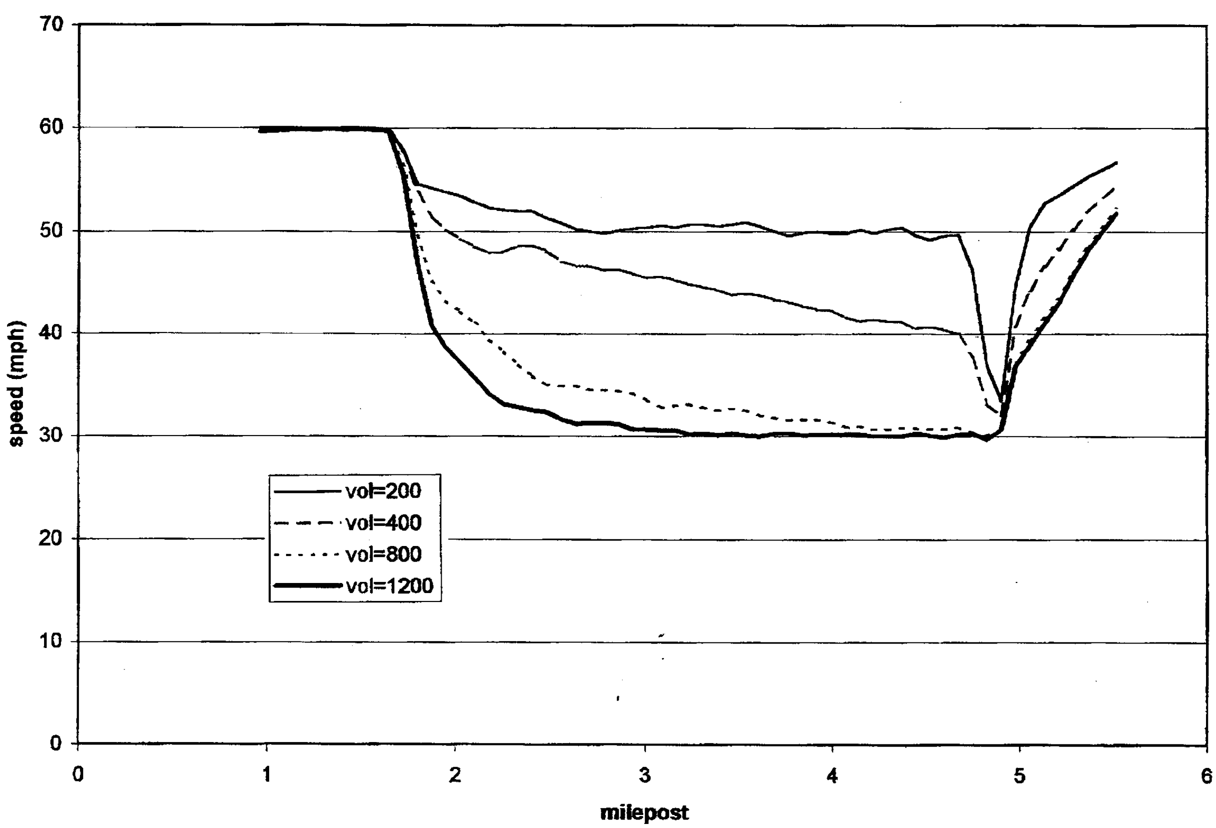


Figure 19. Simulated Speeds of Mixed Traffic on a Downgrade Including 10% Trucks with a Crawl Speed of 30 mph

D. CASE STUDIES SUMMARY

The case studies demonstrate that VDANL has the ability to predict the detailed dynamic behavior of vehicles, while TWOPAS can appropriately model traffic interactions. Regarding upgrade operations, VDANL's automatic transmission shifting appears to be adequate for downshifting as speed declines on a grade. TWOPAS also predicts climbing speeds based on truck upgrade performance characteristics associated with power to weight ratio. Upgrade speed profiles from VDANL and TWOPAS can then be used to assess the need for climbing lanes.

For downgrades, VDANL accounts for brake heating and brake fade that can lead to truck runaway conditions. TWOPAS can account for crawl speeds on downgrades, but does not model the effects of brake heating. Both VDANL and TWOPAS lack a downgrade speed selection model, so that appropriate speed profiles are not represented according to truck weight and downgrade steepness and length.

For horizontal curves, both VDANL and TWOPAS will slow appropriately to maintain modest lateral accelerations. In addition, VDANL also models the cornering limits of vehicles, and can properly account for rollover in cases of excessive cornering acceleration. The TWOPAS traffic interaction capability allows additional predictions of traffic speeds with various levels of traffic volume with and without climbing or passing lanes.

VI. PROPOSED MODEL ENHANCEMENTS

A. OVERVIEW

This section suggests VDANL and TWOPAS model enhancements that will improve the IHSDM design process. These enhancements relate to the characteristics of heavy vehicles (i.e. beyond light passenger vehicles) which are marginally powered for maintaining speed on upgrades, and may have brake overheating problems on long downgrades. The power-to-weight ratio and gearing of a given vehicle will determine the steady speed it can maintain on given upgrades. On downgrades, vehicles must dissipate the change in potential energy due to decreasing altitude through a combination of aerodynamic and rolling drag, engine braking, wheel brakes and retarders. Vehicles that experience brake overheating may lose control over speed and the driver may then have to take advantage of available escape ramps. Speed selection for downgrades depends on grade length, steepness and vehicle weight as discussed in Appendix E. A mathematical model for driver speed and gear selection on downgrades has been developed and validated for 18 wheel tractor/trailer rigs as developed in References [4] and [5] and summarized in Appendix E. Neither VDANL nor TWOPAS currently have such a speed selection model, and this is an area of commonality of modeling that would greatly benefit both programs. The suggested model enhancements include enhancements that are necessary to the upgrade and downgrade analysis software described in Appendices C and D, as well as enhancements that are not necessary to the IHSDIM software, but will improve the accuracy and utility of the models. Appendices C and D specify which improvements are essential to the upgrade and downgrade software.

B. VDANL

1. Wheel Brake Systems

Section M in Appendix A of reference [2] describes the VDANL_IHSDM braking model. The VDANL_IHSDM model takes a composite approach to the entire brake system. Rather than model each component of the system individually, the entire system is modeled as a whole, and the model parameters describe the overall brake system performance.

For vehicles with air brake systems, brake torque is set as a linear proportion of brake pedal force. Two gain terms are used, and control the brake-torque-to-pedal-force ratio for wheels on the steer axle, and the drive and trailer axles. The assumption is made that the brake gain for the drive and trailer axles are the same.

VDANL_IHSDM models the dynamics of the brake-torque-to-pedal-force ratio using separate first order times constants for the steer axle, the drive axle(s), and the trailer axle(s).

Vehicle brake adjustment is modeled in VDANL_IHSDM using the brake torque multiplier parameters to reduce the brake torque gain for a particular wheel. This is a per-wheel brake torque multiplier that can be used to increase or decrease the brake torque for each wheel individually above or below what is computed from the basic brake model. For brake system adjustment modeling, this can be used to have an equivalent effect at a particular pressure, but will not model the behavior at other pressures without changing the torque multiplier parameter.

A brake thermal model is included, which is based on the model developed in [4]. The model uses an energy balance equation for the brakes on each axle. The energy balance equation is of the form:

$$\begin{pmatrix} \textit{Rate of change of} \\ \text{internal } \textit{energy} \\ \textit{in brake system} \end{pmatrix} = \begin{pmatrix} \textit{Rate of conversion} \\ \textit{of mechanical} \\ \textit{energy to heat} \\ \textit{in brake system} \end{pmatrix} - \begin{pmatrix} \textit{Rate of heat} \\ \textit{transfer from} \\ \textit{brake system} \end{pmatrix}$$

In VDANL_IHSDM, the model assumes that both brakes on the steer axle are at the same temperature, and that all brakes on the drive and trailer axles are at the same temperature. All of the parameters for the thermal model are hard coded in the program, and are taken from reference [4]. VDANL_IHSDM contains a brake fade model which linearly reduces brake torque based on the brake temperature above 90 degrees F (assumed to be the ambient temperature). There is a single parameter for all brakes that sets the reduction in brake torque.

2. Rolling and Aerodynamic Drag

VDANL needs additional drag terms to complete the total drag (F_{drag}) formula given earlier, and possible additional terms that prove to be significant in recent SAE *RR* (tire rolling resistance) expressions. This may require the addition of terms associated with inverse and linear forward velocity and the product of weight and velocity. A tire pressure term may be important for passenger vehicles, but may not be as critical for heavy trucks. Additional research will be required to determine the most significant terms to be included. This research will require data on modern long haul trucks as discussed further on. The treatment of the inverse velocity term as velocity approaches zero also needs some additional work to determine the zero speed limit value of this term. VDANL currently has a simple drag term that is proportional to weight, and an aerodynamic term that is a function of the square of forward velocity.

3. Engine Braking Systems and Retarders

The VDANL_IHSDM engine drag model is sufficient to model the retarding force from an engine with no exhaust flap and/or throttle valve. A separate model should be added to the engine model that computes the retarding force from an engine braking system. This empirical model should be of the same form as the engine drag model; however, it should be turned on/off by the driver model or a user-specified control file. The equation for the engine braking system should be:

$$T_{brake} = K_{E_7} + K_{E_8}\omega_E + K_{E_9}\omega_E^2$$

where the K_{E_i} are polynomial coefficients and ω_E is engine speed in rad/sec. T_{brake} should be added to engine torque, T_E, when the engine brake system is activated.

Modeling of electrodynamic or hydrodynamic retarders can be broken down into four issues. First, what is the form of the retarders torque versus input shaft speed relationship. Secondly, what is the effect of temperature on this relationship and how should the temperature be computed/modeled. Third, where is the retarder installed: between the engine and transmission or between the transmission and drive axle. This will determine the input speed for the retarder and where the retarder torque should be applied. The final issue is how is the retarder controlled: by the driver model, or by a user-supplied control file.

The literature review indicates that the torque/speed curves of both types of retarders are similar to those shown in Figure 20. For the purposes of IHSDM, modeling the exact shape of these curves is not critical, and a simple empirical model can be used. This will keep the number of parameters in the VDANL_IHSDM data set manageable. The curves in Figure 20 were generated using an equation of the form:

$$T_{retarder} = T_{\max}\left(1 - e^{-S_{retarder}\omega_R}\right)$$

where $T_{\max}$ is the maximum retarder torque, ω_R, is the input shaft speed in rad/sec, and $S_{retarder}$ is the shaping parameter that determines how quickly the retarder reaches full torque. It is proposed that this empirical model be used in VDANL_IHSDM.

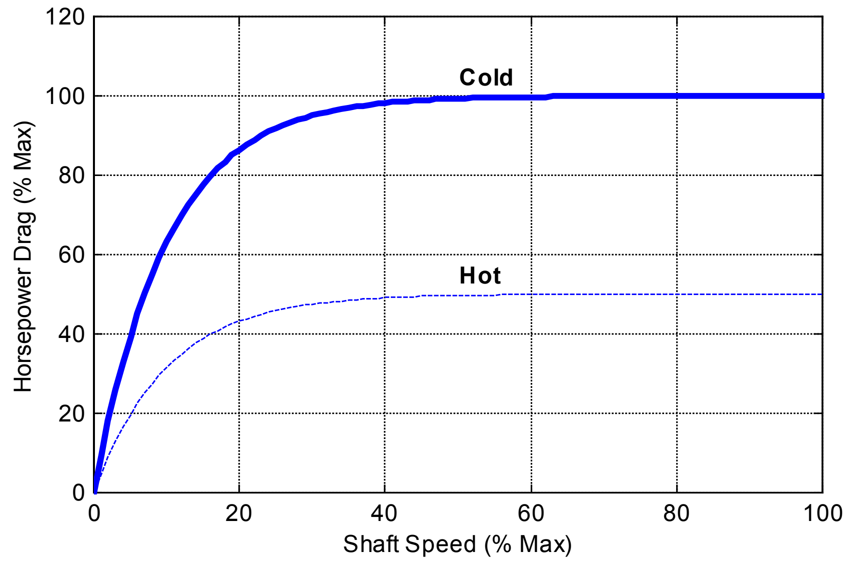


Figure 20. Generic Retarder Horsepower Dissipation Both Hot and Cold

The thermal model for the retarder is of the same formulation as the brake system thermal model. The proposed brake thermal model for each will use the following equations:

$$m_R C_R \frac{\partial T_R}{\partial t} = HP_R - h_R A_R \left(T_R - T_\infty\right)$$

where:

m_R	=	Effective mass of the retarder (*lbm*)
C_R	=	Effective specific heat capacity of the retarder (*Btu/lbm-* °F)
T_R	=	Temperature of retarder (*°F*)
HP_R	=	Power input into the retarder (*Btu*/sec)
h_R	=	Effective heat transfer coefficient of the retarder (*Btu*/sec-ft^2-°F)
A_R	=	Effective surface area of the retarder (ft^2)
T_∞	=	Ambient temperature (°F)

The power input into the retarder is the product of retarder torque, $T_{retarder}$ (*ft-lb*), and retarder speed, ω_R (*rad/sec*), given by:

$$HP_R = T_{retarder}\omega_R 1.285\cdot 10^{-3} \quad \left(\frac{Btu}{\sec}\right)$$

The effective heat transfer will be modeled as a linear function of vehicle speed, u (*ft/sec*) by:

$$h_R = K_{hRo} + K_{hR1} u \quad \left(\frac{Btu}{\sec \cdot ft^2 \cdot {}^\circ F} \right)$$

Where K_{hRo} and K_{hR1} are model parameters. The model is numerically integrated using the VDANL_IHSDM integrator in the same way as the brake thermal model. The equation to be integrated is:

$$T_R(t) = \int \frac{HP_R - h_R A_R \left(T_R - T_\infty \right)}{m_R C_R} \partial t$$

The reduction in retarder torque as its temperature increases is an important issue. A linear reduction in torque with temperature rise is proposed. Using the same form as the brake fade model, the proposed model is:

$$T_{retarder} = T_{retarder} \left[1 - K_{Rfade} \left(T_R - T_\infty \right) \right]$$

Where K_{Rfade} is the coefficient that controls the reduction in retarder torque with temperature rise.

The retarder input speed and output torque are treated differently for Primary and Secondary retarders. For Primary retarders, mounted between the engine and transmission, the retarder input speed, ω_R, is set equal to the transmission input speed, ω_C. The output torque, $T_{retarder}$, is added to the transmission input torque, T_C. For Secondary retarders, mounted between the transmission and differential, the retarder input speed, ω_R, is set equal to the transmission output speed, ω_T. The output torque, $T_{retarder}$, is added to the transmission output torque, T_T.

4. Engine

The basic form of the VDANL_IHSDM engine model is appropriate for modeling truck upgrade and downgrade performance. There are some engine torque nonlinearity's in actual engine performance that can not be accounted for in VDANL_IHSDM's empirical engine torque function. To overcome this limitation, it is proposed that the throttle position in the engine torque equation be made a nonlinear function of the throttle specified by the driver model. The proposed equations for engine torque are:

$$\theta_T' = 1 - e^{-K_{T_1} \theta_T^{K_{T_2}}}$$
$$T_E = \left(K_{E_1} + K_{E_2} \omega_E + K_{E_3} \omega_E^2 \right) \theta_T' + \left(K_{E_4} + K_{E_5} \omega_E + K_{E_6} \omega_E^2 \right) \left(1 - \theta_T' \right)$$

where $\theta_T^{'}$ is the adjusted throttle used in the engine torque equation and K_{T1} and K_{T2} are shaping coefficients for the adjusted throttle versus throttle input function. To maintain compatibility with existing VDANL_IHSDM data sets, if K_{T1} and K_{T2} are not specified in a parameter set, then $\theta_T^{'}$ should be set equal to θ_T and the engine torque will change linearly with throttle input at a constant engine speed.

5. Transmission and Differentials

Heavy truck transmissions often have a high and low range, and a five speed transmission with two ranges would have ten forward gear ratios. Some truck transmission options (e.g. offered by Peterbilt for Fuller and Rockwell transmissions, http://www.peterbilt.com/pb/trukfram.htm) allow for 9, 10, 13, 15 and 18 gears. For the purposes of VDANL_IHSDM, there is no difference between a ten speed transmission and a five speed with two ranges. Therefore, there is no need to add multiple ranges to the transmission model. However, the current limit of eleven forward gears may be insufficient for some trucks. It is recommended that the upper dimension of the transmission variables be changed from eleven to twenty.

If it is desired to allow secondary retarders to be simulated on trucks with multiple speed differentials, then VDANL_IHSDM must be upgraded to allow multiple speed differentials. Parameters K_{DF} and K_{DB} are the front and rear differential ratios (lines 2 and 3 of the drivetrain parameter file). K_{DF} and K_{DB} will need to be changed from single variables to arrays and multiple ratios will be specified. Logic for changing differential ratio will have to be added to the driver model (described in section of driver modeling).

6. Downgrade Speed Control and Gear Selection Driver Model

Both VDANL and TWOPAS can use a downgrade speed selection model as defined in [4] and [5] that give the complete equations and tips for applications. The equations are quite nonlinear, and will require a solution procedure to be added as discussed in Appendix E. The inputs to the solution procedure will be the vehicle type and weight and grade description. Figure 21 gives example maximum speeds for an 80,000 lb five-axle truck in terms of a simple description of length and percent grade. It should be noted that the implementation of this grade severity speed selection model would also provide a direct measure of grade severity. As noted earlier, the slope of the constant grade lines in Figure 21 is a direct indication of grade severity. The speed selection model can be implemented to provide this slope as an indication of grade severity:

$$\text{Grade Severity Metric} = \left.\frac{dV_{\max}}{dL}\right|_{grade=const.}$$

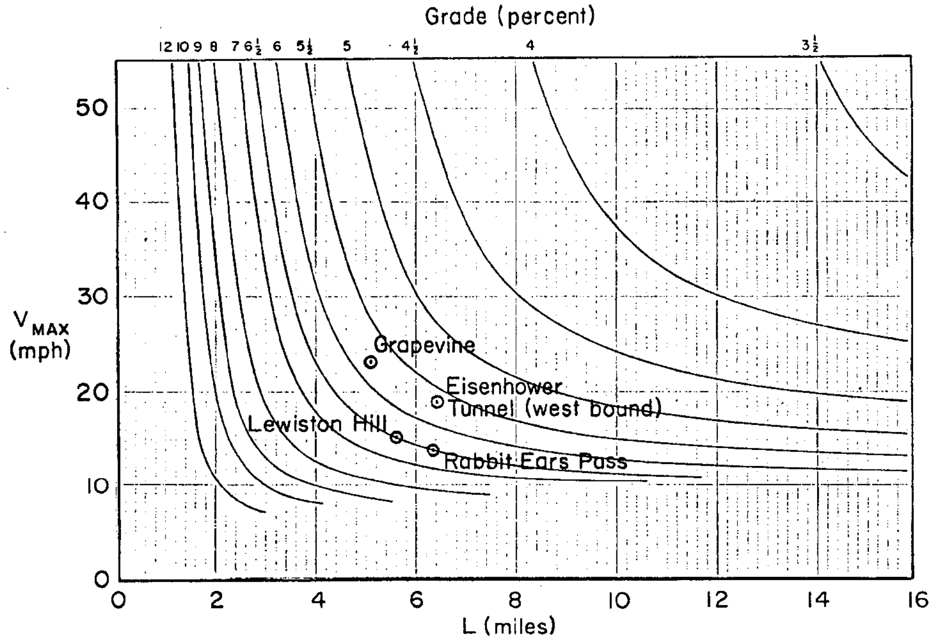


Figure 21. Maximum Safe Downgrade Speed for Five Axle Trucks with an 80,000 lb Load
(Adapted from Ref. 6)

This metric is a direct measure of the maximum descent speed sensivity to length. Grade severity is directly related to this metric, and a grade with a smaller absolute value would be a less severe grade.

The procedures for determining maximum speeds for multiple grade hills are discussed in detail in [4] and [5] and summarized in Appendix E. Different parameter sets are required for vehicles other than five-axle trucks, and will require future research. The effect of a retarder should be accounted for as an equivalent wight decrease [6]:

$$\Delta W \frac{375 \bullet \Delta HP_R}{\theta \bullet \bar{V}}$$

where ΔHP_R is the horsepower absorbed by the retarder, θ is the grade slope and $\bar{V}$ is vehicle speed. This procedure will have to be expanded for multiple grade hills along with the speed selection algorithm.

For downgrade descents VDANL will also need logic for gear selection that will result in maximum engine RPM (i.e. maximum engine braking) at the desired maximum speed.

7. User Interface

The user interface is critical for programs that will be used as applications by users not familiar with their intricacies and underlying theory. The program interface should allow the user to select reasonable operating conditions through menus that clearly present meaningful options necessary for desired analyses. Results from running the program should also be presented in a clear, meaningful fashion.

VDANL currently allows roadway design analysis through selection of one of twelve AASHTO vehicles, a specified speed profile or a speed limit and desired cornering acceleration. Output options allow the user to produce vehicle performance plots as a function of the roadway design station. Vehicle performance measures include lateral acceleration, lateral lane position and variables directly related to rollover including roll angle and lateral load transfer. A series of roadway safety metrics and station of occurrence are also available including the maximum values of friction demand, roll angle, lateral load transfer and lateral acceleration.

Given the enhancements discussed in this report, the specification of additional input options will be required. These options will involve vehicle performance including horsepower, weight and retarder availability. The options could be expressed as standard vehicle configurations such as are currently defined for TWOPAS, or alternately the specific operating conditions could be individually specified. Additional output options should include brake temperature which is directly related to downgrade descent safety.

C. TWOPAS

Five recommended enhancements to the TWOPAS model have been identified to make the model a more useful tool in evaluating traffic operations on upgrades and downgrades. These enhancements are:

Upgrades

- Increase the number of truck types or permit specification of a range of truck weight-to-power ratios for each truck type
- Increase trucks speeds on approaches to upgrades
- Update basic parameters in truck performance equations

Downgrades

- Automate determination of crawl zone locations and crawl speeds of specific trucks
- Test and, if necessary, improve capability to simulate crawl speeds for RVs

Each of these recommended enhancements is discussed below. The research required to implement these enhancements is discussed in the next section of the report.

1. Increase the Number of Truck types or Permit Specification of a Range of Truck Weight to Power Rations for Each Truck Type

Currently, TWOPAS allows 13 vehicle types to be specified, of which 5 are passenger cars, 4 are RVs, and 4 are trucks. The performance of the 4 truck types on grade is simulated using truck performance equations that are distinctly different from the performance equations used for passenger cars and RVs. Each truck type has a specified value of weight-to-power ratio and weight-to-frontal-area ratio. As such, the performance capabilities of trucks are limited to four unique sets of values. On level terrain, this is generally satisfactory because driver characteristics (e.g., normal desired speed) cover a range of values, so the actual truck speeds will be spread over a range and are not simply limited to four values. However, on a modest or steep grade, truck drivers will normally use maximum available power and may still not be able to maintain their desired speed. In this situation, in the absence of other traffic or horizontal curves with reduced speeds, all truck speeds will be reduced to precisely four values. This not sufficiently realistic to permit assessment of upgrade traffic operations.

Figure 22 shows the cumulative distribution of 248 truck crawl speeds measured fairly recently by MRI on a long 4.37% grade in California as part of NCHRP Project 3-55(3). They ranged from a low of 17 mph to a high of 65 mph, plus one outlier at 71 mph. From the truck speeds, using the TWOPAS truck performance equations, the weight-to-power ratio can be deduced. Also shown on the figure are the speeds of the four TWOPAS truck types, with maximum speeds on this grade of 22, 27, 33, and 48 mph, respectively.

One possible means to enhance the TWOPAS model is to expand the number of truck types beyond 4, to better represent the distribution of truck performances shown in Figure 22. Conceptually, this would seem to be a fairly simple change to program. However, familiarity with the TWOPAS model suggests otherwise. There are many variables in the program subscripted by vehicle type (i.e., in arrays with a dimension of 13) and other variables subscripted by vehicle category (passenger car, RV, and truck) which can be determined from the vehicle type. Since vehicle types are central to the program, extensive changes to the program logic would be necessary. This would require a major effort for programming and debugging to make sure that the additional truck types were implemented without affecting the operation of the program.

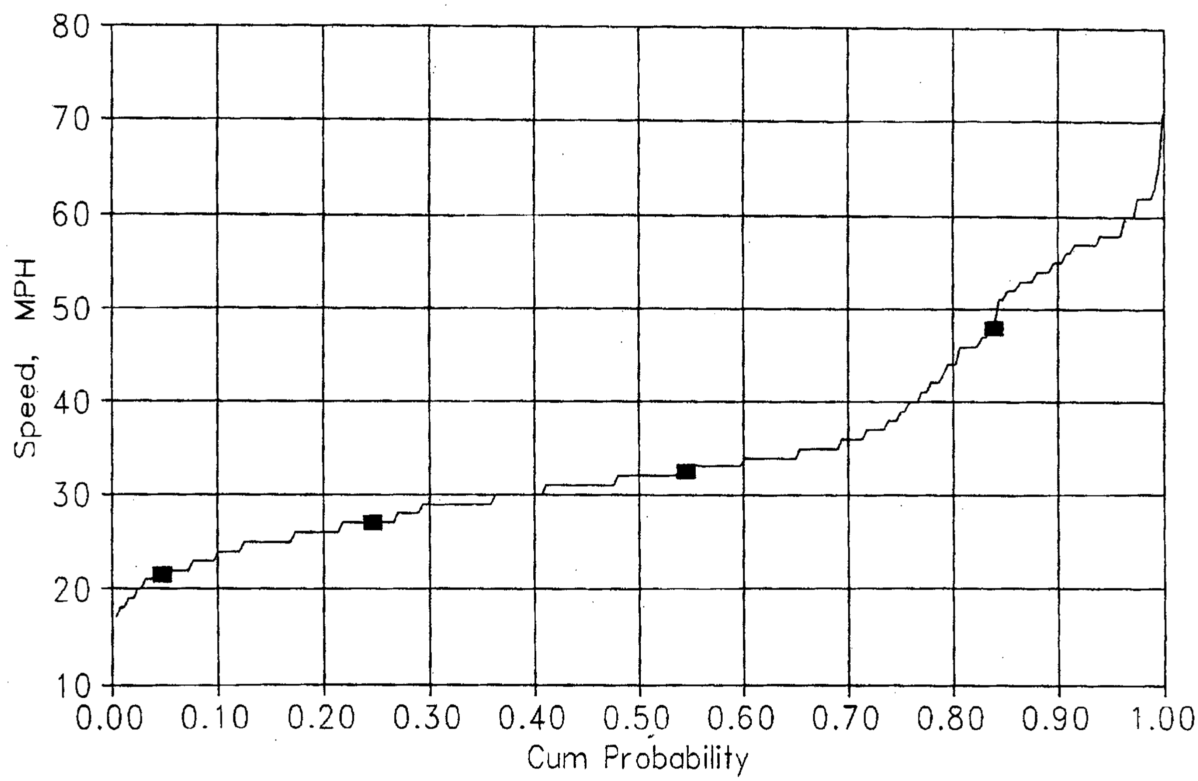


Figure 22. Cumulative Distribution of Truck Crawl Speeds Measured a Long 4.37% Grade

An alternative approach to achieving the desired result of a greater variation in truck characteristics would be to assign to each of the four truck types not a single value for weight-to-power, but rather to assign, for example, a mean and a standard deviation, much as is done with desired speeds. That way, when a truck is "created" at the beginning of a simulation run, its driver is assigned a desired speed from the desired speed distribution, and the weight-to-power ratio is assigned from the weight-to-power ratio distribution for that truck type. Desired speeds are assigned according to the normal distribution. Figure 22 suggests that a normal distribution is not appropriate for the distribution of truck weight-to-power ratios. Therefore, instead of a mean and standard deviation of weight-to-power ratios, it might be more desirable simply to specify points on the cumulative distribution curve of weight-to-power ratio for each truck type.

As noted above, TWOPAS uses not only the weight-to-power ratio, but also the weight-to-frontal-area ratio, in modeling truck characteristics. Logic would need to be provided so that as each truck is assigned a weight-to-power ratio, it is assigned a weight-to-frontal-area ratio that is consistent with (or, at least, not inconsistent with) its weight-to-power ratio.

If a distribution of truck characteristics is assigned to a truck type, as discussed above, then in theory it might not be necessary to have four truck types; one could do for many TWOPAS applications. However, it is recommended that the four truck types be retained because this makes it possible to evaluate explicitly the traffic operational effects of incorporating unique truck types into the traffic stream. In other words, if the distribution of existing trucks were to be represented by Truck Type 1, then Truck Types 2, 3, and 4 could be used to analyze the effects of introducing heavier, lower-powered trucks, such as turnpike doubles or triples, into the traffic stream.

2. Increase Truck Speeds on Approaches to Upgrades

It is commonly observed that many truck drivers will, as they approach an upgrade, accelerate to a higher speed than they were using on the level alignment (their desired speed), so as to lessen the amount of speed decrease on the upgrade. This practice is perhaps more common with shorter grades, as with longer grades the truck speed will be reduced to a crawl speed anyway. TWOPAS presently does not model this phenomenon, but it is recommended that this be added to the model. Incorporating this phenomenon in the model may have some impact on determining where a climbing lane should start, or in some instances, whether one is even needed.

3. Upgrade Basic Parameters in Truck Performance Equations

The mathematical modeling of truck performance in TWOPAS is believed to be conceptually sound. However, the model contains a number of numerical parameters such as rolling resistance, aerodynamic resistance, drive train losses, gear shift delays, and effect of altitude on engine performance, whose values were established in the mid-1970's based on truck characteristics of that time. In the mid-1980's, some minor revisions were made. However, with improvements in truck technology, it is possible that some of these parameters may need adjustments. Therefore, it would be desirable to update these parameters, as needed, to represent the current truck fleet.

4. Automativc Determination of Crawl Zone Locations and Crawl Speeds for Specific Truck Types on Downgrades

TWOPAS currently has the capability to simulate trucks operating at crawl speeds on downgrades. However, the current logic has a number of limitations:

- The locations of downgrade crawl regions must be specified by the TWOPAS user. The program lacks the capability to determine for itself which downgrades are long and steep enough that drivers of heavy vehicles would use crawl speeds.

- The TWOPAS user must specify which heavy vehicle types (trucks or RVs) would use crawl speeds within the specified crawl zones and which would not. The program lacks the capability to determine for itself which heavy vehicles would need to crawl down specific grades.
- The TWOPAS user must specify the distribution of crawl speeds (mean and standard deviation of an assumed normal distribution) for each individual crawl zone. The mean and standard deviation of crawl speed can vary from one crawl zone to another, but within any specific crawl zone all trucks that crawl have crawl speeds drawn from the same distribution.

To remove these limitations, it is recommended that TWOPAS should be modified to incorporate logic that evaluates each downgrade on the specified roadway for each type of heavy vehicle that is present in the traffic stream and determines:

- whether that vehicle type will crawl down that particular grade and
- if so, what crawl speed (or distribution of crawl speeds) will that vehicle type use on that grade.

The key parameters in making this determination would be the weight of the truck and the length and steepness of the grade. Past research on grade severity ratings, together with the capability of VDANL to simulate brake temperatures on downgrades, should provide sufficient data to improve the crawl zone logic for trucks.

5. Test and, If Necessary, Improve Capability to Simulate Crawl Speeds for RVs

Not only trucks, but RVs (and even, in some extreme conditions, passenger cars) use crawl speeds on some grades. TWOPAS has the capability to simulate downgrade crawl speeds for RVs and passenger cars, as well as trucks, but only when the user specifies that particular types of RVs or passenger cars should use crawl speeds and only when those crawl speeds are specified by the user. However, this logic for RVs has never been fully tested. Furthermore, unlike trucks, there does not exist any research study or data base of which we are aware that indicates whether, and at what speed, RVs are likely to crawl on specific downgrades. Thus, improvement of the crawl zone logic will require substantially greater effort for RVs than for trucks because field data collection is likely to be required.

VII. RESEARCH REQUIREMENTS FOR MODEL ENHANCEMENTS

A. VDANL

A range of vehicle parameters are needed for the VDANL enhancements proposed herein as summarized below:

1. Engine and Transmission Characteristics

A survey of modern engine and transmission characteristics would be appropriate to account for recent trends in increased horsepower (this data is not ordinarily reported in the open literature). This effort would probably require soliciting truck and engine manufacturers and organizations such as the American Trucking Association.

Drag Modeling

Modern trucks also have improved drag properties, including aerodynamics and tires. Figure 23 gives some reasonable data for aerodynamic coefficients. Rolling resistance is the area most in need of data for modern vehicles. This data can be obtained with roll down tests at various loads. Data can be collected with a speed sensor and longitudinal accelerometer. Data acquisition can be easily provided by a laptop computer. Tire manufacturers also should be solicited for rolling drag data.

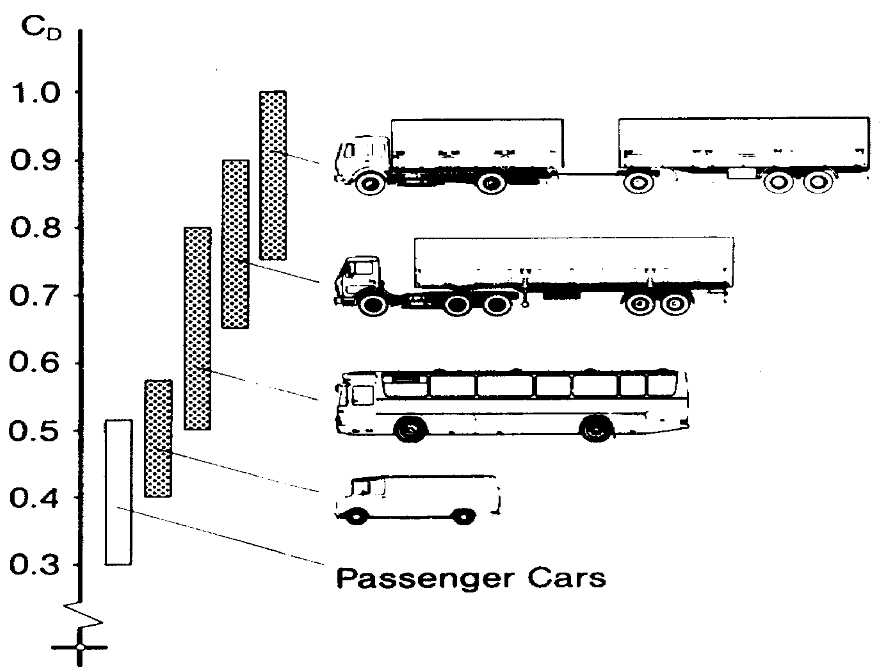


Figure 23. Aerodynamic Drag Coefficients for Various European Vehicle Designs (Adapted from Ref. 45)

Brake Thermodynamics

Braking thermodynamics are a key factor in overheating and fade which lead to runaways. Thermodynamic tests can be conducted by instrumenting brake lining material with thermocouples or using non-contact pyrometers. Additional instrumentation would include speed sensors and longitudinal accelerometers. Coast down and downgrade braking tests are then performed as discussed in [4] and Appendix E. Data acquisition can easily be provided with a laptop computer.

B. TWOPAS

This section discusses the research required for the five TWOPAS model enhancements identified previously. Each individual enhancement is discussed below.

Increase the Numbers of Truck types or Permit Specification of a Range of Truck Weight-to-Power Ratios for Each Truck Type

The recommended change to the model logic is to introduce an option for the user to specify a distribution of weight-to-power ratios for a specific truck type rather than a single-value of weight-to-power ratio. The weight-to-power ratio of each truck would then be generated randomly from that distribution as each truck is "created" at the beginning of a simulation run. The development of program logic to accomplish this is relatively straightforward and can be accomplished without additional field data collection.

One issue that must be addressed is how the weight-to-frontal-area ratios of trucks would be determined if the logic for assigning weight-to-power ratios is changed. The weight-to-frontal-area ratio is important in modeling the effect of aerodynamic drag on truck performance. If weight-to-power ratio for a specific vehicle type is represented by a distribution of values (which might cover a very broad range), it would not be reasonable to retain a single value of weight-to-frontal area ratio for that vehicle type. Two options are available:

- Develop a "rule of thumb" for estimating the weight-to-frontal-area ratio for the value of the weight-to-power ratio.
- Specify a distribution of weight-to-frontal-area ratios for each vehicle type, just as the distribution of weight-to-power ratios is specified. Use the same random number to select both the weight-to-power ratio and the weight-to-frontal-area for each individual truck. This will assure that the both the weight-to-power ratio and the weight-to-frontal-area ratio for each truck represent the same percentile of their respective distributions.

Each of these approaches would require collection of additional field data to implement successfully because the available data on weight-to-frontal-area ratios for trucks are limited. It is recommended that additional field studies like those used to develop Figure 22 be performed and that the data be used to develop corresponding default distributions for weight-to-power ratio and weight-to-frontal area ratio.

One portion of the TWOPAS logic would have to be enhanced if distributions of truck characteristics were implemented. It deals with passing on an upgrade. Current passing logic includes an examination of whether a potential passer would gain significant advantage by performing the passing maneuver, vs. following its leader at the leader's desired speed. If the leader and the potential passer have nearly the same desired speeds, the potential passer will not be sufficiently motivated to pass, so will follow. On an upgrade, however, it is not so much desired speed as vehicle capability that may govern passing maneuvers.

If truck A has a maximum speed of 30 mph on a given grade, and truck B has a capability of 31 mph, the current logic may cause truck B to initiate a passing maneuver. With the small differential in truck speeds, the two trucks would then essentially block both lanes to passenger vehicles capable of 60 or more mph. (In this example, if truck B has a flying start at the passing maneuver -- e.g. it is already traveling at 31 mph -- it will require over 0.8 miles to complete the maneuver, assuming each truck is about 60 ft long and 15 ft of clearance between trucks before and after the pass are required. If truck B has to accelerate to 31 mph from 30 mph, a longer distance will be required because truck B can reach 31 mph only asymptotically.) It is expected that truck drivers do not normally create such situations; they initiate passes on upgrades only if they believe they can complete them over a reasonable distance. Field data would be needed to place realistic bounds on such passing behavior, and then the model would have to be modified to incorporate appropriate logic.

Increase Truck Speeds on Approaches to Upgrades

It is known that truck drivers often increase their speeds on approaches to upgrades, but there are no field data available of which we are aware that indicate the magnitude of the speed increase or the distance in advance of the upgrade at which it begins. Therefore, a field study of truck speed profiles on approaches to upgrades will be required to implement this improvement.

Once the field study is complete and the data have been analyzed, the development of the program logic to implement truck speed increases on approaches to upgrades should be relatively straightforward. This will require introduction of an approach region for each upgrade, within which trucks may exceed their desired speed. The logic for such approach regions would be analogous to the approach regions for horizontal curves and crawl zones that are already in the program, except that trucks would increase rather than decrease speed within the approach region to an upgrade. Testing of the new logic would be needed to assure that lower speed features, such as horizontal curves, negated any effect on truck speed that might be attributed to an approaching grade.

Update Basic Parameters in Truck Performance Equations

It is recommended that basic parameters in the TWOPAS truck performance equations -- such as rolling resistance, aerodynamic resistance, drive train losses, gear shift delays, and effect of altitude on engine performance -- should be updated from their existing values (determined in the mid-1970's and updated during the 1980's) to values more representative conditions. Such an update will require a thorough review of truck manufacturer's literature, and possibly field data collection. However, before such data collection is undertaken, it is recommended that a sensitivity analysis be performed to determine whether the likely changes in these parameters are sufficient to have a substantial effect on the macroscopic output of the model.

To perform this sensitivity analysis, the parameters of interest should be adjusted some amount, perhaps 10 to 20 percent, probably one at a time, and the changes in performance noted. Acceleration performance on level terrain and reduced crawl speed on an upgrade should be examined. If the effect is minimal, then perhaps no further work would be required. For example, for the heaviest trucks, crawl speed on a significant upgrade will be so low that aerodynamic drag will be quite unimportant, although aerodynamic drag will be very important in determining top speed on level terrain or on a downgrade.

For those parameters found to be of importance in predicting some aspect of the trucks performance, efforts should be devoted to quantifying values representative of current conditions. Literature should be of some assistance, as should contacts with vehicle manufacturers, and acquisition of manufacturers' literature. As a last resort, experimentation and/or field data collection may be required.

Automatic Determination of Crawl Zone Locations and Crawl Speeds for Specific Truck Types on Downgrades

It is anticipated that the determination of crawl zone locations and crawl speeds for specific truck types in TWOPAS can be automated using existing data without the need for extensive field data collection. The two primary resources that will be used for this effort are the downgrade severity rating system developed for FHWA by STI. and the VDANL model which can simulate brake temperature as a truck proceeds down a grade and can thus be used to determine the crawl speed (and corresponding gear) required to avoid a runaway truck. We do not see any advantage in trying to incorporate the VDANL brake temperature logic in TWOPAS. Instead, VDANL can be used as a research tool to determine which combinations of steepness and length of grade will require specific truck types to use crawl speeds and what those crawl speeds need to be. Those results can then be used to develop program logic to incorporate in TWOPAS.

One issue that needs be addressed in implementing this logic is that evaluation of downgrade truck operations requires data on the weight of the truck. Currently in TWOPAS, the weight-to-power ratio and the weight-to-frontal-area ratio of the truck are specified, but the weight of the truck itself is not. Either TWOPAS would need to be changed to specify truck weights explicitly or logic would need to be developed to estimate representative weights from the available performance data. This could require field data. Such data might be obtained in conjunction with the evaluation of weight-to-frontal-area of trucks recommended above as part of the change in the manner in which truck performance characteristics are specified for upgrades.

The revised program logic will need to be extensively tested. In addition to normal downgrades, testing should also include downgrades with passing lanes to assure that the crawl-speed logic and passing-lane logic are compatible with one another. In particular, as noted above for climbing lanes on upgrades, logic should assure that a truck with a very small speed advantage in crawl speed over another truck does not try to pass on the downgrade, thereby denying passing opportunities to vehicles (such as passenger cars) with greater speed advantages.

Test and, If Necessary, Improve Capability to Simulate Crawl Speeds for RVs

The improvements to TWOPAS needed to simulate crawl speeds for RVs are similar to those for trucks, but will require a greater effort to implement. There is no existing guide for RV gear selection or crawl speeds on downgrades similar to the STI downgrade severity rating system for trucks. Therefore, development of crawl-speed logic for RVs is likely to require extensive field data collection on downgrades that are long and steep enough to require RVs to use crawl speeds. Appropriate study locations are likely to be found in the western United States and in the Canadian Rockies.

APPENDIX A – OTHER VDANL FEATURES

1. Brake Systems

Chapter 8 of reference [27] presents a plot of three different trailer brake chamber air pressure responses to a rapid application of the brake pedal. Figure 2.4.3 of reference [28] shows the measured time response of brake pressure for both a drive axle and trailer axle brake. All of the responses shown are basically a time delay followed by a "first-order like" rise in chamber pressure. The time delays are on the order of 50 to 200 milliseconds, and the first order time constants on the order of 250 to 350 milliseconds. While many aspects of the brake system contribute to these brake pressure dynamics, typical modeling practice is to treat the system as a whole and model the overall effect of the system. Often an equivalent first order lag is used to model the entire response. For slightly more fidelity, a time lag can be added preceding the first order lag.

In actual air brake systems, brake chambers convert air pressure in the brake system into the force applied to the brake shoe. Brake chambers have a diaphragm that moves a piston through some stroke. Brake system adjustments, temperature, and wear can cause the initial piston position to change. For poorly adjusted brakes it is possible that during brake application, the piston can bottom out and not apply full force to the brake shoe. Detailed modeling of the force applied to the brake shoe involves specifying sizes of all brake system components from the piston diameter and stroke at the brake pedal to the brake chamber volume, diameter, and stroke. This level of detail is necessary for brake system designers. Simpler models that treat the overall brake system performance will use linear, bilinear, or nonlinear functions to specify brake torque as a function of pedal force.

Reference [29] contains results of testing on four heavy truck brake assemblies that show that the torque versus air pressure relationship is quite linear <u>at a given vehicle speed</u>. The data also shows that the brake torque gain decreases with increasing vehicle speed. At a given pressure, the measured brake torque at 40 mph is ten to twenty five percent lower that the measured torque at 20 mph for the four brakes tested.

Brake system thermal modeling reported in the literature, [4], [27], [29], [30], and [31] ranges from lumped parameter models treating the brake system as a whole, to detailed finite element models. Some of the lumped parameter models in the literature separate the brake system into components and model each as a separate thermal mass. This level of detail may be appropriate for a brake system designer. The level of detail and the computational burden of the finite element models make them undesirable for IHSDM. For overall brake system thermal affects, the entire brake system at each wheel can be modeled as a single thermal mass. For analysis of brake thermal properties during single hard stops, a heat flow equation can be used. The major assumption that is made is there is no appreciable heat loss during the stop. For downgrade brake thermal predictions, this is not appropriate. For modeling brake thermal properties during downhill descents, References [4] and [27] present a model using an energy balance equation. The assumptions are made that the entire brake system thermal mass has a constant temperature and that heat is dissipated during the stop. The power into the brake system is computed from the brake torque and the rotational wheel speed. The brake heat transfer is based on the effective heat transfer coefficient(s) as functions of differential brake system temperature above ambient and vehicle speed. This type of model is appropriate for IHSDM from both the parameter specification and computational perspective.

Brake torque fade due to increased temperature is a complex phenomenon, and modeling the details is beyond the scope of the IHSDM program. Few actual models are found in the literature, however, references [27], [28], [29] above and [32] do discuss the subject and a simple linear model is presented. The model presented uses a "fade factor" to adjust the brake torque from the "unfaded torque" as a linear proportion of the brake temperature difference from the ambient temperature.

2. Rolling and Aerodynamic Drag

In the vehicle dynamics longitudinal force equation, the sum of forces equals vehicle mass times longitudinal acceleration. The forces include components due to generated or absorbed power (engine, brakes and retarders) and drag due to tires, drive train components, aerodynamic resistance and road grade. The force balance under steady state conditions will affect top speed, maximum speed capability on upgrades, and speed selection on downgrades. Thus it is important to quantify each of the drag components. Drag terms can generally be classified into components due to chassis friction, rolling resistance and aerodynamic drag [4]. The drag components are of the form;

$$F_{drag} = \underbrace{(a+bW)/\overline{V}}_{\text{Chassis Friction}} + \underbrace{(c+d\overline{V})W}_{\text{Rolling Resistance}} + \underbrace{f\overline{V}^2}_{\text{Aerodynamic Drag}}$$

where F_{drag} is the total drag, W is the total vehicle weight, $\bar{V}$ is the forward velocity and *a, b, c, d,* and *f* are coefficients to be determined. VDANL currently has a simple weight term and an aerodynamic term. Recent research has led to a more complex formula for tires alone [33]. The formulas are complex exponentials, however, and not numerically convenient to implement. Also, data for the new tire drag formulation given in [33] may be hard to acquire. The SAE Committee on Rolling Resistance currently uses the formula [34]:

$$RR = A_0 + A_1 L + A_2 V + A_3 L^2 / P + A_4 L V + A_5 V^2$$

where RR = rolling resistance, P = inflation pressure, L = vertical load, V = speed and $A_1 - A_5$ are regression coefficients. There are common terms in the RR and F_{drag} equations, while there are some unique terms in each. The RR equation is intended specifically for tires, while the F_{drag} equation is a composite of tire and vehicle effects.

A reasonable review of truck drag components is given in [35]. Figure 24 shows the percentages of the various drag components in terms of their effect on fuel consumption for a diverse driving environment. Note that aerodynamic drag is most important for short vehicles, while rolling resistance becomes important for large vehicles. At higher speeds aerodynamic drag most likely dominates the majority of vehicles. Figure 24 gives ranges of aerodynamic drag coefficients for several classes of vehicles. These ranges are probably good enough for most applications of VDANL-IHSDM since aerodynamic drag scales properly with speed. At lower speeds rolling resistance will dominate, and terms associated with inverse velocity, linear velocity and linear load, and the product of velocity and load will be most important. As velocity approaches zero the chassis friction term involving inverse velocity approaches infinity which is physically impossible. This term needs some additional scrutiny. Ultimately, available data, ease of data collection and the importance of each of the terms will determine what components to include in a composite F_{drag} equation.

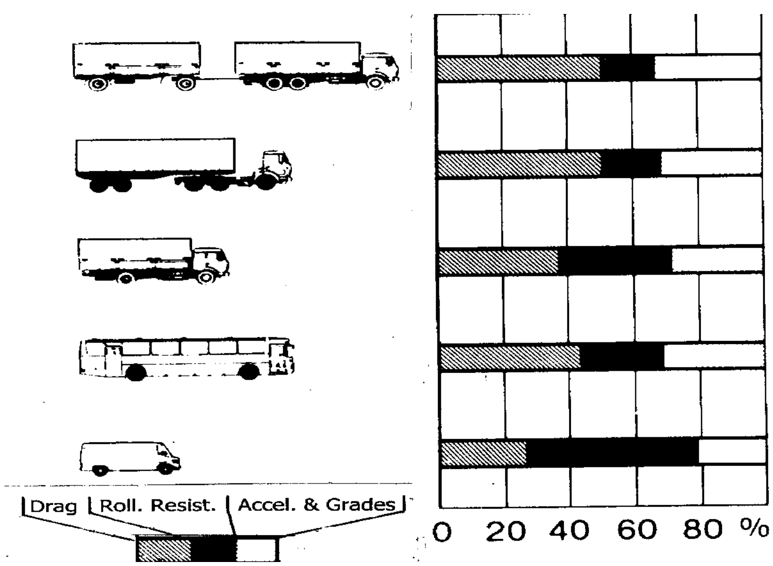


Figure 24. Fuel Consumption of Various European Vehicle Designs
(Adapted from Ref. 45)

3. Engine and Drive Train Retarders

References [28], [36], and [37] discuss heavy truck down hill braking and the use and operation of engine braking systems and retarders in detail. Engine braking systems use the drag caused by throttling the engine and often the exhaust flow to apply continuous drag to the drive wheels of the truck. This drag force increases with engine speed, and works through the transmission and differential. Engine braking systems are typically effective at low decent speeds, but can not supply sufficient drag at high vehicle speeds.

Retarders are mounted either between the engine and transmission (Primary Retarders), or between the transmission and the drive axle (Secondary Retarders). Retarders translate the mechanical energy in the shaft into heat. Both electrodynamic and hydrodynamic retarders are in use, and the energy dissipated by both is dependent on their temperature. As retarders get hot from use, they translate less energy into heat and become less effective.

Figure 25 shows a generic plot of the horsepower consumed by an engine braking system. This is the closed throttle horsepower consumed by the engine. Some systems increase the horsepower consumption of the engine be adding a pneumatically actuated flap in the exhaust system and/or an additional throttle valve to the combustion chamber. These valves are actuated by the driver or brake management system to assist the vehicles service brakes. Models for engine brake systems are straightforward. The basic engine braking is included in the engine torque (torque as a function of throttle

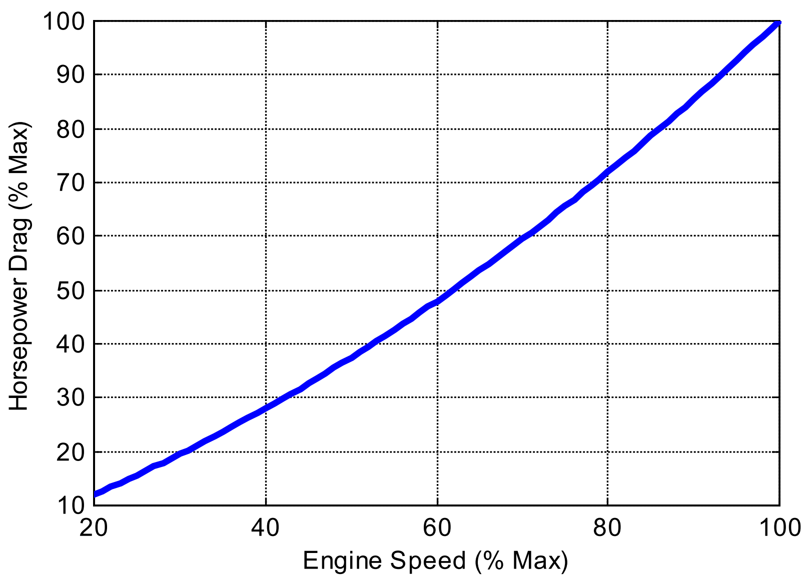


Figure 25. Generic Engine Braking System Horsepower Dissipation

and engine speed). For vehicles equipped with exhaust or throttle valves, a low order polynomial function of engine speed can be used to model the additional power consumed. This additional power consumed is then added to the engine power and is propagated through the drive-train model.

Electrodynamic and hydrodynamic retarders are somewhat more complex. If they are mounted as a primary retarder between the engine and transmission, their power consumption is added to the engine power like an engine braking system. If they are mounted as a secondary retarder on the output of the transmission, their power consumption is added to the transmission output torque. The added complexity of the retarders is that their power consumption is temperature dependent. This means that not only is a model required for their power consumption, a thermal model must be included.

Figure 20 shows a generic plot of the power dissipation by a retarder as a function of its shaft speed. The power dissipation is strongly influenced by the retarder temperature. However, no thermal models for retarders were found in the literature. With the assumption that the temperature buildup is fairly slow, a model with the same form as the proposed thermal would be appropriate. The assumptions would be that the entire retarder was at the same temperature (no temperature gradients), and that the heat transfer coefficient would be a function of retarder temperature above ambient and vehicle speed. An additional term, similar to the brake fade term would be added to the thermal model to linearly reduce the power consumption as a function of retarder temperature above ambient.

Little retarder data was found in the literature. Reference [36] presents measurement data from a few in-service retarders and engine brake systems. Unless more becomes available, either through a measurement program or directly from manufactures, the utility of retarder and engine brake system models will be greatly reduced.

4. Heavy Vehicle Engine Modeling

The literature on automotive and truck engine modeling divides the modeling approaches into two basic categories. First are the engine models composed of sub-models of its components [38], [39], [40]. These models are of varying complexity, but are typically used for studies on engine control systems design and engine performance tuning.

The second general type of engine model found in the literature are the empirical models, [1], [41], [42], and [43]. These models treat the engine torque generation as a quasi-static process and typically model the dynamic engine response with a first order time constant or first order differential equation. This class of model is appropriate for overall vehicle performance simulations like VDANL_IHSDM where only the vehicle performance is of interest, and "how the engine did it" is not.

The main portion of the empirical engine models is the function that describes the engine torque as a function of engine speed and throttle position. Reference [42] uses a two-dimensional table look up to specify the engine "torque map". A 200 point table is specified with engine torque at eight different throttle positions and 25 different engine speeds. Reference [1] uses an empirical function with six parameter to specify the engine torque as a function of engine speed and throttle position. Both models use a first order differential equations with a single lumped inertia for the entire engine to model the engine dynamic response.

5. Speed Control and Gear Selection Driver Model

During development of a prototype Grade Severity Rating System (GSRS), a mathematical model was developed for determining the safe descent speed of 5 axle trucks (i.e. tractor/semitrailer) [4]. This model determines the brake temperature at the bottom of a grade, which is primarily dependent on grade length and steepness, and truck weight and speed. Brake temperature is a direct correlate of a vehicle's ability to stop, and thus is an inferential measure of safety. The model can be used to determine at what maximum speed a vehicle can safely descend a given grade, assuming the driver selects an appropriate gear to give maximum RPM which will then give maximum engine braking.

Figure 21 shows a plot of maximum descent speeds for an 80,000 lb 5-axle truck with no retarder as a function of grade length and steepness. Several famous grades are also spotted on Figure 21 in terms of their steepness and length. Note that for steep grades, maximum allowable safe speed is extremely sensitive to length. The use of a retarder is the equivalent of a weight decrease, which can be calculated based on the horse power absorbed by the retarder [5]. Procedures have also been worked out for accounting for multiple grades [4] and [5].

It should be noted that the maximum safe speed for a five-axle truck provides a measure of grade severity. Furthermore, the steepness of the constant grade lines on Figure 21 also is an additional measure of grade severity because speed is so sensitive to grade length. This sensitivity is indicative of the difficulty a driver would have in selecting an appropriate descent speed. This speed versus length sensitivity also makes descent speed sensitive to several other operational conditions, including ambient temperature and wind conditions, brake adjustment and engine/retarder RPM (i.e. gear selection) during the descent.

APPENDIX B – OTHER TWOPAS FEATURES

This appendix discusses other features of TWOPAS that are potentially relevant to evaluation of upgrades and downgrades but do not have directly corresponding features in VDANL. These include desired speeds in downgrade crawl regions, desired speeds in approaches to horizontal curves and crawl regions, driver lane choice at the beginning of a passing or climbing lane section, and driver lane changing behavior in passing and climbing lane sections.

1. Desired Speeds in Downgrade Crawl Regions

On steep downgrades, there is a risk that the driver of a heavy vehicle may lose control of the vehicle due to overheating of the brakes if the brakes are applied too long or too often. Therefore, drivers of heavy vehicles on steep downgrades often slow their vehicle substantially, shift to a lower gear, and choose a crawl speed to proceed down the grade so that the need to apply their brakes is lessened.

Simulation of downgrade crawl speeds is implemented in TWOPAS by allowing the user to specify portions of the roadway, known as crawl regions, where heavy vehicles will use crawl speeds. Within crawl regions, as TWOPAS is presently written, all trucks of user-specified types will automatically slow to a crawl speed if one is specified by the user. The user has the option to require some or all RVs and passenger cars to use crawl speeds as well. The program logic adds an approach region to each user-specified crawl region (see subsequent discussion of desired speeds in approaches to horizontal curves and crawl regions). A maximum of 12 crawl regions may be specified in input. Crawl regions are directional in nature; each crawl region affects vehicles in only one direction.

TWOPAS does not attempt to model the driver's process of deciding whether to slow to a crawl speed on a downgrade and, if so, what crawl speed to use. Rather, these values are supplied as input data by the user. The variables whose values are specified by the user to define each crawl region are as follows:

JD	Direction of travel in which this crawl region is located
XCWN	Position coordinate (ft) for the beginning of the crawl region; the beginning is defined as the first portion of the crawl region encountered in its particular direction of travel
CW2	Position coordinate (ft) for the end of the crawl region
CW0	Mean crawl speed in this region (ft/sec)

SCWL Standard deviation of crawl speeds (ft/sec)

Presently, the mean and standard deviations of crawl speed apply to all vehicle types that are to use crawl speeds. That is, TWOPAS currently does not enable the heaviest trucks to use lower crawl speeds than, say, RVs.

The actual crawl speed that will be used by an individual driver is computed with the values of CW0 and SCWL in a manner analogous to Equation (3) that is used for horizontal curve speeds:

$$V_{cr} = \overline{V}_{cr} + r\sigma$$

where: V_{cr} = desired speed (ft/sec) in a particular crawl region for a particular vehicle

$\overline{V}_{cr}$ = mean desired speed (ft/sec) in a particular crawl region for all vehicles in a particular vehicle category, identified above as CW0

r number of standard deviations above or below the mean desired speed

σ = standard deviation of desired speed (ft/sec) for vehicles in the same vehicle category [identified above as SCWL]

The crawl region desired speed, V_{cr}, influences the speed behavior of a driver in a horizontal curve only if $V_{cr} < V_d$. If both horizontal curves and crawl regions constrain driver speed choices, then the lower desired speed, V_c or V_{cr}, will govern.

There are no plans to modify the crawl region logic in NCHRP Project 3-55(3). No decision has yet been made as to whether crawl regions will be incorporated in the UCBRURAL interface, in which it is not yet implemented.

2. Desired Speeds in Approaches to Horizontal Curves and Crawl Regions

TWOPAS provides a transition region on the approach to each horizontal curve or crawl region specified by the user in input data. The length of the transition region and the mean desired speed within that region is computed within TWOPAS and, thus, is not specified by the user. The transition region comes into effect for any vehicle that is found to have a lower desired speed within the curve or crawl region than on the normal roadway. The transition region supplies a nearly constant deceleration from the normal desired speed to the curve or crawl region desired speed.

TWOPAS assumes that the approach region starts at a specified distance, z_o, upstream of the beginning of the beginning of the curve or crawl region. The value of z_o is determined as:

$$z_o = \frac{\overline{V}_d^2 - \overline{V}_c^2}{2A_a}$$

where:

z_o	=	distance (ft) upstream from beginning of curve or crawl region to start of approach region
$\overline{V}_d$	=	mean of normal desired speeds (ft/sec)
$\overline{V}_c$	=	mean of desired speeds (ft/sec) in curve or crawl region
A_a	=	average deceleration in approach (assumed value of A_a = 3.5 ft/sec^2)

The mean desired speed at any point in the transition region is determined as:

$$\overline{V}_a = \overline{V}_d\Big[\big(1 - c_1 x_o + c_2 x_o^2 \\ + \left(c_1 - 2c_2 x_o\right)x + c_2 x^2\Big]$$

where:

$\overline{V}_a$	=	mean desired speed as a function of location in the approach region
x_o	=	position (ft) where the approach region begins $= x_c - z_o,\ x_o \le x \le x_c$
x_c	=	position where the actual curve or crawl region begins

and c_1 and c_2 are given by:

$$c_1 = -A_a / \overline{V}_d^2$$

and

$$c_2 = -2\left[\left(\frac{\overline{V}_c}{\overline{V}_d} - 1\right)\frac{A_a}{\left(\overline{V}_d^2 - \overline{V}_c^2\right)}\right]^2$$

The standard deviation of desired speeds in the transition region is assumed to be equal to the standard deviation of desired speed within the curve or crawl region. Equation (8) is employed in Subroutine SPDN to determine the mean desired speed at any point in an approach region. The actual desired speed of any particular vehicle at that point is determined by using the value of the mean desired speed from Equation (8) as the mean desired horizontal curve speed in Equation (3) and/or as the mean desired crawl speed in Equation (6).

There is no explicit transition region for vehicles leaving a horizontal curve or crawl region. Drivers will seek to resume their normal desired speeds subject to the limitations of driver acceleration preferences (see below), vehicle performance limitations, local alignment, and the presence of other traffic.

3. Driver Lane Choice at the Beginning of a Passing or Climbing Lane Section

A driver entering an added passing or climbing lane section may choose to enter either the right or left lane. An empirical model based on field data collected by Harwood and St. John is [44] used to make this determination. These data were supplemented by data collected by the University of California-Berkeley in low flows at climbing lanes on steeper grades [45] and by experience with multilane data in level and graded alignments.

The factors that influence a driver's lane choice at a passing or climbing lane addition are:

Variable	Description
LFV or LFAV	Local geometrics and traffic control at the passing or climbing lane addition: 1 = left lane preferred 2 = no lane preference 3 = right lane preferred
JSTAT	Platooning status of the entering vehicle: 1 = free vehicle 2 = platoon leader 3 = low-performance platoon member 4 = high-performance platoon member
JSZ	Vehicle size: 1 = large vehicle (all trucks and RV types 5 and 6) 2 = small vehicle (RV types 7 and 8 and all passenger cars)
ITCR	Category or range of time (sec) required to catch up with next vehicle ahead in right lane
SFLO(JD)	Specified flow rate (veh/hr) for the direction of travel in question
VN	Speed (ft/sec) of the vehicle entering the passing lane

The probability that a vehicle will enter the right lane (PR) is determined by the following algorithm:

CS0	=	AOH + BOH * SFLO (JD)
CS1	=	AONE + BONE * SFLO (JD)
FSPD	=	CS0 + CS1 * VN
PR	=	CTCR * DMIN1 (CSMAX, DMAX1 (CSMIN, FSPD))

where AOH, BOH, AONE, BONE, CTCR, CSMAX, and CSMIN are empirically determined coefficients based on the field data discussed above. The values of these coefficients depend upon LFAV, JSTAT, JSZ, and ITCR.

When the value of PR is greater than zero and less than one, the lane chosen by the driver is determined stochastically. If PR is less than zero, the left lane is chosen; if PR is greater than zero, the right lane is chosen.

4. Driver Lane Changing Behavior in Passing and Climbing Lane Sections

TWOPAS provides the capability for users to specify added passing or climbing lanes in either direction of travel at selected locations. Such added lanes provide an opportunity for drivers with higher desired speeds to pass slower vehicles simply by changing lanes rather than by using the lane normally reserved for opposing traffic, as must be done to make a passing maneuver on the normal two-lane cross section.

The capability to simulate passing and climbing lane operations required the modeling of driver lane-changing behavior. As in passing behavior on the normal two-lane cross section, driver lane-changing decisions involve a two-step process. First, before any lane change can occur a driver must become motivated to change lanes. Once a driver becomes motivated to change lanes, the driver then begins a process of searching for an acceptable gap in traffic in the target lane and then maneuvering to enter that gap.

TWOPAS assesses whether a driver will become motivated to change from the right lane to the left lane of a passing or climbing lane. The two reasons why a driver might become motivated to change lanes to the left are (1) to avoid delay by slower vehicles in the right lane and (2) to avoid an approaching right-lane drop at the end of the passing or climbing lane. (The user can specify whether the right or left lane will be dropped at the end of an added lane.) The probability that a driver will become motivated to change lanes to the left is assessed at each review interval for each vehicle in an added passing or climbing lane. It is based on time until delay, severity of delay, comparative outlook for delay in the left lane, and the likelihood of conflict or blocking by vehicles in the left lane. If the probability that the driver will become motivated to change lanes is greater than zero and less than one, then a stochastic decision is made concerning whether the driver will, in fact, become motivated. The logic for motivation to change to the left lane is based on experience with a multilane highway simulation model.

TWOPAS also assesses whether a driver will become motivated to change from the left lane to the right lane of a passing or climbing lane. The two reasons why a driver might become motivated to change lanes to the right are (1) a general preference for travel in the right lane when this can be done without delay and (2) to avoid an approaching left lane drop at the end of the passing or climbing lane. The probability that a vehicle will become motivated to change lanes to the right has a basic bias by vehicle category; trucks have a probability of becoming motivated to change lanes to the right that is 0.05 higher than RVs, and RVs have a probability that is 0.05 higher than passenger cars. If the left-lane vehicle is traveling faster than its right-lane leader and the right-lane leader would become an impeder in 10 sec or less, then the probability of motivation to change lanes is set to zero so the driver will not become motivated to change lanes. Otherwise, the probability of motivation to change lanes is increased if (1) there will be a delay in the left lane, (2) the left-lane vehicle is delaying its follower, (3) the left-lane vehicle is a free vehicle with small acceleration capability, or (4) the left-lane vehicle is a free vehicle and is traveling at low speed relative to the mean desired speed. If the probability that the driver will become motivated to change lanes is greater than zero and less than one, then a stochastic decision is made concerning whether the driver will, in fact, become motivated.

Once a driver had become motivated to change lanes, TWOPAS sets a limiting risk level to be used in lane changing, and the minimum and maximum risk levels to be used in lane changing in the current review interval.

TWOPAS assesses whether there is a gap in the target lane into which the lane-changing vehicle could move during the current review interval within the constraints set by the minimum and maximum accelerations. Several tests are used to determine whether a particular gap in the target lane is acceptable. The first test for a candidate gap is the simple requirement that there be at least a 4-ft clearance with target lane vehicles when the most favorable acceleration is used. Subsequent tests consider dynamic interactions of the vehicles involved by requiring that a specified limit risk level not be exceeded.

If the lane-changing vehicle cannot clear the first vehicle ahead of it in the target lane, the search is then made to the rear of that vehicle. If a satisfactory gap is found, the acceleration for the interval is set equal to the maximum level that is consistent with the subsequent acceptable risk in the target lane. The vehicle is then advanced and moved into the target lane.

If TWOPAS fails to find an acceptable gap that can be entered during the current review interval, the process of maneuvering toward an acceptable gap is begun.

TWOPAS attempts to find a gap which the driver in question might enter after several reviews (up to 10 sec in the future) and, if such a gap is found, it determines an acceleration (or deceleration) level within vehicle capabilities and driver preferences that will improve future access to the selected gap. If an appropriate gap is found, TWOPAS guides the process of pursuing that gap with acceptable levels of acceleration (or deceleration) over several review intervals. TWOPAS incorporates the assumption that once a driver begins to pursue a gap, the driver will continue to pursue that same gap until reaching it. If the driver were permitted to reassess at each review interval which gap to pursue, this could result in cyclic behavior as the driver constantly changed gaps without ever reaching any. Thus, the lane-changing logic works best if the driver remembers which gap he/she intends to pursue and, once having selected that gap, pursues it to the exclusion of others.

If TWOPAS does not find a workable future gap that the driver can maneuver towards, then the search begins again in the next review interval. However, if the driver is approaching a lane drop and is in the lane to be dropped, the vehicle is assigned a deceleration that will prevent it from running through the end of the lane.

The lane-changing logic in much of TWOPAS was based on a previous multilane highway simulation model. However, some portions of the logic were developed specifically for TWOPAS.

APPENDIX C – FUNCTIONAL PROGRAM SPECIFICATION FOR UPGRADE ANALYSIS SOFTWARE

A. OVERVIEW

This appendix provides a functional program specification for implementing the upgrade analysis methodology in IHSDM. It is recommended that an upgrade analysis software package be developed to implement the recommended methodology. This software package would serve as a user interface to request needed input data from the user and present output reports to the user. The upgrade analysis software package would call TWOPAS as necessary to complete the analysis in a manner that would be transparent to the user. Speed profiles would be calculated using the truck performance equations from TWOPAS without the need to utilize the full TWOPAS model. Level-of-service assessments would utilize output from the full TWOPAS model.

The plan presented here will not require any changes to the TWOPAS model itself. The TWOSUM postprocessor program will also be used without modification. However, the upgrade analysis software will need to be capable of assembling appropriate input files for TWOPAS (duplicating some of the capabilities included in the existing user interfaces) and will need to be capable of reading the TWOSUM output file and extracting values needed for the upgrade evaluation.

B. SUMMARY OF UPGRADE ANALYSIS METHODOLOGY

The upgrade analysis methodology would be implemented in a series of steps as follows:

Step 1 - Select a suitable truck for use the design vehicle for upgrade analysis. The truck to be selected will be specified by the user in terms of a power-to-weight ratio. The software will determine other appropriate characteristics for the truck.

Step 2 - Determine the speed profile for the selected truck on the actual upgrade alignment and calculate the speed reduction of the truck as the difference between the truck entry speed at the foot of the grade and the minimum truck speed at any point on the grade.

Step 3- Assess the level of service on the approach to the upgrade.

Step 4 - Assess the level of service on the upgrade.

Step 5 - Apply the AASHTO criteria (see Items 1 through 3 in Section III.D above) and determine whether the addition of a climbing lane is warranted.

Step 6 - At the IHSDM user's option, reassess the level of service on the upgrade with a climbing lane in place at a location specified by the user.

C. FUNCTIONAL REQUIREMENTS FOR UPGRADE ANALYSIS SOFTWARE

The upgrade analysis software should operate as follows:

1. Ask the user to specify as input:

   - Upgrade geometry to be evaluated (specify name of CAD or non-CAD file)
   - Beginning station of approach region (in advance of the foot of the grade)
   - Ending station of approach region (at foot of grade)
   - Beginning station of upgrade (at foot of grade)
   - Ending station of upgrade (at top of grade)
   - Weight-to-power ratio of truck to be analyzed
   - Desired speed of truck (i.e., assumed initial speed of truck at bottom of upgrade if no other traffic is present)
   - Upgrade flow rate (veh/h) for the peak 15 min of the design hour
   - Upgrade truck flow rate for the peak 15 min of the design hour

Input should be specified in either metric or U.S. customary units at the user's option.

The approach region selected for analysis should normally be at least 0.5 mi (0.8 km) in length. The ending station of the approach region and beginning station of the upgrade should normally be the same, but the software should be written with the flexibility to allow these to be different if desired. In addition, it cannot always be assumed that the geometric data available in the CAD or non-CAD file will extend far enough in advance of the upgrade to include the entire approach region. Therefore, the software should provide the capability for the user to enter the geometrics of the approach region, rather than obtain these from the file.

The user may, if desired, include within the specified upgrade boundaries a short segment beyond the top of the grade if the user wants to consider carrying a climbing lane past the top of the grade. However, this extension of the upgrade segment should be relatively short compared to the length of the upgrade itself.

2. The upgrade analysis software should calculate the speed profile of the specified truck over the entire length of the upgrade. The procedure for computing speed profiles for individual trucks, based on the truck performance equations used in TWOPAS is described here. The performance capability of the truck is characterized by the weight-to-power radio (W/NHP) specified by the user. A corresponding value of weight-to-frontal-area ratio (W/A) should be determined by interpolation between the W/NHP and W/A values shown in Table 8 of the main text of this report. The speed profile analysis also requires the truck driver's desired speed $\left(V_d\right)$, the beginning and ending locations of the upgrade, and the percent grade at every point on the upgrade. The desired speed and beginning and ending locations come from user input. The percent grades (i.e., vertical profile) come from the CAD or non-CAD geometrics file. In the following descriptions of calculating the speed profile, all distances are given in feet, all speeds in ft/sec, and all acceleration in ft/sec^2, because the truck performance equations were originally developed in these units.

The speed profile algorithm begins time 0 (t = 0) with the truck traveling at speed $V_d\left(\text{i.e., } V_{\text{o}} = V_d\right)$ and the truck located at the beginning of the upgrade (i.e., X_{o} = the coordinate of the beginning of the upgrade). The algorithm proceeds iteratively in time increments of 1.0 sec.

For any time t, beginning with t = 0, at which the truck's current speed is V_t, the calculations proceed as follows.

First, compute the truck's performance-limited acceleration $\left(a_p\right)$ given the local grade G at location X_t using Equation (9) in the main text of this report.

Second, compute the truck's coasting acceleration, $\left(a_c\right)$ during gear shifts using Equation (10) in the main text of this report.

Third, compute the effective acceleration $\left(a_e\right)$ as:

$$a_e = \left[\frac{0.4V_t}{0.4V_t + 1.5S_p\left(a_p - a_c\right)}\right] a_p \text{ if } V_t \geq 10 \text{ ft/s}$$

$$a_e = \left[\frac{10}{10+1.5S_p\left(a_p - a_c\right)}\right] a_p \text{ if } V_t < 10 \text{ ft/s}$$

where:

a_e = effective acceleration $\left(\text{ft/s}^2\right)$

S_p = one times the sign of a_p (which can be either + or -);

in other words, $S_p = a_p / \left|a_p\right|$

Fourth, compute the performance-limited speed of the truck $\left(V_p\right)$ where:

$$V_p = V_t + a_e(1.0)$$

The term 1.0 in the preceding equation represents the 1.0 s time interval.

Fifth, determine the speed of the truck as limited by driver preferences $\left(V_{\text{lim}}\right)$ from the following equations:

$$V_{\text{lim}} = V_d \quad \text{if} \quad \left|V_d - V_t\right| < 1.2$$

$$V_{\text{lim}} = \min\left[1.2 + 0.108\left(V_d - V_t\right) + V_t, V_d\right] \quad \text{if } \left(V_d - V_t\right) \geq 1.2$$

$$V_{\text{lim}} = V_d - 1.2 \quad \text{if } \left(V_d - V_t\right) \leq -1.2$$

Sixth, determine the speed of the truck at the end of the 1.0-s interval as:

$$V_{t+1} = \min\left(V_p, V_{\text{lim}}\right)$$

Seventh, determine the location of the truck at the end of the 1.0'-s interval as:

$$X_{t+1} = X_t + V_t + 0.5\left(V_{t+1} - V_t\right)$$

Finally, if X_{t+1} remains less than the coordinate of the end of the upgrade, then set $t = t+1$ and repeat the above steps.

The speed profile on the grade can be plotted as the graph of $\left(X_o, V_o\right), \left(X_1, V_1\right), \left(X_2, V_2\right)$, etc. The speed reduction of the truck on the grade (SR) is:

$$\mathrm{SR} = V_d - \min\left(V_o, V_1, V_2, \ldots, V_n\right)$$

3. The upgrade analysis software should then assess the level of service of the approach to the upgrade by setting up the input for a series of TWOPAS runs, executing the TWOPAS model, and making the runs. The upgrade approved segment is evaluated in TWOPAS by itself, without the presence of the upgrade itself, because if the upgrade were present, it might influence the level of service of the approach segment. Relatively long buffer segments are used in the evaluation of the approach segment in TWOPAS to assure that there is sufficient roadway length for percent time spent following to reach an equilibrium value regardless of the appropriateness of the default value for entering percent of traffic platooned. The input data for these TWOPAS runs should be as follows:

Geometrics:	from the CAD or non-CAD file (or user input) for the roadway from the beginning station to the ending station of the approach region [NOTE: the sight distance profile and passing/no-passing zones can be automatically generated from the alignment data using algorithms developed in NCHRP Project 3-55(3)].
Traffic Volumes:	The flow rate and percent trucks for the direction toward the upgrade should be set equal to upgrade flow rate and percent trucks entered by the user above. Assume the same flow rate and vehicle mix for the opposing direction. Assume that all nontrucks are passenger cars (i.e., no RVs). Use the default performance characteristics for passenger cars. Assume all trucks have performance characteristics equal to those used above in the speed profile analysis.

The simulated roadway in TWOPAS should be set up with a 2.0-mi (3.2 km) level, tangent buffer area at either end of the specified approach roadway. The roadway for which traffic performance measures are collected should not include these buffer areas, but should only include the upgrade approach segment itself. The entering percent of traffic platooned in each direction of travel should be specified as zero, which invokes a default value appropriate to the specified traffic volume level. All other TWOPAS inputs should be set to default values.

TWOPAS should then be run for five arbitrary, but different, sets of random number seeds for 60-min for each run (plus a 10-min warm-up period). Following each TWOPAS run, the TWOSUM postprocessor program should be run. The traffic performance measures of interest for the upgrade approach segment in the direction of travel leading toward the upgrade -- percent time spent following and average travel speed -- should be quantified as the average of the results extracted from the TWOSUM output file for each of the five TWOPAS runs.

4. The upgrade analysis software should next be used to assess the level of service of the upgrade itself by setting up the input for a TWOPAS run, executing the TWOPAS model, and making the runs. The upgrade is now simulated by itself using as input conditions the results obtained above for the approach segment. The required TWOPAS runs should be formulated in the background, transparent to the TWOPAS user. The input data for these TWOPAS runs should be as follows:

Geometrics:	from the CAD or non-CAD file (or user input) for the roadway from the beginning station to the ending station of the upgrade region [NOTE: the sight distance profile and passing/no-passing zones can be automatically generated from the alignment data using algorithms developed in NCHRP Project 3-55(3)].
Traffic Volumes:	The flow rate and percent trucks for the upgrade direction should be set equal to upgrade flow rate and percent trucks entered by the user above. Assume the same flow rate and vehicle mix for the opposing (i.e., downgrade) direction. Assume that all nontrucks are passenger cars (i.e., no RVs). Use the default performance characteristics for passenger cars. Assume all trucks have performance characteristics equal to those used above in the speed profile analysis.

The simulated roadway in TWOPAS should be set up with a 0.25-mi (0.4-km) level, tangent buffer area at either end of the specified upgrade roadway. The roadway for which traffic performance measures are collected should not include these buffer areas, but should only include the upgrade segment itself. The entering percent of traffic platooned in each direction of travel should be specified as equal to the average percent time spent following determined from the approach runs discussed above. All other TWOPAS inputs should be set to default values.

TWOPAS should then be run for the upgrade using the same five sets of random number seeds used for the approach segment for 60-min for each run (plus a 10-min warmup period). Following each TWOPAS run, the TWOSUM postprocessor program should be run. The traffic performance measures of interest for the upgrade direction -- percent time spent following and average travel speed -- should be quantified as the average of the results extracted from the TWOSUM output file for each of the five TWOPAS runs.

5. The results of the TWOPAS runs discussed above are then used to determine the level of service for the upgrade approach and the upgrade based on the criteria of the *Highway Capacity Manual*. Because of problems in compatibility between the level-of-service definitions for general terrain segments and specific grades in the current HCM procedures (1985, 1994, and 1997 editions), it is recommended that the revised level-of-service criteria proposed for the HCM2000 be used. These criteria are presented in Table 12 for Class I highways and in Table 13 for Class II highways. When using Table 12, both the maximum percent time spent following criterion and the minimum average travel speed criterion must be met in order for any particular level of service to apply.

Table 12. Level-of-Service Criteria for Two-Lane Highways in Class 1

Level of Service	Percent Time Spent Following	Average Travel Speed (km/h)
A	≤35	>90
B	>35-50	>80-90
C	>50-65	>70-80
D	>65-80	>60-70
E	>80	≤60

Note: Level of service F applies whenever the flow rate exceeds the segment capacity.

Table 13. Level-of-Service Criteria for Two-Lane Highways in Class II

Level of Service	Percent Time Spent Following
A	≤40
B	>40-55
C	>55-70
D	>70-85
E	>85

Note: Level of service F applies whenever the flow rate exceeds the segment capacity.

To determine the level of service, the IHSDM user will need to indicate whether the highway being analyzed is a Class I or Class II facility. Class I highways are highways on which motorists expect to travel at relatively high speeds. Two-lane highways that function as major inter-city routes, primary arterials connecting major traffic generators, daily commuter routes, or as primary links in state or national highway networks are generally assigned to Class I. Class I facilities generally serve long-distance trips or provide connecting links between facilities that serve long-distance trips.

Two-lane highways on which motorists do not necessarily expect to travel at high speeds are assigned to Class II. Two-lane highways that function as access routes to Class I facilities, serve as scenic or recreational routes that are not primary arterials, or pass through rugged terrain where motorists do not expect to travel at high speed are generally assigned to Class II. Class II facilities generally serve relatively short trips, the beginning and ending portion of longer trips, or trips for which sightseeing activities pay a significant role in route choice.

The classes of two-lane roads are closely related to their functional classification since most arterials would normally be classified as Class I facilities and most collectors and local roads would normally be considered as Class II facilities. However, the primary factor in determining the appropriate classification of a facility for operational analysis is the assessment of motorist expectations for that facility, which may differ from its functional classification. Because the level-of-service criteria for Class I and II facilities in Table 12 and Table 13 differ, it is vital that the same table be used for assessing the level of service on both the approach segment and the upgrade. The decision to perform an upgrade evaluation or to consider a climbing lane for an upgrade is a strong indication that the facility in question is a Class I facility. Therefore, it is recommended that Table 12 , and not Table 13, be used for level-of-service assessment for upgrade approach segments and upgrades.

Thus, if an approach segment is found from TWOPAS runs to operate with percent time spent following equal to 45 percent and average travel speed equal to 95 km/h, then the level of service on the approach is B. If the upgrade operates with percent time spent following equal to 60 percent and average travel speed equal to 65 km/h, then the level of service on the upgrade is D.

If the directional flow on the upgrade exceeds the capacity of 1700 pc/h, then level-of-service F applies. The upgrade flow rate and percent trucks in veh/h can be converted to pc/h using the heavy vehicle equivalency tables for two-lane highways in the HCM2000.

6. Addition of a climbing lane is considered warranted if each of the three criteria stated in the AASHTO Green Book is met:
   - The upgrade traffic flow exceeds 200 veh/h for the peak 15 min of the design hour
   - The upgrade truck flow exceeds 20 veh/h for the peak 15 min of the design hour
   - One of the following exists:
     - The speed reduction (SR) on the upgrade for the selected design truck is 15 km/h or greater
     - Level of service E or F exists on the upgrade
     - A reduction of two or more levels of service is experienced when moving from the approach segment to the grade (e.g., an upgrade level of service of D, E, or F, when the approach level of service is B).
7. The evaluation results should be displayed to the user including:
   - Upgrade traffic flow rate
   - Upgrade truck flow rate and percent trucks
   - Passenger-car equivalent flow rate
   - Length of upgrade
   - Average percent grade (= rise*100/length)
   - Approach segment:
     - Percent time spent following
     - Average travel speed
     - Level of service
   - Upgrade segment:
     - Percent time spent following

- Average travel speed
- Speed profile on upgrade (percent graphically)
- Level of service

- Climbing lane warranted (YES/NO)

8. The user should be provided with the choice to perform a supplementary analysis of the level of service with the climbing lane in place. The user should be asked to specify the beginning and ending stations of the climbing lane (including tapers). The beginning and ending stations of the climbing lane may be different than the user-specified beginning and ending stations of the upgrade, but must be within the specified upgrade section. It was noted above that, at the beginning of the analysis, the user may choose a slightly extended upgrade segment to permit any added climbing lane to be carried a short distance past the top of the upgrade.

   The level of service of the climbing lane should be evaluated by repeating the exact same five TWOPAS runs that were used to evaluate the level of service of the upgrade, with the only difference being the addition of the climbing lane. Following the completion of the TWOPAS runs, the following additional results should be added to the report to the user:

- Length of proposed climbing lane
- Location of proposed climbing lane (beginning and ending stations)
- Upgrade containing climbing lane:
  - Percent time spent following
  - Average travel speed
  - Level of service

APPENDIX D – FUNCTIONAL PROGRAM SPECIFICATION FOR DOWNGRADE ANALYSIS SOFTWARE

A. OVERVIEW

This appendix provides a functional program specification for implementing the downgrade analysis methodology in IHSDM. It is recommended that a downgrade analysis software package be developed to implement the recommended methodology. This software package would serve as a user interface to request needed input data from the user and present output reports to the user. The downgrade analysis software package would call VDANL and TWOPAS as necessary to complete the analysis in a manner that would be transparent to the user. The basic downgrade analyses to determine the maximum safe speeds would be performed with VDANL. VDANL would need to be modified for this purpose to appropriately select a gear and speed for the downgrade descent. TWOPAS would be used only for level of service analysis in assessing the warrants for downgrade passing lane.

B. SUMMARY OF DOWNGRADE ANALYSIS METHODOLOGY

The downgrade analysis methodology would be implemented in a series of steps as follows:

Step 1 - Select a suitable truck for use the design vehicle for downgrade analysis.

Step 2 - Determine the speeds designated below as Criteria 1 through 4. From these speeds, determine the recommended truck operating speed and the margin of safety to the loss of control speed.

The speeds used as criteria in downgrade analysis are:

1. The maximum speed at which the specified truck can descend the specified grade without losing braking ability.
2. The maximum speed at which the specified truck can descend the specified grade with rolling over on a horizontal curve.
3. The maximum speed at the specified truck can descend the specified grade without losing the ability to brake safely to a stop using a deceleration rate of 3.4 m/sec^2 or more.
4. The maximum speed at which the specific truck can descend the specified grade without losing the ability to slow to the appropriate desired for any horizontal curve.

Criteria 1 and 2 are safety criteria that represent the thresholds at which accidents are expected. Speeds higher than the speed for Criterion 1 would be expected to result in loss of braking control (i.e., a "runaway" truck). Speeds higher than Criterion 2 would be expected to result in a truck rollover.

Criteria 3 and 4 are more conservative and represent thresholds for good design that do not approach impending loss of control. Criterion 3 assures that a truck will be able to brake to a stop using a deceleration rate of at least 3.4 m/sec^2, the deceleration rate assumed in the proposed new criteria for stopping sight distance design. [14] Criterion 4 assures that the truck will not only not rollover on a horizontal curve, but also will be able to traverse each curve on the grade at the speed that drivers normally select for such curves when they are not on a downgrade.

The speeds for Criteria 1 through 4 will be determined by repeated application of VDANL for the selected truck and the selected roadway alignment for initial speeds in 5 mi/h (or 10 km/h) increments from 10 mi/h (or 15 km/h) to the maximum truck speed on the approach roadway, a value that will be supplied by the user.

Step 3 - Present the recommended truck operating speed and other output data to the user. The user must then assess whether the recommended truck operating speed will be maintained by the vast majority of truck drivers. This assessment could be made with formal risk assessment logic based on further research, or it could be left to the judgement of the IHSDM user.

The output data that will be provided to the user include:

- Recommended truck operating speed to provide adequate margin of safety for trucks on the downgrade (the lesser of the speeds determined for Criteria 3 and 4)
- Loss-of-control speed fro the grade (the lesser of the speeds determined for Criteria 1 and 2)
- Percent of downgrade length with adequate safety margin as a function of initial speed
- Location (station) at which loss of safety margin occurs as a function of initial speed

- Location (station) at which loss of control occurs as a function of initial speed
- Speed profile on the downgrade as a function of initial speed
- Maximum percent of brake fade temperature reached as a function of initial speed

To judge the acceptability of the downgrade design, the IHSDM user must assess whether, with appropriate warning signs, it is reasonable to expect truckers to slow to the recommended truck operating speed before reaching the top of the grade.

Step 4 - The user may then modify the geometrics of the downgrade, if the user considers this to be necessary and feasible. This could involve using less steep slopes, flattening horizontal curves, or both. The analysis of the revised downgrade geometrics can then be repeated starting with Step 1.

Step 5 - If the recommended truck operating speed is deemed too low and it is physically or economically infeasible to modify the geometrics of the downgrade, the IHDSM outputs, specifically, the loss-of-control locations and the speed profiles following loss of control can be used to identify potential sites for emergency escape ramps. The speed profile data can also be used to anticipate potential truck entry speeds to the emergency escape ramp. The truck entry speed is an important design parameter in determining the required length of the ramp.

This portion of the analysis will not be automated, but the user will have available the output data described above in making this assessment.

Step 6 - A traffic operational assessment, patterned after the assessment procedure used for upgrades, should be made to determine whether the provision of a passing lane on the downgrade is warranted to reduce the delays to other traffic by trucks operating at crawl speeds. The warrants for downgrade passing lanes should be the analogous as those used for climbing lanes:

- Downgrade traffic flow rate in excess of 200 veh/hr for the peak 15-min of the design hour
- Downgrade truck flow rate in excess of 20 veh/hr for the peak 15-min of the design hour

- One of the following exists:
  - a speed reduction of 15 km/h or greater is expected for a typical heavy truck
  - level-of-service E or F exists on the downgrade
  - a reduction of two or more levels of service is experienced when moving from the approach segment to the downgrade

The assessment of total traffic and truck flow rates will be made with input data supplied by the user. The level-of-service of the downgrade will be assessed by application of TWOPAS. To accomplish this, the downgrade analysis software will need to use the VDANL results to identify the boundaries of truck crawl regions and the truck crawl speed to be used within those crawl regions for use as input data to TWOPAS.

C. FUNCTIONAL REQUIREMENTS FOR DOWNGRADE ANALYSIS SOFTWARE

The downgrade analysis software should operate as follows:

1. Ask the user to specify as input:
   - Downgrade geometry to be evaluated (specify name of CAD or non-CAD file)
   - Beginning station of downgrade (uphill end)
   - Ending station of downgrade (downhill end)
   - Type of vehicle and weight to be analyzed (select from menu of available vehicles)
   - Maximum vehicle speed on approach to downgrade

Input should be specified in either metric or U.S. customary units at the user's option.

2. In the background, transparent to the user, the software should formulate the input data for a series of VDANL runs and make those runs. The input data for all runs will be identical, except that the speed that the truck driver tries to maintain (i.e., the driver's "desired speed") should be varied from 10 mi/h (or 15 km/h) to the maximum truck speed on the approach to the grade (provided by the user as input) in steps of 5 mi/h (10/km/h). The desired speed will represent the speed at which the driver enters the downgrade and the speed at which the driver attempts to descend the entire grade (except where the geometry of a horizontal curve requires a slower speed). The horizontal and vertical

alignment of the grade should be that presented in the user-specified CAD or non-CAD file between the specified stations. The VDANL simulation should begin at the user-specified beginning station. The input data to VDANL should force the driver to choose the most appropriate gear for that particular truck to descend the grade at the selected speed.

Output should be provided from each VDANL run to allow the downgrade analysis software to record:

- Result of run (one or more of the following):
  - loss of control due to brake fade
  - loss of control due to rollover on a horizontal curve
  - loss of safety margin to stop with a deceleration rate of 3.4 m/sec^2 or more
  - loss of safety margin to slow to the desired speed of a horizontal curve
  - successful descent of grade (none of the above)
- Speed profile on the downgrade
- Location (station) at which loss of safety margin occurs
- Location (station) at which loss of control occurs
- Maximum percent of brake fade temperature reached

Process the results of runs across all speeds to determine:

- Recommended truck operating speed to provide adequate margin of safety for trucks on the downgrade (the lesser of the truck entry speeds at which Criterion 3 or 4 is satisfied)
- Loss-of-control speed for the grade (the lesser of the truck entry speeds at which Criterion 1 or 2 is satisfied)
- Percent of downgrade length with adequate safety margin as a function of initial speed
- Location (station) at which loss of safety margin occurs as a function of initial speed
- Location (station) at which loss of control occurs as a function of initial speed
- Speed profile on the downgrade as a function of initial speed

- Maximum percent of brake fade temperature reached as a function of initial speed

3. The software should present the recommended truck operating speed and the loss-of-control speed to the user and should allow the user to access the other output items by viewing them, printing them, or saving them to a file for further analysis.

4. The software should allow the user to request an assessment of passing lane warrants for the downgrade. This will be accomplished by application of TWOPAS in a manner transparent to the user. The following additional input data will need to be supplied by the user:

   Traffic flow rate by direction of travel (upgrade and downgrade)

   Percent trucks and percent RVs by direction of travel

   The geometrics of the downgrade should be determined from the CAD or non-CAD input file. Sight distance and passing/no-passing zones should be computed with automated routines developed in NCHRP Project 3-55(3). For the passing zone warrant determination, TWOPAS should be run with no passing lane present. The entire downgrade from specified beginning to end should be designated as a crawl region in the TWOPAS input and the recommended truck operating speed determined above should be set as the crawl speed. All other TWOPAS inputs should be set to default values.

   The TWOPAS results should be utilized to apply the passing lane warrants discussed above and to indicate to the user whether or not the passing lane warrants are met. The average travel speed, percent time spent following, and level of service on the downgrade should be reported to the user.

   An option could also be provided to allow the user to assess the improvement in level of service with a downgrade passing lane in place. The location of the passing lane could be specified to be coincident with the specified crawl regions. Output reported to the user should include the average travel speed, percent time spent following, and level of service on the downgrade with the passing lane in place, for comparison to the case without the passing lane in place.

D. FUNCTIONAL REQUIREMENTS FOR IMPROVEMENTS TO VDANL

Application of VDANL in analysis of downgrades, as described above, will require several functional improvements. Each of these improvements is described below.

1. Wheel Brake Systems

The VDANL_IHSDM brake gain model should upgraded to the form:

$$T_{B_F} = [K_1] F_{\mathrm{BP}} \quad \text{front brake torque gain, per wheel}$$
$$T_{B_R} = [K_2] F_{\mathrm{BP}} \quad \text{drive brake torque gain, per wheel}$$
$$T_{B_T} = [K_3] F_{\mathrm{BP}} \quad \text{trailer brake torque gain, per wheel}$$

Where the addition is the K_3 term for the trailer brake torque gain.

VDANL_IHSDM does not have any modeling of the vehicle speed affect on brake torque gain. This is a significant affect that will affect the steady state braking. Because of this, it is proposed that the brake model be upgraded. The data in [12] indicates that to first order, the effect of vehicle speed on brake torque is linear. The proposed model is:

$$T_{B_{ij}} = T_{B_{ij}} \left[1 - K_{VEL\,j}\, u \right]$$

where TB_{ij} is the brake torque at wheel *ij*, *u* is the vehicle forward speed, and K_{VEL_j} is the coefficient that controls the reduction in brake torque with speed for axle j. This equation would be computed before the brake temperature fade model is computed (equation A-87 in [2]).

The formulation of the existing brake system thermal model in VDANL_IHSDM is appropriate, however, it currently only computes two temperatures and most of its parameters are hard coded. Suggested upgrades to this model are to first “parameterize” it, and second to make separate thermal models for brake at each wheel. The proposed brake thermal model for each will use the following equations:

$$m_{B_j} C_j \frac{\partial T_{ij}}{\partial t} = HP_{B_{ij}} - h_j A_{C_j} \left(T_{ij} - T_\infty \right)$$

where:

i	=	Subscript denotes Left or Right side wheel (L or R)
j	=	Subscript denotes Front or Rear wheel (F or R)
m_{Bj}	=	Effective mass of the brake system (*lbm*)
C_j	=	Effective specific heat capacity of the brake system (*Btu/lbm*-°F)
T_{ij}	=	Temperature of brake system (°F)

HPB_{ij} Power input into the brake system (*Btu*/sec)

h_j Effective heat transfer coefficient of brake system (*Btu*/sec-ft^2-°F)

A_{C_j} Effective surface area of brake system (ft^2)

T_∞ Ambient temperature (°F)

The power input into the brake system is the product of brake torque, TB_{ij} (ft-lb), and wheel speed, ω_{ij} (rad/sec), given by:

$$HP_{B_{ij}} = T_{B_{ij}} \omega_{ij} 1.285 \cdot 10^{-3} \quad \left(\frac{Btu}{\text{sec}}\right)$$

The effective heat transfer will be modeled as a linear function of vehicle speed, u (ft/sec) by:

$$h_j = K_{ho_j} + K_{h1_j} u \quad \left(\frac{Btu}{\text{sec} \cdot ft^2 \cdot {}^\circ F}\right)$$

Where K_{ho_j} and K_{hl_j} are model parameters. The model is numerically integrated using the VDANL_IHSDM integrator in the same was as the current model. The equation to be integrated is:

$$T_{ij}(t) = \int \frac{HP_{B_{ij}} - h_j A_{C_j} \left(T_{ij} - T_\infty\right)}{m_{B_j} C_j} \partial t$$

The form of the current brake fade model is appropriate, however, there is currently only a single fade parameter, and the ambient temperature is hard coded. It is proposed that the ambient temperature specified for the brake thermal model be used for the brake fade model, and that the brake fade parameter be specified separately for each axle type. The proposed model is:

$$T_{B_{ij}} = T_{B_{ij}} \left[1 - K_{fade_j} \left(T_{ij} - T_\infty\right)\right]$$

Where $T_{B_{ij}}$ is the brake torque at wheel *ij*, and K_{fade_j} is the coefficient that controls the reduction in brake torque with temperature rise.

2. Rolling Drag

VDANL currently models tire rolling drag as a linear function of tire normal load. A linear speed affect should be added to the model in the form:

$$R_{drag_{ij}} = \left(DRAGC_{ij} + DRAGV_{if} \cdot V_{X_{ij}} \right) F_{Z_{ij}}$$

Where R_{drag} is the tire rolling drag in pounds, *DRAGC* is the current normal load parameter, *DRAGV* is the new speed affect parameter (lbs/ft/sec), V_X is the tire longitudinal velocity, and F_Z is the tire normal load.

3. Engine Braking Systems and Retarders

Referring back to section I.1.c, a separate model should be added to the engine model that computes the retarding force from an engine braking system. This empirical model should be of the same form as the engine drag model; however, it should be turned on/off by the driver model or a user specified control file. The equation for the engine braking system should be:

$$T_{brake} = K_{E_7}, + K_{E_8} \omega_E + K_{E_9} \omega_E^2$$

Where the K_{Ej} are polynomial coefficients and ω_E is engine speed in rad/sec. T_{brake} should be added to engine torque, T_E, when the engine brake system is activated.

Retarder drag as a function of input speed should be computed using an equation of the form:

$$T_{retarder} = T_{\max} \left(1 - e^{-S_{retarder} \omega_R} \right)$$

Where $T_{\max}$ is the maximum retarder torque, ω_R, is the input shaft speed in rad/sec, and $S_{retarder}$ is the shaping parameter that determines how quickly the retarder reaches full torque.

The thermal model for the retarder is of the same formulation as the brake system thermal model. The proposed brake thermal model for each will use the following equations:

$$m_R C_R \frac{\partial T_R}{\partial t} = HP_R - h_R A_R \left(T_R - T_\infty \right)$$

where:

m_R	=	Effective mass of the retarder (*lbm*)
C_r	=	Effective specific heat capacity of the retarder (*Btu/lbm-* °F)
T_R	=	Temperature of retarder (°F)
HP_R	-=	Power input into the retarder (*Btu/*sec)
h_R	=	Effective heat transfer coefficient of the retarder (*Btu/*sec-ft^2-°F)

A_R Effective surface area of the retarder (ft^2)

T_∞ Ambient temperature (°F)

The power input into the retarder is the product of retarder torque, $T_{retarder}$ (*ft-lb*), and retarder speed, ω_R (*rad/sec*), given by:

$$HP_R = T_{retarder}\omega_R 1.285\cdot 10^{-3} \quad \left(\frac{Btu}{\sec}\right)$$

The effective heat transfer will be modeled as a linear function of vehicle speed, u (*ft/sec*) by:

$$h_R = K_{hR0} + K_{hR1}u \quad \left(\frac{Btu}{\sec\cdot ft^2\cdot {}^\circ F}\right)$$

Where K_{hR0} and K_{hR1} are model parameters. The model is numerically integrated using the VDANL_IHSDM integrator in the same was as the brake thermal model. The equation to be integrated is:

$$T_R(t) = \int \frac{HP_R - h_R A_R (T_R - T_\infty)}{m_R C_R}\partial t$$

The reduction in retarder torque as its temperature increases is an important issue. A linear reduction in torque with temperature rise is proposed. Using the same form as the brake fade model, the proposed model is:

$$T_{retarder} = T_{retarder}\left[1 - K_{Rfade}(T_R - T_\infty)\right]$$

Where K_{Rfade} is the coefficient that controls the reduction in retarder torque with temperature rise. The retarder input speed and output torque are treated differently for Primary and Secondary retarders. For Primary retarders, mounted between the engine and transmission, the retarder input speed, ω_R, is set equal to the transmission input speed, ω_C. The output torque, $T_{retarder}$, is added to the transmission input torque, T_C. For Secondary retarders, mounted between the transmission and differential, the retarder input speed, ω_R, is set equal to the transmission output speed, ω_T. The output torque, $T_{retarder}$, is added to the transmission output torque, T_T.

4. Engine

Referring to section I.1.d, the proposed equations for engine torque are:

$$\theta_T' = 1 - e^{-K_{T_1}\theta_T^{K_{T_2}}}$$
$$T_E = \left(K_{E_1} + K_{E_2}\omega_E + K_{E_3}\omega_E^2\right)\theta_T' + \left(K_{E_4} + K_{E_5}\omega_E + K_{E_6}\omega_E^2\right)\left(1-\theta_T'\right)$$

Where θ_T' is the adjusted throttle position used in the engine torque equation and K_{T1} and K_{T2} are shaping coefficients for the adjusted throttle versus throttle input function.

5. Transmission and Differentials

Referring to section I.1.e, it is recommended that the upper dimension of the transmission gear variables be changed from eleven to twenty to allow twenty forward gear ratios, rather than the current eleven..

E. FUNCTIONAL REQUIREMENTS FOR IMPROVEMENTS TO TWOPAS

No functional improvements to TWOPAS itself are necessary to employ the downgrade analysis procedures. Two necessary improvements to enhance TWOPAS operation can be performed outside of TWOPAS. First, the automated calculation of sight distance and passing/no-passing zones developed in NCHRP Project 3-55(3) should be implemented within the downgrade analysis software so that appropriate sight distances and passing zones can be specified in TWOPAS input. Second, logic described above should be incorporated in the downgrade analysis software to specify the location of truck crawl regions and the truck crawl speed in those regions in TWOPAS input.

APPENDIX E – TRUCK DOWNGRADE SPEED-GEAR SELECTION MODEL

A. INTRODUCTION AND OVERVIEW

This appendix lays out a framework for a driver selection of gear and downhill descent speed based on reaching the bottom of a hill with adequate braking capacity for coming to a complete stop. In general, the driver should use as much engine retarding power as possible, then supplement that with additional braking to maintain a constant speed. The amount of power the brakes need to absorb is directly related to several factors, including the weight of the truck, the selected speed, and the steepness and length of the grade. The objective of this appendix is to review the quantitative relationships of these various factors, and define a method for basing driver gear and speed selection. The operational problem is that if the speed is too high and/or the gear is too high (so that engine speed is too low), the truck brakes will overheat before reaching the end of the grade. As a practical matter this is a potential problem only for large, heavily loaded trucks. The underlying mechanics of the truck brake-heating problem is reasonably well understood and a relatively simple mathematical model of the phenomena, reviewed below, is available based on work reported in Ref. [4]. Representative parameter values for this model are available although knowledge of the range of variation of these parameters over the population of trucks currently operating on US highways is clearly deficient. The truck brake-heating math model involves the grade and length of the hill, the speed and gear used in descent, the weight of the truck and a number truck characteristics related to drag, brake heat transfer and brake effectiveness variation with temperature.

The truck brake-heating model can be used as a basis for predicting the *appropriate* speed and gear to be used on a given grade, for a given truck with a given load. This is a necessary but not sufficient basis for developing the desired speed-gear selection model. This follows because the speed-gear selection problem is more than a mechanics problem – it is a human factors problem as well. That is the truck driver must know the characteristics of the grade (slope and length) and the characteristics of his truck including weight to make an intelligent decision for speed and gear. In effect the driver must do the equivalent of solving a differential equation derived from the brake-heating model. Drivers obviously do not do this formal calculation but instead must combine the information available to them at the grade with experience to make a decision in a short period of time. But due to inadequate information and/or lack of experience, drivers do not always make the correct decisions, which results in brake overheating and in some cases dangerous truck "runaways". This lead to an FHWA-sponsored study almost 20 years ago (Ref. [4]) to develop a Grade Severity Rating System (GSRS) to assist drivers in speed-gear selection. The GSRS was based on the brake-heating model and accounted for both slope and length of the grade. The GSRS is complicated by the sensitivity of brake heating to truck weight. The GSRS was never implemented so drivers still perform speed-gear selection based on experience and available grade information which is only the grade slope. However, the GSRS is an appropriate means for basing downgrade speed selection criteria in the IHSDM, and can be used by both VDANL and TWOPAS.

For transportation safety or traffic flow studies, we would like to be able to predict the statistics of truck speed on arbitrary downgrades accounting for real-world truck variables and human decision making. Such statistical representations are used in traffic flow software such as TWOPAS, but there is currently no well-founded model for the downgrade statistics. The human factors element of this problem complicates it such that empirical data is essential. Ideally statistically significant samples of truck speeds on relevant grades carefully correlated with gear and weight and other key truck characteristics would be obtained. Obtaining such statistically reliable data sets would be an involved process and would require special field tests and specialized observations of in-service trucks operating on a variety of grades. An innovative approach to obtaining this data is discussed below.

With such empirical data, raw means and variances of speed and gear selections could be developed for individual grades, but to be really useful, that is to say *predictive*, this data must be related to the truck braking model. The braking model will provide a basis for establishing the correct (optimal) speed-gear combination for a given grade, truck (or truck category) and payload weight. This could be used to determine errors in speed and gear selection. The speed error would be based on the difference between the actual (observed) speed and the correct speed for the situation (computed from the model). Ultimately it is the statistics of the speed and gear *errors* that are of interest in predicting safety factors (i.e., downgrade runaway probability) and for designing truck runaway lanes. For traffic flow estimation it is the statistics of the *absolute* speed selection that is of interest. This is consistent with the current strategy used in the TWOPAS program to estimate truck downgrade speeds although the formulation implied here would be a considerable refinement to the TWOPAS estimate. However, to estimate this absolute speed distribution for *arbitrary* hills (with lengths and grades distinct from those on which operational measurements were made), the brake-heating model will need to be used. Thus the truck runaway and the traffic flow estimations problems are essentially the same.

If the correct speed and gear can be defined from the brake-heating model, as functions of operational and vehicle parameters, statistical data from in situ observations of in service trucks on downgrades could be used to separate the human factors in the speed-gear selection process from the truck-related factors. The brake-heating model can reasonably represent the truck-related factors. The values of the parameters in this model may vary over a significant range but, as mentioned above, there is little data available to define the statistics of these parameter variations. The parameter values for the brake-heating model as presented Ref. [4] are felt to be representative of heavy over-the-road trucks circa 1980. But the evolution of trucks in the last twenty years could have changed the typical characteristics significantly. For example aerodynamic drag and rolling resistance reductions made in recent decades will tend to aggravate the downgrade problem by absorbing less potential energy. This trend may be offset by a trend to greater use of retarders. But no compete, statistically reliable data on the U.S. truck population is available with sufficient detail to quantify these issues. A concept for obtaining such detailed technical data is discussed below.

B. PREDICTION OF CORRECT DOWNGRADE SPEED AND EAR FOR A SPECIFIC HILL, TRUCK AND LOAD

The fundamental problem is prediction of the correct speed and correct gear for a specific truck with a given load on a given hill. This can then be generalized to a population of trucks with specified distributions of weight and other parameters. The fundamental problem can be approached using the GSRS developments in Ref. [4] with slight modifications and knowledge of the specific parameter values for the truck. Further we assume that the hill can be reasonably well characterized by a constant slope, θ, over a total length, L. If the slope varies significantly along the hill, such that the constant slope assumption is inadequate, the slope variation could be accounted for using procedures in Ref. [4]. The solution is more complex, but conceptually the same.

The basic premise for correct speed and gear selection is that the descent speed and gear will be selected so that the brake temperature at the end of the grade, T(L), will just equal the maximum allowable temperature, T_{lim}. Some safety margin should also be allowed for the vehicle to come to a complete stop, although that is not accounted for in the development here in Appendix E. The development here is based on the formulation of the brake-heating model as given in Table 3 of Ref. [4]. This formulation includes approximations, notably for drag and engine braking, which might need to be revised when more truck characteristic data becomes available.

Thus the brake-heating model equivalent to that in Table 3 of Ref. [4] can be formulated to compute temperature as a function of distance, $T(x)$:

$$
\begin{aligned}
T(x) &= T_0 + [T_\infty - T_0 + \frac{HP_B}{C_B}][1 - e^{-H_c x / \bar{V} C_B}] \\
HP_B &= (W\theta - F_{drag})\frac{\bar{V}}{375} - HP_{eng} \\
H_c &= H_{c_0} + H_{c_{\bar{V}}}\bar{V} \\
F_{drag} &= F_{drag_0} + F_{drag_{\bar{V}}}\bar{V} \\
HP_{eng} &= HP_{eng_0} + HP_{eng_{ret}} K_{ret}
\end{aligned}
\tag{1}
$$

Here the model is expressed in terms total heat transfer coefficient, H_c, and the total heat capacity, C_B, as explained in the Annex to this appendix. Note that the Table 3 model in Ref. [4] specified fixed values for ambient temperature (T_∞ = 150°) and initial brake temperature (T_0 = 90°). These typical values were used to simplify the GSRS. For correct speed-gear selection actual values should be used to the extent that they can be determined.

Calculation of the correct descent speed begins by setting

$$
\begin{aligned}
x &= L \\
T(L) &= T_{\lim}
\end{aligned}
\tag{2}
$$

and then solving for the speed, $\bar{V}$. This theoretical value for the correct speed is the maximum allowable speed (in MPH) on the grade for the given truck and load and is, consistent with Ref. [4], denoted $\bar{V}_{\max}$. Because of the nonlinear transcendental characteristics of the brake temperature equation, a closed form solution cannot be obtained. Thus an iterative numerical solution is required. Figure 21 in the main text, taken from Ref. [4], shows representative $\bar{V}_{\max}$ variations with grade characteristics.

The *ideal gear ratio* is then determined from

$$
G_{T_{ideal}} = \frac{\pi R_w n_{e\max}}{44 G_D \bar{V}_{\max}}
$$

where

$n_{e\max}$ = maximum engine speed (RPM)

$G_{T_{ideal}}$ = ideal transmission gear ratio (ratio of engine speed to driveshaft speed)

G_D = differential gear ratio (ratio of driveshaft speed to axle speed)

R_w = effective drive wheel radius (ft)

The descent should be made at maximum engine speed to maximize engine power absorption. This maximum may be set by the engine or engine brake manufacturer. If driveline retarders are used, use of maximum engine speed will result in maximum power absorption by these devices as well. The ideal gear ratio will inevitably fall between two adjacent gear ratios that are actually available in the transmission. The correct gear ratio, $G_{T_{correct}}$, is the *lowest* available transmission gear ratio that is higher than the ideal transmission gear ratio, $G_{T_{ideal}}$. The correct gear selection is that which sets this actual gear ratio.

The correct speed is thus

$$\bar{V}_{correct} = \frac{\pi R_w n_{\mathrm{emax}}}{44 G_D G_{T_{correct}}} \le \bar{V}_{\max}$$

C. PREDICTION OF CORRECT DOWNGRADE SPEED AND GEAR DISTRIBUTIONS FOR A TRUCK POPULATION ON A GIVEN HILL

The estimation of the correct speed and gear for a *specific* truck on a given hill can be extended to a population of trucks on that hill in a statistical sense. That is the correct speed and gear would be distributions, which could probably be characterized by means and variances. This is consistent with the representation of descent speeds in the TWOPAS software. The primary complication in this process is obtaining the statistics of variations in the truck parameters including load. This problem is addressed in the next section. Once the parameter statistics of a class of truck have been satisfactorily defined, the most straightforward numerical procedure would be to repeatedly compute the correct speed and gear for sets of parameter values and weights selected randomly from their respective distributions. This process should account for covariance between parameters. For instance, as discussed in the Annex to this appendix, the total heat transfer coefficient, H_c, and the total heat capacity, C_B, are determined by distinct physical phenomena. However, this phenomenological independence does not imply that they are statistically independent. It can be expected that the total heat transfer characteristic is proportional to the square of some characteristic length for the brakes such as drum diameter. Total heat capacity might vary as the square or cube of this characteristic length. Thus the two parameters would co-vary with the characteristic length. Determination of these covariances would be part of the parameter identification process discussed in the next section.

The distribution of correct speed would then be plotted and fitted with a theoretical distribution (e.g., a normal distribution). Defining the statistics of the distribution of gear ratios actually available would be complex and probably not necessary. It may be reasonable to simply define

$$\overline{V}_{correct} = \overline{V}_{\max}$$

or $\overline{V}_{correct}$ could simply be reduced by a fixed factor applied to $\overline{V}_{\max}$ to represent the probable effects of finite gear selection availability.

D. STRATEGY FOR EMPIRICAL DETERMINATION OF TRUCK PARAMETER STATISTICS

1. Concept

As noted above reliable characterization of the human factors in the speed-gear selection problem will almost certainly require quantitative observation of operational trucks (i.e., trucks in revenue service) operating on significant downgrades. With appropriate measurements and data analysis as outlined below, it would be possible to estimate the statistics of the truck parameters and loads for relevant truck populations as well. *The key to accomplishing this is to acquire data from very large samples of trucks (hundreds or even thousands) in actual operation on significant downgrades.* A significant sample of hills would be desirable but this would not have to be nearly as large as the truck samples. A variety of hills would provide not only variations in slope and length, but other highway factors such as curves, nominal traffic and road condition that affect descent speed. Truck parameters and loads may vary around the county as well.

Conducting such quantitative field observations will require a sophisticated strategy and special instrumentation and data processing. This process might be conducted by stopping trucks at the bottom of a hill and measuring brake temperature and collecting other data. But this implies interfering with normal truck operations and a significant labor cost for crews involved in manual data taking. *What is proposed here is a highly autonomous data collection system that will not require human intervention to perform individual truck observations and data acquisition.* Further the procedure will be non-interfering with truck operations and the trucks will be neither stopped nor touched. The truck drivers would not normally be aware that data was being collected. The primary motivation for this is to drive the marginal cost of each additional data set as low as possible. Focusing on operational trucks is a key to the strategy because the experimental budget would not be required to pay for their operation (i.e., fuel, maintenance, driver wages).

2. Data Acquisition Using Remote-sensing

This strategy will be based on the development of specialized "remote monitoring" stations to be placed just off the roadway at intervals along a grade and for some distance along the relatively flat roadway below the grade. Remote in this context implies sensors placed on the order of ten feet from the trucks to be observed. These stations would be networked together and linked to a remote data collection/processing center perhaps with wireless communication. The data to be collected would be essentially the same as the data collected to formulate the Ref. [4] model. However, some significantly different measurement strategies would be employed to avoid having to place instrumentation on trucks or even to stop trucks to take measurements. This is essential to minimizing labor and thus cost per truck observation. This would also minimize the likelihood that drivers would modify their behavior or avoid the grade. This will maximize the likelihood that data sets reflecting the critical overloaded and poorly maintained trucks will be properly represented in the statistics.

This remote sensing procedure can be expected to introduce some measurement errors beyond those that would appear if the instrumentation were installed on the truck and/or measurements were made on trucks that had been stopped. To the extent that these errors are random, it should be possible to largely remove their effects from parameter estimates by applying appropriate statistical methods to adequately large samples. Thus again minimizing interaction with the subject trucks implies maximizing sample sizes. Quantities to be measured and remote sensing/non-invasive measurement options are:

Grade slope as a function of distance, $\theta(x)$: this can be obtained from existing highway design drawings, standard surveying techniques or barometric measurements in a moving vehicle as done in the Ref. [4] study. The last technique could now be improved GPS data. This geometry only needs to be defined once for each hill, but the measurement stations would need to be precisely located with respect to the hill geometry so defined.

Ambient temperature, T_∞: conventional meteorological thermometer with electrical output.

Truck speed, V: radar speed guns coordinated with precise times each truck passes each monitoring station.

Truck weight, W: truck "weigh-in-motion" scales installed on the roadway would measure each axle in sequence. Units that can be temporarily installed on the highway without cutting away the roadway surface would be desirable. An option that might be advantageous and consistent with the overall strategy, would involve using seismometers to estimate truck weight. It might even be possible to measure shearing stresses in the road surface related to rolling resistance.

Engine speed, n_{eng}: it might be possible to record and spectral analyze the sound field around the truck and detect the spectral peak corresponding to the engine rotation fundamental frequency. Overall drivetrain gear ratios can then be determined from measured vehicle speed and engine speed.

Brake temperature, *T*: radiation thermometers/optical pyrometers would be used. These would be positioned to view areas where the far side brakes will appear as the truck passes the monitoring station. Pyrometers could be aimed ±20-30 degrees from normal to the lane centerline so the far brake would be "seen" before or after it was covered by the near wheel.

Aerodynamic drag: it might be possible to measure dynamic and static pressure transients near the roadway and use these to estimate the aerodynamic drag. This would be done using a simple math model of the bow wave and momentum wake of the truck calibrated with test trucks for which the aerodynamic drag has determined independently, i.e., with coast down tests**.**

Engine braking and retarder usage: engine retarders (e.g., "Jake brakes") make a distinctive sound that might be detected from acoustic analysis in conjunction with engine speed determination. Electric and hydraulic retarders may be too quiet to identify in this way. Thus retarder effects may constitute one of the major truck characteristic uncertainties. Probably the only way to estimate basic engine braking capability is to correlate it with engine size or power. Engine power might be estimated from the acceleration of the truck on relatively flat roadway at the bottom of the grade or from the speed on an adjacent upgrade.

Vehicle size and type: while weight provides an indicator of size and type, it would not always be possible, based on total weight alone, to separate lightly loaded larger trucks from smaller trucks heavily loaded. Truck weigh-in-motion devices would provide axle weights separated by time intervals from which axle separation distances can be calculated. Axle number and spacing will be indicative of truck size and type but actual measures of length, height and width would be helpful particularly in drag estimation from aerodynamic measurements. Simple optical devices could be used for this and such systems are available for ITS applications.

Vehicle image and license plate: vehicle images could be readily and conveniently captured with digital cameras. This would allow the vehicle to be identified down to make and model and through license plates down to the specific vehicle. This would make it possible to obtain specifications from operators and manufacturers. This would, however, require some manual labor so, consistent with the philosophy of autonomous operation, would be done only on a "spot check" basis or the resolve data questions. There are a number of vehicle classification/electronic license plate systems in use or in development for ITS applications that could be used.

3. Parameter Identification

The strategy to extract the statistics of the parameters of the heavy truck population would be related to the experimental procedures used to estimate the parameters in the Ref. [4] model. But because this procedure is intended to be "non-interfering" the special "coast down" and "cool down" tests used in the Ref. [4] procedures cannot be performed on the operational trucks. But a small sample of trucks (perhaps just a single representative truck) could be instrumented and tested on tracks and on the grade, using the Ref. [4] procedure, to provide a basis for calibrating the remote sensing instruments and the data reduction process.

The data processing procedures to be used will be a form of system identification. System identification procedures of various sorts are routinely used to identify the parameters of models of *individual* vehicles. The problem here is to characterize the statistical distributions of these parameters for the *population* of heavy trucks or any sub-populations that may be of interest. The problem has other special constraints due to the remote-sensing and non-interfering operational procedures. Thus it is useful to begin by considering how the parameters of one specific truck might be estimated using the remote-sensing/non-interfering procedure. We assume initially that we could have as many monitoring stations as we desire although the ultimate goal will be to reduce these to the minimum to minimize cost.

Parameter identification of dynamic systems can be approached using a variety of strategies. It is common to work with the differential equations representing the system dynamics. Here the differential equation for the brake temperature would be

$$\frac{dT}{dt} = \frac{HP_B}{C_B} - \frac{H_c}{C_B}(T - T_\infty)$$

where HP_B, etc. are as defined for equation set (1). This approach would require estimating the derivative dT/dt from measured data. In typical system identification applications, sufficiently high sample rates are used such that good estimates of derivatives with respect to time can be made. The measurement situation is quite different here. Each sample corresponds to the event in which the truck passes a roadside monitoring station. We desire to minimize the number of stations to be used which in effect decreases the sample rate and makes it more difficult to accurately estimate the local temperature derivative. Beyond this, variations in vehicle speed and separation between the monitoring stations creates a variable sample rate measurement. Most identification procedures assume a fixed sample rate.

It appears that these problems can best be dealt with by working with the integral of the above differential equation. If the slope of the hill is constant, integration of this differential equation results in the brake-heating equation (1). If θ varies along the hill, the variation will known along with the truck weight and the differential equation can be reformulated so the slope function, multiplied by truck weight, appears as a known forcing function. The differential equation can be solved using convolution (Duhamel) methods. For simplicity here we will assume the slope as roughly constant and use the simplified brake-heating model (Eqn. 1) to outline the identification scheme. This model contains three directly measured constants

$$T_\infty, T_0, W$$

and three directly measured variables which vary as the truck descends the grade

$$\theta, \bar{V}, T$$

Note that slope, θ, would be determined at arbitrarily small increments along the hill independent of the location of the monitoring stations. Speed and brake temperature measurements would, on the other hand, only be available at the monitoring stations.

The six unknown parameters to be identified are

$$H_{c_0}, H_{c_{\bar{V}}}, C_B, F_{drag_0}, F_{drag_{\bar{V}}}, HP_{eng}$$

Note that, in this formulation, no attempt would be made to decompose the engine baking, HP_{eng}, into engine-alone and retarder components. While this would be interesting, it is not essential to estimating truck speed on grades. It is reasonable to expect that HP_{eng} may exhibit the largest standard deviation of the six parameters to be identified. This would be due largely to the presence or absence of retarders. If the distribution of HP_{eng} is defined it should be possible to predict speed on arbitrary grades even if the statistics of retarder use are not explicitly known. The practical problem is that of non-interfering detection of retarder use on individual trucks. As noted above engine brakes might be detected from acoustic signatures, but electrical or hydraulic driveline retarders may be too quiet to detect. The statistics of retarder *installation,* if not actual *use*, might be obtained from separate manual surveys at truck stops correlated with manufacturer data if desired.

The identification of the six unknown parameters might best be done with regression techniques. In rinciple to identify six independent parameters, six evaluations of the governing equations based on independent measurements from the monitoring stations would be required. This system of six equations would then be solved for the six unknowns. But the inevitable measurement errors would make such a solution highly unreliable. A much larger number of evaluations could be used to determine the six unknown parameters in a "best-fit" sense using regression techniques. Standard statistical tests would be used to estimate required sample size for given error criteria and to verify that the final results are statistically significant.

A separate monitoring station could, in principle, be used to obtain the data set for each evaluation. This would imply a large number of stations and attendant high equipment cost. A simple alternative, for identifying the characteristics of a specific truck with a minimal number of monitoring stations, would be to simply run the same truck down the hill as many times as necessary to obtain the required data sets. Looking ahead to determining parameter distributions for truck populations, this would correspond to reducing the number of required monitoring stations by simply observing more downgrade descents. Since the costs of operation of observed *operational* trucks would not come out of the reasearch budget, significant savings can be made with this trade.

Returning to the problem of identifying parameters of a specific truck, repeating descents at a constant weight implies the same descent speeds. Thus many of the evaluations of the equations will be similar, creating nearly "singular" solutions which have poor properties for numerical solution. This can be remedied by making repeat grade descents with the load randomly varied over the range from empty to fully loaded. This will create a corresponding variation of descent speeds, which will be required to accurately define parameters that characterize speed dependence (i.e., $H_{c_{\bar{V}}}, F_{drag_{\bar{V}}}$). Again looking ahead to characterizing truck populations, trucks in operation on the highways will naturally have random distributions of weight and speeds.

It will probably be useful to obtain data not only on the downgrade but also on relatively flat roadway below the grade. If a downgrade were followed by an immediate upgrade, as in crossing a valley, this would serve as well. The idea is to take measurements on a section of roadway where there is no braking so that the brakes are cooling. Measurements in this region would correspond conceptually to the "cool-down" tests used in the Ref. [4] procedure, however, the data analysis here would be integrated with that for the downgrade sections. Again this is consistent with using the data as it can be obtained without interfering with normal truck operations.

The above "multiple-descent" option would allow parameter identification with a minimal number of monitoring stations. Determining the optimal number and configuration of monitoring stations will take more detailed analysis. It can be expected that, as a minimum, stations would be installed at

- the top of the grade just before descent begins
- at the bottom of the grade where brake temperatures should peak
- at a distance beyond the bottom of the grade where the brakes will have cooled significantly.

It is likely that a few intermediate stations would improve the process, but this would be traded off against cost. Again the number of stations can be traded off against obtaining larger observation data sets. Each station would record brake temperature and vehicle velocity. The brake temperature at the top of the grade provides the initial temperature, T_o. Strictly speaking the ambient temperature would only need to be measured at one station. The cost associated with the ambient temperature would be relatively low, so it might be included in each station. There could be some differences in ambient temperature along the grade. These measurements may also be useful in correcting optical pyrometer data. Thus a basic monitoring station would consist of a radar (or other) speedometer, optical pyrometer and ambient temperature sensor. One weigh in motion unit would be required, but this could be installed anywhere along the test region and linked to the data network. Other acoustic, aerodynamic and vehicle size sensors and cameras could be installed as feasible and desired.

The regression procedure applied to a specific truck with a range of known loads should produce values for the six unknown parameters. Each parameter will have an associated probable error that can be expressed as a mean and variance. If the sample size were large enough we would expect the variance to be low implying that the mean was close to the true value. In fact the experimental design procedure would be to set the sample size to set desired probable errors. As a practical matter additional runs could be made as necessary if the initial results were too uncertain. Of course we would expect a certain amount of actual variation in the parameters from run to run. This would most likely indicate un-modeled factors. These would contribute the parameter variance in addition to measurement error. Conceptually dealing with un-modeled effects that appear to be significant is a matter of model structure determination. Well-developed strategies exist for model structure determination in regression procedures and these can be applied to this problem.

4. Truck Population Parameter and Human Error Statistics

The above development has focused on the identification of the parameters of a *specific* truck performing downgrade descents as dictated by the experimental design. The key problem is that of performing the identification for a *population* of trucks of a specified class based on observation of operational trucks. Basically the procedure would be the same as for a single truck making multiple descents. The key difference that we would expect is larger variance in the parameter value distributions. The mean and variance determined would constitute the parameter statistics we seek.

A practical problem that must be dealt with in making autonomous observations of operational trucks is that of "marking" each truck so that it can be tracked from station to station. Given the velocity of a truck at one station and the distance to the next station, the time of arrival at the next station could be estimated. But variations in vehicle speed could put this system out of synch and it might loose track of vehicles from station to station. A more reliable alternative, consistent with autonomous operation, would be to mark each truck with combinations of acoustic, seismic or optical signatures. Some quickly computed but reliable metric, such as a paint color characterization, would be used to provide a measurable identifier for each truck.

Once the parameter statistics of a class of truck have been satisfactorily defined, these would be combined with the statistics of the observed truck weights to estimate the statistics of the correct speed and gear selection *for the hill on which the observations were made* The most straightforward numerical procedure would be to repeatedly compute the correct speed and gear for sets of parameter values and weights selected randomly from their respective distributions. The distribution of correct speeds would then be plotted and fitted with a theoretical distribution (e.g., a normal distribution).

Finally the distribution of the actual descent speeds observed on the hill would be compared with the computed distribution of correct speeds. One would expect a difference in means between these two distributions that would represent the mean (human) error in speed selection. One would also expect a larger variance in the actual speeds due to the additional variance associated with driver speed selection errors. If it is possible to determine engine speeds through remote sensing (e.g., from acoustical signatures), it should be possible to similarly define the mean and variance of driver errors in gear selection. The gear selection error statistics are not really needed for traffic flow analyses, but would be of interest in traffic safety studies.

The determination of correct speed and gear implies that the limit temperature for the braking system, T_{lim}, is known. In fact this parameter is not well defined. An assumed value of T_{lim} = 425°F was used in many Ref. [4] examples but this was based on informed speculation rather than adequate data. It would be possible to perform separate tests on one or more test trucks to define this limit. These could be performed on a flat track by cycling the truck through repeated braking and acceleration cycles and noting the onset of reduction in braking capability with brake temperature. Since the measured brake temperature could vary considerably depending on how and where on the brake it was measured, it would be important to determine T_{lim} consistent with the remote sensing instrumentation.

It might also be possible to develop T_{lim} estimates from the operational truck observations. This would require detecting trucks that go out of control on the downgrade. This might be evidenced by speed increases on grade, use of "runaway" ramps and accidents. Since these are singular events the minimal number of monitoring stations on grade might not be sufficient to obtain adequate data. Since runways will be relatively rare events, even larger numbers of observations would be needed to capture these events than to determine the basic parameter statistics. The availability of autonomous remote sensing stations in place on a grade over a long period would, however, be the only way quantitative data could be obtained on actual tuck runaway events.

While the observational procedure outlined above is based on the established methods of Ref. [4] it has a number of measurement and procedural innovations which will require careful detail design and optimization. Setting up a digital simulation of the observational procedure to use in the system design could best do this. This would include a model of the truck dynamics, driver speed-gear selection, and brake heating which could be readily implemented with VDANL. This would be augmented with models of the various remote sensors that include sensor error characterizations. Estimates of truck parameter statistics would be made to operate the simulation in a Monte Carlo procedure. Obviously these statistics would be required before the actual parameter statistics could be obtained. But even rough estimates would be adequate to support the measurement and analysis system design process. This process would include determining the optimal number and location of measurement stations and testing the system identification software on simulated observational data.

ANNEX:– REPRESENTATION OF HEAT TRANSFER AND HEAT CAPACITY

Two equations in the Ref. [4], Table 3 model will be re-expressed to replace the two thermodynamic parameters K_1 and K_2 defined as

$$K_1 = \frac{hA_C}{m_B C} = K_{1_0} + K_{1_{\bar{V}}} \bar{V}$$
$$K_2 = \frac{1}{hA_c} = (K_{2_0} + K_{2_{\bar{V}}} \bar{V})^{-1}$$

with

$$H_c = hA_c = H_{c_0} + H_{c_{\bar{V}}} \bar{V}$$
$$C_B = m_B C$$

Note that the parameter K_1 is a function of K_2 whereas the *total heat transfer coefficient*, H_c, and the *total heat capacity*, C_B, are independent in that they are determined by distinct physical phenomena. This formulation should be more suitable in system identification procedures. Further the total number of coefficients drops from four ($K_{1_0}, K_{1_{\bar{V}}}, K_{2_0}, K_{2_{\bar{V}}}$) to three ($H_{c_0}, H_{c_{\bar{V}}}, C_B$). This should simplify the parameter identification problem. The reason for this is that heat transfer depends on the rate of airflow past the brakes, which in turn depends on truck speed. The heat capacity, however, is independent of airflow and depends only on mass and material. These relationships are consistent with the experimentally determined numerical values given in Ref. [4].

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