EFFECTIVE SUPERELEVATION FOR LARGE TRUCKS ON SHARP CURVES AND STEEP GRADES

West Virginia Department of Transportation Research Project #153

by

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16. Abstract

This project was undertaken to identify the particular problems faced by trucks on sharp curves on steep grades, such as rebuilt switchback curves on mountainous two-lane, two-way roads and the high-speed downgrade curves found on West Virginia's limited access roadways, to determine appropriate superelevation rates for trucks under these circumstances. A review of the engineering literature relative to the influence of roadway design and truck characteristics on vehicle handling and stability indicated that for large trucks on such geometry the margin of safety is small.

Several analytical models (static in nature) were developed to evaluate the situation. It was concluded that on sharp curves on steep downgrades additional superelevation is indicated in the downgrade direction, while less superelevation is needed in the upgrade direction. However, this preliminary analysis left many unanswered questions. Crash data were analyzed, spot speed data collected and truck drivers interviewed in an effort to gain additional insight into the problem. Before using the models developed in this research in the geometric design of roadways, the models need to be critically reviewed and further enhanced, including inclusion of vehicle dynamics.

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CHAPTER 1 – INTRODUCTION

Background and Problem Statement

In view of the margins of safety that existing roadways provide for the operation of large trucks, it is apparent that the considerations which underlie horizontal alignment design recommendations in the American Association of State Highway and Transportation Officials (AASHTO) design policy (1994) make little or no allowance for the special requirements of trucks. Of particular interest here are the requirements that govern the limits of vehicle stability and control.

One area where this issue is encountered in West Virginia involves switchback-type alignments on older two-lane, two-way roadways in mountainous terrain. In reconstruction projects (e.g., adding climbing lanes on portions of upgrades while retaining existing horizontal and vertical alignment), the Division of Highways (DOH) has been using a superelevation rate of 8 percent as called for by the AASHTO design policy. However, the existing superelevation rates range from 12 to 17 percent and, according to district-level highway agency personnel, have generally worked well. At one of these locations, the rebuilt section (with the lowered superelevation) is showing a high accident experience in the initial curve for downgrade traffic.

There is a similar problem on high-speed highways with long and relatively steep grades that end on maximum-degree-of-curvature horizontal curves. The combination of the grade and the superelevation can create a situation where possibly the superelevation is inadequate in the downhill direction.

This project was undertaken to identify the particular problems faced by trucks on sharp curves on steep grades, such as the rebuilt switchback curves and on the high-speed downgrade curves found on West Virginia’s limited access roadways, to determine appropriate superelevation rates for trucks under these circumstances.

Project Objectives

To meet the overall goal of the project, several specific objectives were identified:

To review the engineering literature relative to the influence of roadway design and truck characteristics on vehicle handling and stability.

To select or adapt a theoretical model relating roadway design parameters and truck characteristics to vehicle stability and performance.

To apply the model to different roadway geometry situations to predict truck performance.

To identify appropriate superelevation rates to be used in roadway design/re-design for the conditions identified above.

To document the work.

Organization of the Report

This report is divided into six chapters. Chapter 1 has discussed project background and problem statement and presented project objectives. Chapter 2 presents the results of a critical review of the literature. Development of the theoretical analysis, in the form of two models, is described in Chapter 3. Study sites, data collection and results of data analysis are discussed in Chapter 4. Chapter 5 addresses human factors aspects of this issue. Conclusions and recommendations derived from the work along with suggestions for implementation are presented in Chapter 6.

CHAPTER 2 – REVIEW OF LITERATURE

The literature relative to the influence of roadway design and truck characteristics on vehicle handling and stability was reviewed. The overall results of the literature review have been summarized in Figure 1, which shows some of the possible contributory elements to truck crashes on sharp curves on steep downgrades such as those found on two-lane, two-way roads in mountainous areas of West Virginia. Literature relative to each of the factors is discussed below. Note that without before-and-after speed data, and without detailed police reports to permit reconstruction of the crashes occurring at these locations, it is not possible to attribute a level of significance to these factors in contributing to crashes.

Drivers Exceeding the Design Speed

Because of the sharpness of these curves on steep, and in many cases, long downgrades, it is expected that the design speed is routinely exceeded by both cars and large trucks. Keller's paper (1993) on ramp design noted that long, steep negative grades (greater than 5 percent) require the drivers of large trucks to be extra cautious with braking and encourage speeds above the design speed.

Fancher and Winkler (1983), in examining truck behavior in mountainous terrain, found that for types of signing that do not indicate speed, drivers tend to select speeds that are (1) slower than necessary on moderate grades and (2) too high on severe grades. They point out that there is evidence which suggests that without other aids, drivers use perceived grade, but not length of grade to select descent speed. The physics of the situation indicate that appropriate descent speeds are very sensitive to grade length.

HIGH SPEEDS

- Grade
    - Additional Acceleration
    - Driver Misjudgement in how to Handle the Added Acceleration
- Geometric Inconsistency
    - Downhill Tangent => Low Design Speed Curve
    - Drivers tend to wait until entering the curve to decelerate
    - “High-Type” Cross-Section implies a higher speed facility that is not expected to have such sharp curvature

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UNFORGIVING CURVE

- No Spiral Transition
    - Do not have full superelevation at PC
    - Drivers follow a spiral path then <u>oversteer</u> at some point (driven radius is less than centerline radius, reducing the margin of safety)
- Trucks need more friction than cars, and can crash at small increments over the design speed. They particularly need full superelevation at the PC.
- Lower design speed curves assume higher side friction values (f) which leave less margins of safety
- Articulation of large trucks can cause unusual sensations, leading to erratic driving maneuvers when trying to compensate for them.

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CRASHES

The post-climbing lane increase in crashes at the top of Allegheny Mountain could have been caused by either or both factors. The superelevation was lowered, making the curve less forgiving. In addition, it is expected that speeds have increased due to the “high-type” cross-section. Therefore, without a “before improvements” speed data set, there is no way determine the degree to which each attribute contributed to the increase in crashes.

This topic is expanded upon in more recent work by Winkler, et al. (2000) which presents a modern compilation of the state of knowledge on truck rollovers. They indicate that AASHTO guidelines for highway curve design result in lateral accelerations as high as 0.17 g at the advisory speed. Therefore, even a small degree of speeding beyond the advisory level will easily cause actual lateral accelerations to reach 0.25 in everyday driving. On the other hand, tire frictional properties limit lateral acceleration on flat road surfaces to slightly less than 1 g at most. The authors indicate that these two observations clearly imply that the rollover threshold of light vehicles lies above, or just marginally at, the extreme limit of the vehicles' maneuvering ability, but the rollover threshold of loaded heavy trucks extends well into the emergency maneuvering capability of the vehicle and sometimes into the "normal" maneuvering range.

The above statements point to the fact that truck drivers have difficulty in selecting an appropriate speed in descending a grade. This problem is compounded when the grade contains sharp horizontal curves, because drivers then have an additional factor to consider in speed selection. There is no guarantee that the speeds required to safely traverse a sharp horizontal curve will be factored into the selection (by the driver) of speed to descend the grade. On steep grades, drivers may not be able to slow their vehicle to safely traverse a sharp horizontal curve if the approach speed is too high. This is particularly true if driver mismanagement of the grade has overheated truck brakes. The work of Winkler, et al. (2000) also supports the conclusion that truck accidents on downgrade curves are attributable to speed-keeping behavior.

With respect to drivers generally, the following statement by Neumann in a discussion of a paper by Zador, et al. (1985) is relevant to the crash problem at sharp curves on steep downgrades. “Furthermore, drivers’ approach speeds are influenced very little by the impending curve, whether it is visible, signed, or not evident. Drivers also tend not to adjust their speed completely until they are well within the curve.”

When drivers attempt to traverse curves at speeds greater than the design speed, they require more side friction to keep them from sliding off the road. When they attempt to decelerate in the curve, a portion of the available friction at the tire-road interface is devoted to the deceleration, leaving less for side friction demands. These two elements combine to erode the margin of safety provided by using a lower than maximum coefficient of friction (f) to calculate superelevation and curve radius. Simply maintaining a steady speed on a downgrade erodes some of the friction. This is particularly troublesome at low design speed curves, where higher f values are assumed (relative to high speed curves). Furthermore, as will be shown, available side friction is less on downgrades, and a portion of the downgrade acts to the outside of the curve, both of which further reduces the margin of safety.

Finally, in discussing speeding problems on downgrades, and the implications for horizontal curve design, Zador, et al. (1985) reported on a statistical study where accident rates were found to be higher on horizontal curves on steep downgrades as opposed to flat land. For horizontal curves on steep downgrades, the authors believed that the design speed is simply set too low, so that the superelevation is nominally adequate but not in line with actual travel speeds.

The AASHTO Green Book (1994) reinforces the notion that design speeds for horizontal curves on long steep downgrades should be higher. The Green Book indicates that on long or fairly steep grades, drivers tend to travel somewhat faster in the downgrade than in the upgrade direction. “In a refined design this tendency would be recognized, and some adjustment in superelevation rates would follow.” For a divided highway with each roadway independently superelevated, such an adjustment can be made readily. AASHTO (1994) notes that in the simplest practical form, values from the design element tables can be used directly by assuming a somewhat higher design speed for the downgrade and a somewhat lower design speed for the upgrade. “The variation of design speed would depend necessarily on the particular conditions, especially the rate and length of grade and the relative value of the radius of the curve as compared with other curves on the approach highway section.”

AASHTO (1994) goes on to say that it is questionable whether similar adjustments should be made on two-lane and multilane undivided highways. However, the design policy notes that the downgrade speed is the most critical and adjustment for it may be desirable in some cases. “Although not common practice, it is possible to construct the lanes at different cross slopes in the same direction. More practical would be an adjustment for the whole traveled way as determined by the downgrade speed, because the extra cross slope would not significantly affect upgrade travel, with the possible exception of heavy trucks on long grades. Also to be considered is the overall emphasis to avoid minor changes in design speed values. In general, it is advisable to follow the common practice of disregarding such superelevation adjustments on undivided highways.” While the Green Book acknowledges that higher design speeds, which given an unchanged alignment translate into higher superelevation rates, are required in these circumstances, the issue of whether superelevation rates greater than 0.08 are warranted is not addressed.

Horizontal Curve Transition

There are two methods of transitioning from tangent to curve, the two-thirds rule and a spiral transition. Relative to the two-thirds rule, Harwood and Mason (1994) indicate that typical design practice is to place two-thirds of the superelevation runoff on the tangent approach and one-third on the curve. Using this method, full superelevation is not developed until some distance into the curve, and is not available at the point of curvature (PC).

Several problems relevant to superelevation of sharp curves on steep downgrades have been documented in the literature. Keller (1993) states that superelevation helps prevent truck rollover by tilting the truck in the direction opposite the lateral acceleration forces. He notes, however, that the superelevation is not effective unless it is developed early in the curve, where the truck will typically receive the highest lateral acceleration. In discussing interchange ramp design, Keller (1993) cautioned, “Unless the curve is transitioned with spirals, the designer should also calculate the friction factor at the point of curvature to ensure that the suggested maximum side friction factor is not exceeded.” Neuman’s discussion of Zador, et al. (1985) indicates that it is noteworthy that the Jack E. Leisch and Associates curve studies uncovered a slightly statistically significant contribution of amount of superelevation at the PC to high-accident location prediction.

The fact that full superelevation is not developed at the point of curvature is significant in the matter at hand because this further erodes the margin of safety provided since the superelevation deficiency is compensated for by using additional side friction. As noted earlier, the margin of safety against sliding off the road is also eroded by (1) the downgrade (2) speeding and (3) the deceleration activity taking place in the curve instead of on the approach. It was also noted earlier that the sharper the curve, the lower the margin of safety implicitly provided by the design.

Another deficiency of the two-thirds rule method of transitioning is that it leads to oversteering on the part of motor vehicle operators. Drivers naturally choose not to travel the path of the road, which is a tangent section followed immediately by the curve, but instead drive a transition path of decreasing radius from tangent to curve. Harwood and Mason (1994) stated that there is a gradual (rather than an instantaneous) change in lateral acceleration, because drivers steer a spiral or transition path as they enter or leave a horizontal curve. A portion of this path occurs once in the curve, and culminates with the need to drive the path of a curve with a radius less than that of the actual curve. That the margin of safety implied by AASHTO side friction factors is eroded by a significant number of drivers who do not track the designed circular path, but follow a sharper curve path has been noted by several authors (e.g., Keller, 1993 and Olson, et al., 1984).

The alternative method of transitioning from tangent to curve is with spiral transitions. Spiral transitions alleviate the problems caused by two-thirds rule transitions because (1) full superelevation is provided at the point of curvature and (2) it more closely follows the driver’s path, eliminating need for oversteering and other erratic manuevers. Keller (1993), in a discussion of horizontal curves on interchange ramps, noted the significant benefits of spiral transitions:

-“Spiral curves significantly reduce side friction for operating speeds at or above design speeds.

-The changes in lateral acceleration and truck roll angle are smoother, requiring less driver correction.

-Spiral curves follow the driver’s natural path.

-Spirals provide the appropriate location for superelevation transition.”

In discussing design for large trucks, Donaldson (1986) also noted the importance of spiral curves. He indicated that properly spiraled curves radically decrease the hazards of path overshoot. This in turn substantially lowers lateral tire acceleration, thereby ameliorating undue reliance on tire side friction demands.

Friction Available in Curves

Another factor that erodes the margin of safety in horizontal curves in general is available friction. It was noted by Neuman in his discussion of Zador, et al. (1985) that pavement wear is variable, with curves (particularly sharper ones) wearing faster than tangent sections.

Throughout the preceding discussion, the coefficient of friction was a central topic. Specifically, a side coefficient of friction must be selected in the design of the radius and superelevation. This coefficient of side friction is supposedly somewhat less than the maximum, thus providing a margin of safety against sliding off the road. The discussion preceding this section suggests that there is a greater friction demand on downgrades than on flat land due to speeding, deceleration, and gravitational effects. This section suggests that there may be less overall friction supply available at the pavement-tire interface in curves, which further erodes the margin of safety, but in a different way.

A number of the sharp curves on steep downgrades in West Virginia carry significant truck traffic, both local trucks and some longer distance trucks. It has been noted many times in the literature that such curves provide less margin of safety for trucks than for passenger cars. One reason is that these curves have a higher friction demand. Harwood and Mason (1994) suggest that trucks typically demand approximately 10 percent higher side friction than passenger cars. The authors term this higher side friction demand the *effective side friction demand of trucks*.

Gillespie (1992) points out that they also have a lower friction supply. He notes that truck tires generally exhibit lower coefficient values because of their higher unit loading in the contact patch and different tread rubber compounds.

As would be expected, the combination of these two elements leads to a small margin of safety in the curves relative to passenger cars. Four of the more relevant concerns raised in the literature were documented by Harwood and Mason (1994):

-- The margins of safety against skidding by trucks are in the range of 0.17g to 0.22g, which is lower than that for passenger cars.

-- Special care should be taken for curves with design speeds of 30 mph or less to ensure that the selected design speed will not be exceeded, particularly by trucks.

-- For design speeds of 10 to 20 mph, minimum-radius horizontal curves may not provide adequate margins of safety for trucks with poor tires on a worn wet pavement or for trucks with low rollover thresholds.

-- At lower design speeds, overdriving of the design speed by even a small amount can produce side friction demands above the rollover thresholds of some trucks.

Two special concerns regarding the issue of truck traffic in mountainous terrain are (1) retarders and (2) switchback curves. Fancher and Winkler (1983) note that heavy vehicles with good brakes and a retarder may be expected to be 11 times less likely to run away than a comparable vehicle with poorly adjusted brakes and no retarder.

With respect to switchback curves, one item of note was found. Switchback curves require drivers to turn the steering wheel in one direction followed by a turn in the other direction. Traversing them is similar to traversing a slalom course. Gillespie (1992) noted that if this type of steering is performed at a frequency equal to the "roll resonant frequency," the vehicle will rock with increased amplitude until it rolls over. With their high centers of gravity, trucks are particularly susceptible to this phenomenon. The "roll resonant frequency" for trucks is less than one second. Thus, Gillespie (1992) noted that experience has shown that "lane-change" type maneuvers executed over two seconds (one-half Hz) are well capable of exciting roll dynamics that can precipitate rollover of heavy trucks. Depending on the spacing and length of the curves in a switchback, this could become a factor in large truck safety. However, it is expected that in most cases, the driver will not traverse the curves at a speed high enough to require the steering changes every half second.

CHAPTER 3 - THEORETICAL MODELS

Several simulation packages which model truck performance, identified during the literature review, were evaluated. The simulation approach was rejected for this project since the models either oversimplified the roadway geometry or required extensive pre-processing of geometric data. Instead, analytical models were used to evaluate the situation. One involved a decrease in available friction and the other involved an increase in lateral acceleration. Each is outlined below.

Decrease in Available f Model

The theoretical model found in standard highway engineering and design texts (and shown as Equation 1) was examined initially. This is a model based strictly on the friction circle and accounts only for the loss of side friction because of increased braking friction. Typical output of the model, in the form of speed versus radius plots for different superelevation rates and friction factors, is shown in Figure 2.

$$\sqrt{\left(W\sin\theta+\frac{w}{g}a\right)^{2}+\left(\frac{WV^{2}}{gR}\cos\alpha-W\sin\alpha\right)^{2}} \qquad (1)$$

$$\leq \mu W\left(\cos\alpha\cos\theta+\cos\theta\sin\alpha\frac{V^{2}}{gR}\right)$$

where:

W = vehicle weight (pounds)
V = vehicle speed
g = acceleration due to gravity (32.2 ft/sec/sec)
R = radius of curve (feet)
a = acceleration (ft/sec/sec)
μ = coefficient of friction
θ = grade expressed as an angle
α = superelevation expressed as an angle

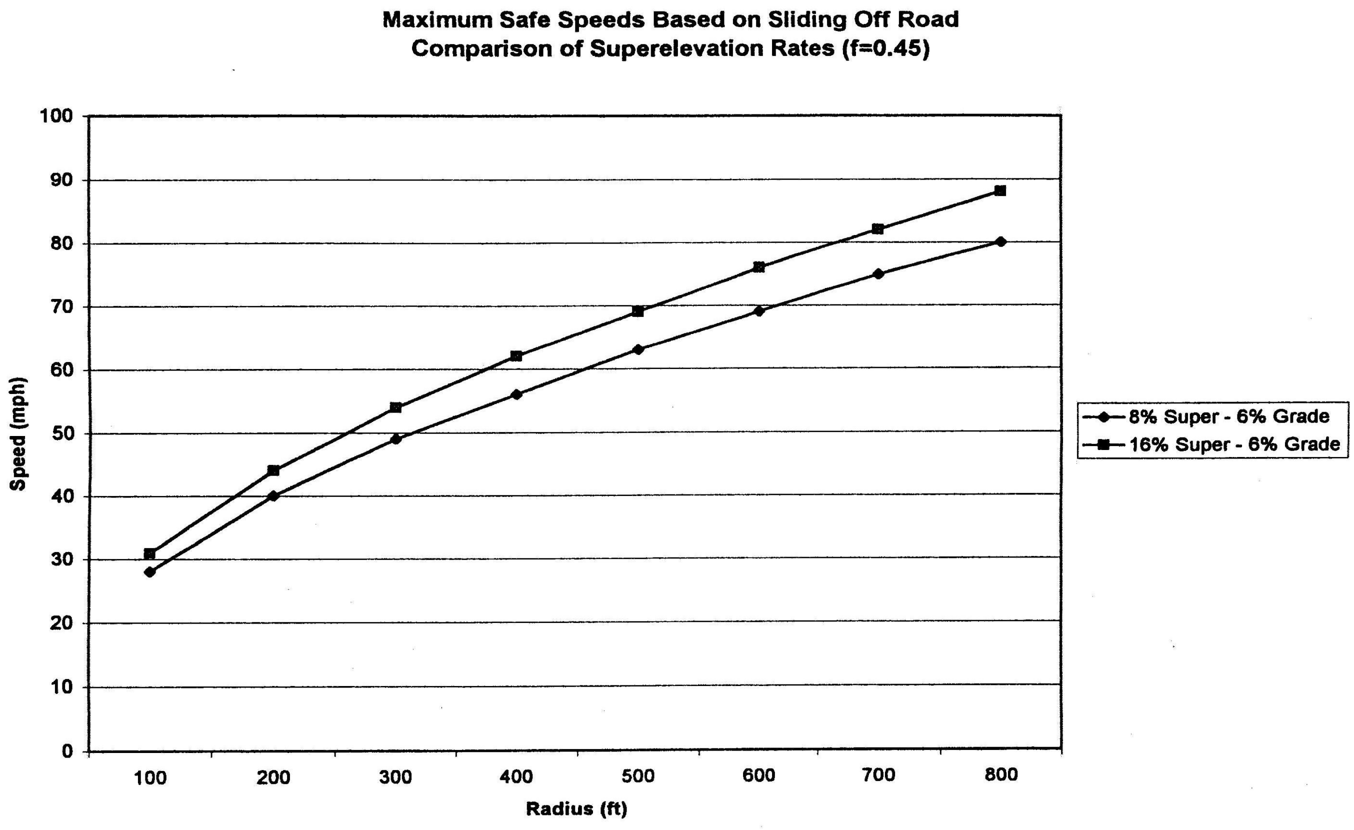


Figure 2. Sample of Speed Versus Radius Plot Used in Evaluating Switchback Curve Issue.

From the plot, it appears that the 16 percent superelevation allows about a 10 percent higher vehicle speed than an 8 percent superelevation on downgrades. This difference appears to remain constant at any speed. Thus, for the speeds for curves like those of interest (radii of 200 to 300 feet), the 16 percent superelevation allows an increase in speed of about 4 miles per hour compared to an 8 percent superelevation. For an 800-foot radius curve, the increase is about 8 miles per hour.

The additional superelevation also reduces the lateral acceleration felt by vehicle occupants by 0.08g. Neither of these effects will improve the travel time of a particular trip or permit the driver to use significantly higher speeds. However, these effects make the curve more forgiving of drivers who enter the curve at a speed which is slightly too high. This assumes that the superelevation is adequate at the design speed, which may not be the case for trucks on downgrades.

Increase in Lateral Acceleration Model

Figure 3 is a sketch (exaggerated) of the forces acting on a vehicle on a steep downgrade in a horizontal curve. The key to determining how much of the gravitational force is acting to the outside of the curve is to determine the angle at which the front wheels are turned (shown as “ è “ in the drawing). It is hypothesized that the vehicle follows a path that is tangent to the curve at the rear wheels. The front wheels are turned relative to the vehicle. They follow a path that is tangent to the curve at the front wheels. Combining two equations for a horizontal curve:

$L = 100\_\Delta\_/ D$

$D = 5729.6 / R$

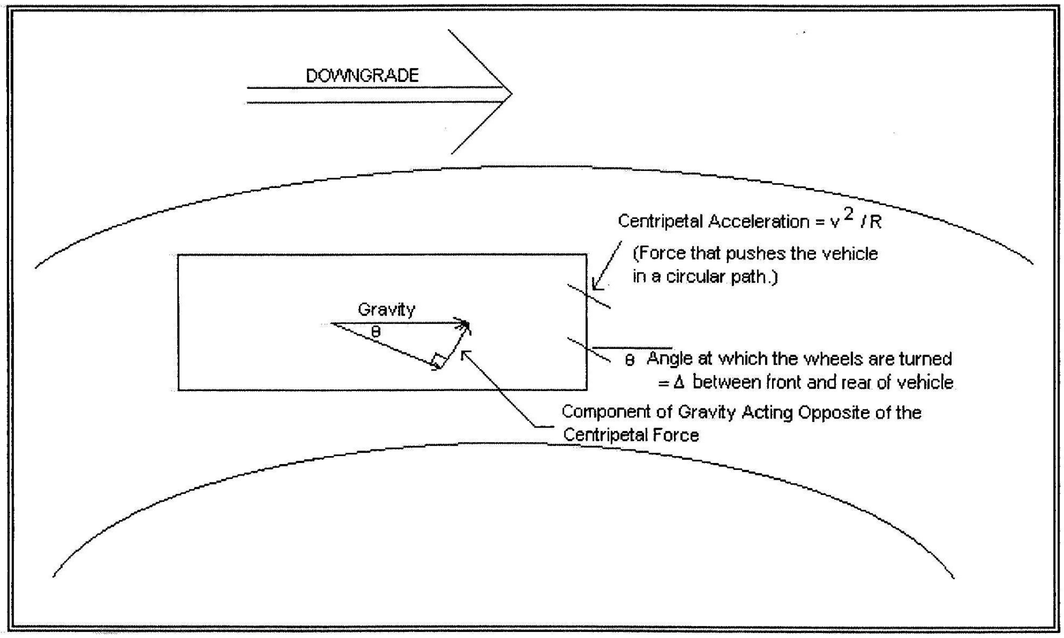


Figure 3. Forces Acting on Vehicle on Steep Downgrade in Horizontal Curve.

and solving for Δ:

$\Delta = L*5729.6 / (100 * R)$

In this equation, Δ represents the deflection angle between two tangents on a curve that are a distance L apart. Therefore, if the wheelbase of the vehicle is used for L, then:

$\Delta = \theta$_=_Deflection angle between path of vehicle and front tires

Furthermore, the gravitational acceleration acting opposite of the centripetal force is $G * \sin \theta$ (Figure 3). In the AASHTO equation for calculating superelevation:

$e + f = v^2 / 15R$

It is argued that e+f not only have to counteract "$v^2 / 15R$", but must also counteract "G * sin è". Thus, the superelevation equation can be revised as follows:

$e + f = v^2 / 15R + G(\sin \theta)$

e = Rate of Superelevation (ft/ft)
f = Coefficient of Side Friction
v = Velocity (mph)
R = Radius (ft)
θ = Deflection angle between path of vehicle (center of gravity) and tires (Figure 3)
G = Grade (decimal form)

Articulated Vehicle

The above equation is valid for single-unit vehicles. However, for articulated vehicles, the analysis becomes more complicated for two reasons. First, the trailer is at an angle to the tractor, which means that it is at a more severe angle to the front wheels than the body of the tractor. Second, since each part of the vehicle is at a different angle relative to the front wheels, the weight distribution between the two vehicle components is important. As more weight is placed in the trailer (the component with the more severe angle relative to the front tires), more of the downhill gravitational force acts in opposition of the centripetal force as shown in Figure 4.

The analysis for articulated vehicles is based on the same theory as that presented above for single unit vehicles. Two angles need to be calculated: the angle between the tractor and the front tractor wheels, and the angle between the trailer and the front tractor wheels. The trailer portion of the vehicle is assumed to be traveling a path that is tangent to the back wheels. Therefore, in determining the angle between the front wheels of the Htractor and the back wheels of the trailer, the overall wheelbase is used. In addition, the weight distribution between tractor and trailer is handled as shown in the following equation:

$$e + f = v^2 / 15R + G * \frac{W_{tractor}*\sin(\theta_{front\ wheels\ -\ tractor}) + W_{trailer}*\sin(\theta_{front\ wheels\ -\ trailer})}{W_{overall}}$$

For example, consider a WB-50 vehicle negotiating a 190-foot radius curve on a 9% downgrade:

R=190 feet
WB_1 = 20 feet (wheel base of the tractor)
WB_2 = 30 feet (wheel base of the trailer)
Tractor Weight = 20,000 lb
Trailer Weight = 50,000 lb

$\theta\_=L*5729.6 / (100 * R)$
$\theta_{front\ wheels\ -\ tractor}$ = 20-ft * 5729.6 / (100 * 190-ft) = 6.03 degrees
$\theta_{front\ wheels\ -\ trailer}$ = 50-ft * 5729.6 / (100 * 190-ft) = 15.07 degrees

Amount of additional superelevation needed because of the downgrade:

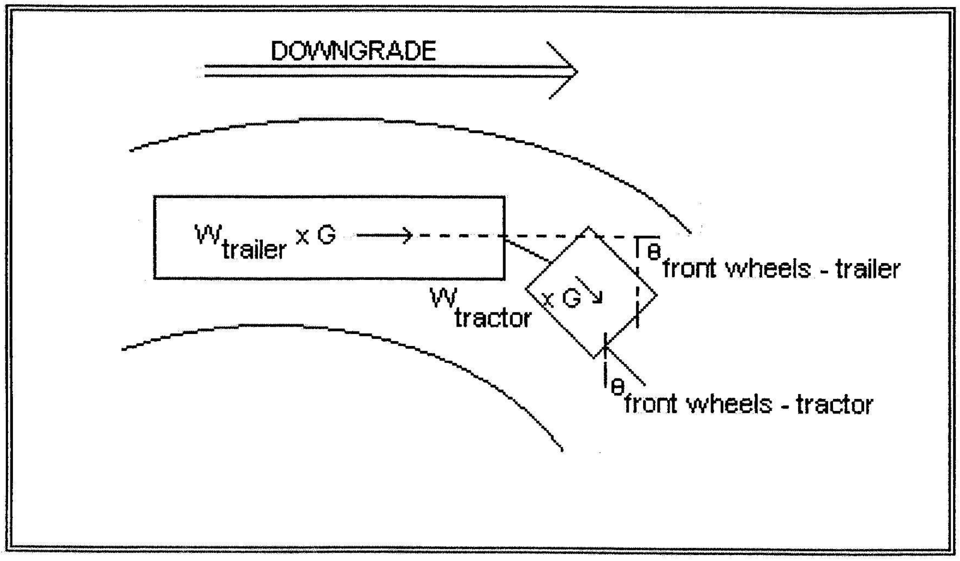


Figure 4. Angles Between Components of an Articulated Vehicle and the Front Tires.

$$\frac{20{,}000\text{-lb} * \sin(6.03) + 50{,}000\text{ lb} * \sin(15.07)}{70{,}000\text{ lb}} \quad X \quad G$$

$$= \quad 0.22 \quad X \quad G$$

In this case, the road has a 9% downgrade through the curve, thus:

0.22 * 0.09 = 0.02

Therefore, this analysis indicates that an additional 0.02 ft/ft of superelevation should be provided.

Note that the previous discussion which indicated that some of the side friction was lost in maintaining a steady speed on the downgrade is valid and must be accounted for in addition to what this model showed. This effect can range from negligible to requiring a significant amount of additional superelevation, depending upon the amount of additional braking for deceleration that is to be accommodated.

Related Issue

Another question raised about trucks on roads with sharp curves and steep grades was: What does this combination of geometry do to the transverse forces on the center of gravity of the vehicle? For example, assume that a truck with a 60-foot wheelbase and a 6-foot wide axle is traveling on a 6 percent downgrade with an 8 percent superelevated curve to the left. The right front wheel (outside) is lower than the left rear wheel (inside) by 3.12 feet ((60 x 0.06) - (6 x 0.08) = 3.6 - 0.48 = 3.12). Does this affect the centrifugal force resistance, which could result in loss of vehicle control?

According to a conversation with Thomas Gillespie of the University of Michigan, it does not matter that the inside rear wheels are higher than the outside front wheels. In his opinion, the important thing is that, for each axle, the outside wheel is higher than the inside wheel. Thus, he opines that the rearmost axle, which has to handle its part of the load, sees the 8 percent superelevation; as long as the axles experience the superelevation, they will function as intended. Since proving the validity of this statement is mathematically very complex, the authors made the decision not to include the derivation in this report. However, based on Dr. Gillespie's description, it appears that he is using a two-dimensional analysis.

Design Implications

This chapter has demonstrated that part of the gravitational force acting on a vehicle on a grade acts perpendicular to the front wheels when the vehicle is in a horizontal curve. This force acts to the outside of the curve on downgrades, and to the inside of the curve on upgrades. This chapter also demonstrated that less friction is available under these circumstances. One conclusion that can be drawn from these analyses is that additional superelevation is required in the downgrade direction, while less superelevation is required in the upgrade direction. However, this finding leaves many unanswered questions, a few of which are mentioned below:

- How does this apply to actual geometric design standards and practices? For example, does the need for additional superelevation extend to cases where $e > 0.08$?
- In particular, how does this apply on two lane roads where providing more superelevation on the outside of the curve than on the inside will cause an inverse crown to the roadway?
- Does this apply to all classes of roadway?

- At what degree of curve and/or grade does the effect become negligible?

- Does the point of rotation for establishing superelevation have any influence?

- What ramifications does this have for transitions between tangent sections and curve sections?
  -- Should spiral curve transitions be required for certain classes of roadway when curves on steep downgrades occur?
  -- Should a greater amount of the superelevation be achieved before entering the curve when spirals are not used?

To provide additional insight with respect to these issues, data were collected for several sites and truck drivers were interviewed. Data collection and analysis are described in Chapter 4; results of discussions with drivers are presented in Chapter 5.

CHAPTER 4 – DATA COLLECTION, ANALYSIS AND RESULTS

Study Sites

To gain first-hand knowledge of the problem and to assist in understanding and evaluating the analytical model, three study sites were selected on US Route 33 in Pendleton County, West Virginia. In the area of interest, US 33 is a two-lane, two-way bituminous surface roadway traversing the mountainous terrain of rural eastern West Virginia. Because the roadway contains numerous sharp curves on steep grades, it provided several excellent study sites. In addition, on portions of three substantial grades, climbing lanes had been recently constructed within the existing alignment. That is, the cross section had been widened to provide two lanes in the uphill direction with shoulders on both sides of the road while retaining the original curves and grades.

US 33 in Pendleton County had been constructed relatively early in the 20th century and, for the most part, had remained unchanged since then. On a number of long and steep grades, the superelevation rate on curves was on the order of 16 percent. Apparently, this alignment had performed well, even in an area with relatively severe winter weather, which could have caused vehicles to slide to the inside of curves on icy pavement. When the climbing lanes were added, an 8 percent superelvation rate, consistent with current AASHTO design policy was utilized within the limits of these projects.

Three sites on US 33 were selected for study: (1) Allegheny Mountain, (2) Convict Curve and (3) Shenandoah Mountain. At Allegheny Mountain, the eastbound downgrade, located just east of the Randolph County line, was of interest. Due to the length of the grade and a history of runaway truck crashes, a mandatory brake check area had been installed at the summit a number of years ago. The added climbing lane (for westbound traffic), which opened in June of 1996, was also near the summit. It was the post-climbing lane crash experience at this location that attracted the attention of WVDOH engineers.

Convict Curve is located in central Pendleton County. The Convict Curve climbing lane, near the top of the grade for westbound traffic, opened in October 1998.

The westbound downgrade on Shenandoah Mountain adjacent to the Virginia State line was also of concern. An eastbound climbing lane near the summit was being installed as this research project was initiated in spring 1999.

Data Collection

"As-built" plans were obtained for the Allegheny Mountain and Convict Curve climbing lane projects. All three sites were visually inspected via walk- and drive-throughs. This provided an opportunity to examine the roadway environment and pavement and shoulder conditions. One striking observation of the site visits was the evidence of damaged sign supports, vehicle debris, and gouge and tire marks in the roadside on the outside of the first downgrade curve at the top of Allegheny Mountain.

Return visits were made to several sites to collect data in the field. Vehicle speeds were measured by stopwatch methods at the Allegheny Mountain site.

In an effort to determine at least relative quantities with respect to tire-pavement friction, a "drag sled" was constructed. A section of a truck tire was filled with a known weight of concrete and a spring-type pull scale attached. Coefficient of friction measurements were made at tangent and curve locations at the top of Allegheny

Mountain. However, the researchers recognized that this device did not replicate coefficients of friction for trucks since it was pulled across the pavement at slow speed compared to the relatively high truck speeds.

Obviously, human factors are a significant issue relative to truck safety in mountainous terrain. To obtain information in this regard, informal discussions about mountain driving in general, and US 33 in particular, were held with truck drivers who exited their vehicles at the brake check area at the summit of Allegheny Mountain.

Accident summaries for the four locations noted above were obtained and analyzed. Unfortunately, the unavailability of hard copy accident reports prior to 1996 prevented an in-depth analysis of the relationship between roadway geometry and specific nature/location of the accidents. Allegheny Mountain was the only reconstructed site for which there was both “before” and a viable “after” reconstruction accident experience. At the other two sites, added climbing lanes had just opened and no “after” data were available.

Results from Speed Studies

From an elevated vantage point that provided an unobstructed view of the first curve at the top of Allegheny Mountain, stopwatch methods were used to determine speeds for a sample of eastbound vehicles. The truck speed profile for this location is shown in Figure 5. The distribution of passenger car speeds is shown in Figure 6.

Clearly, truck speeds on this section of US 33 were lower than passenger car speeds. Field observations indicated that trucks, in general, used the brake check area at the summit. Hence, they were in low gear and traveling at relatively slow speed approaching the first curve. In many cases, it was obvious from the sound of the truck

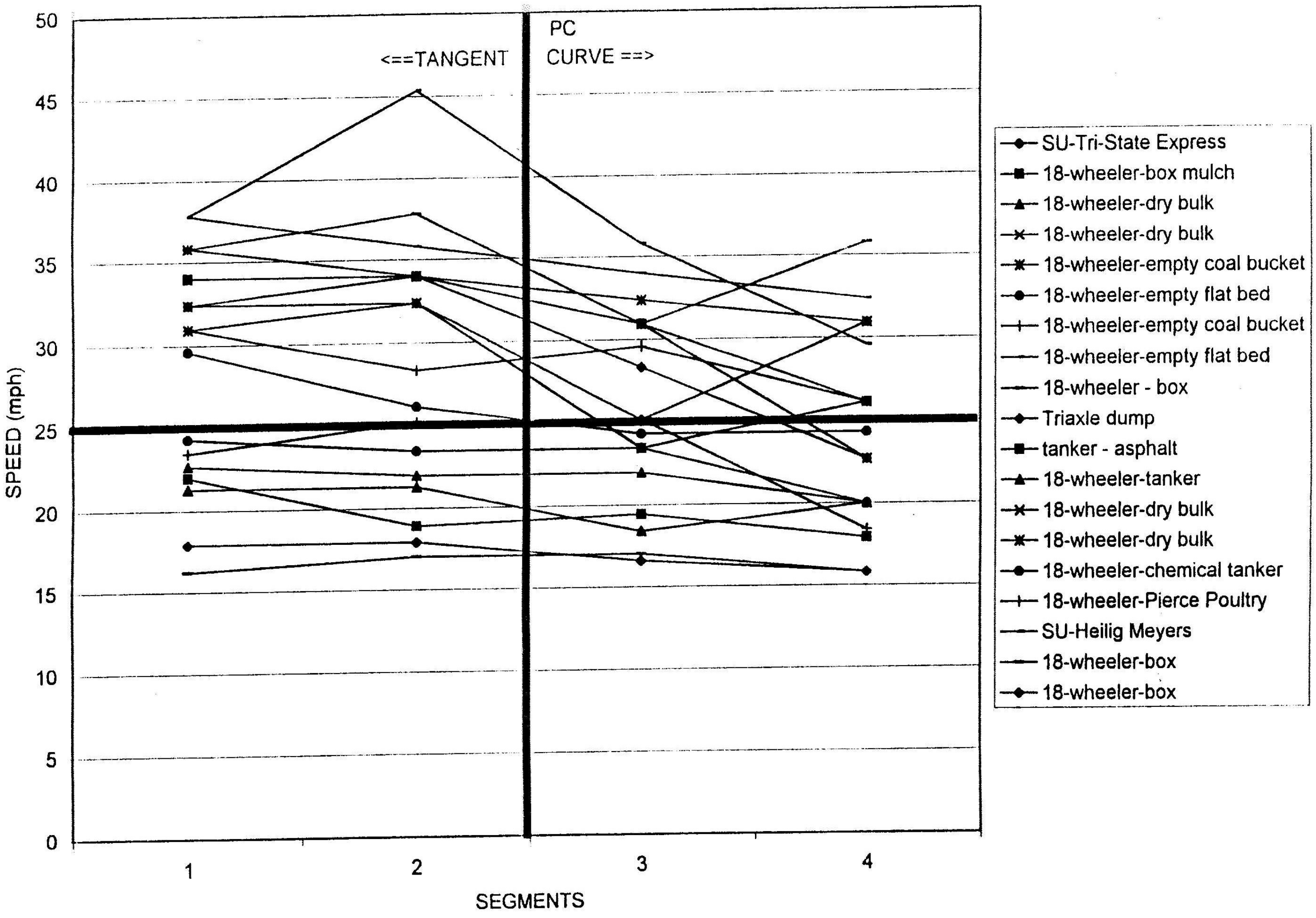


Figure 5. Speed Profiles for Eastbound Trucks at First Downgrade Curve on US 33 at Allegheny Mountain (July 15, 1999).

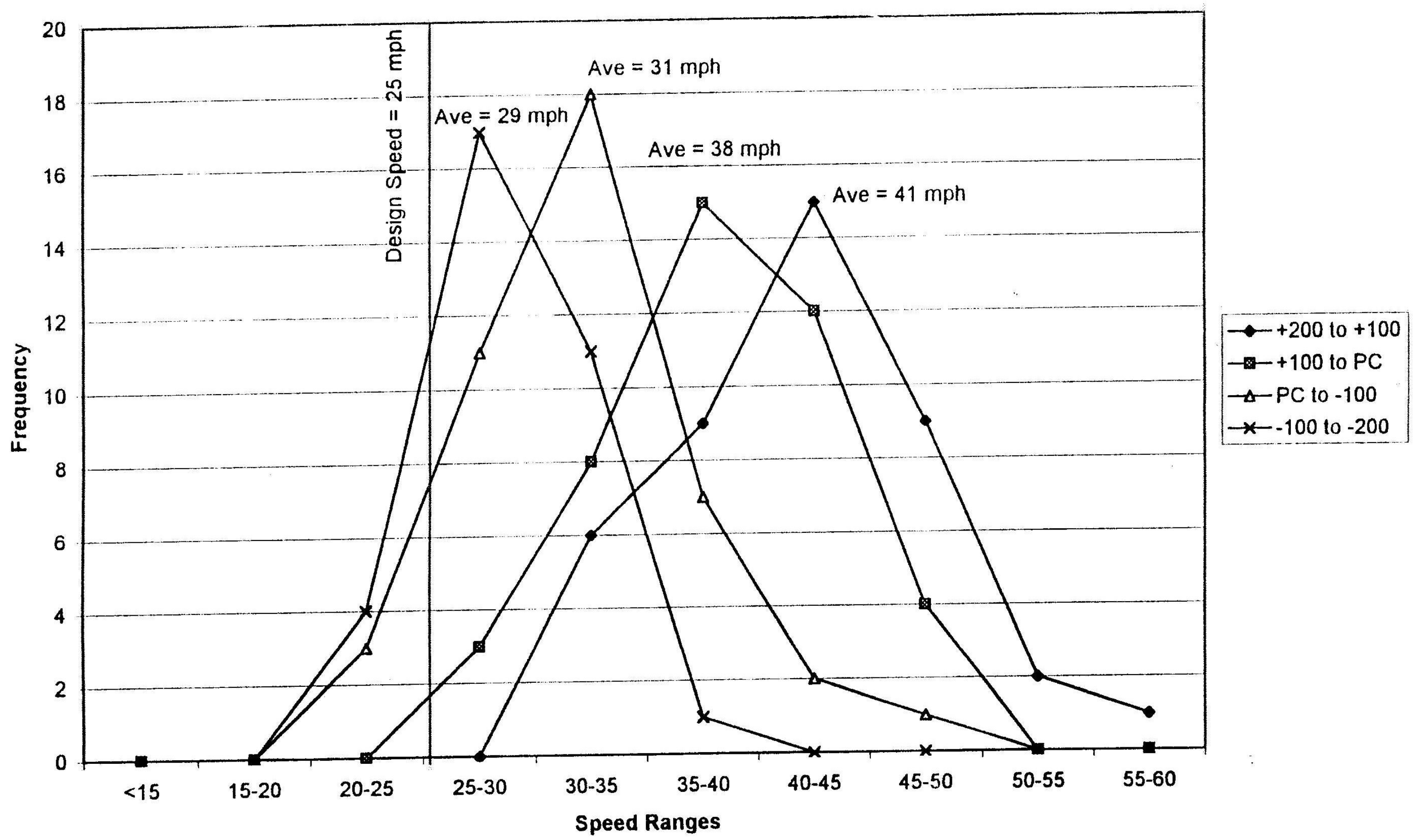


Figure 6. Distribution of Eastbound Passenger Car Speeds at First Downgrade Curve on US 33 at Allegheny Mountain (July 15, 1999).

that the engine brake had been engaged. Thus, high entering speed was not a problem for trucks at this location.

Passenger car speeds, as shown in Figure 6, were high and passenger cars were decelerating in the curve. As described in the next section, the accident data bear this out.

Results from Crash Data Analysis

As expected, while the crash summaries were useful in locating crashes, they did not provide enough detail about the nature of truck crashes. Consequently, hard copies of the police reports were ordered for selected crashes, particularly those involving commercial vehicles.

Analysis of the crash data for Allegheny Mountain indicated that at the first curve east of the summit, there was a significant increase in the crash rate after the superelevation rate was reduced (9.8 crashes per million VMT before versus 52.2 crashes per million VMT after). This confirms the physical evidence observed at the scene.

Although it was sometimes difficult to tell from the hard-copy reports, it appeared that “rollover” was not the primary reason for crashes at the first curve east of the summit at Allegheny Mountain. Rather, the commonly cited circumstance was sliding off the road or “failure to maintain control.” Involved vehicles at this location were typically passenger cars rather than trucks.

For the first curve east of the summit of Allegheny Mountain, drag sled results indicated a relatively low wet pavement coefficient of friction. The accident history indicated that wet-weather crashes were over-represented in crashes in the first curve at the top of Allegheny Mountain.

At many of the curves, stone from the shoulder was present on the pavement surface. The loose stone can cause a reduction in available friction.

Observations and discussions with truck drivers indicated that, on switchback alignments, truck wheels track outside their lane, including into the opposing lane of traffic. Consequently, pavement widths in the curves are sometimes not adequate for cornering trucks, causing some tires to leave the roadway and creating the potential for overcompensation in the form of steering and/or braking. This is also a mechanism by which stone from the shoulder reaches the traveled way.

Results from As-Built Roadway Cross Section Analysis

Although the as-built plans were available, a field survey was performed to confirm the cross slopes in the first horizontal curve east of the crest of Allegheny Mountain on US 33. The cross slopes are shown in Figures 7 and 8. Figure 7 shows the downgrade lane; Figure 8 shows the upgrade lanes.

The superelevation at the PC in the downgrade direction was slightly over 6% (0.06) compared to the full superelevation for this curve of 8% (0.08). Full superelevation is not usually achieved at the PC when spiral transitions are not used, therefore, this is not considered unusual. However, both the accident data and the physical evidence at the site indicate that vehicles tend to leave the traveled way in the vicinity of the PC.

In the downgrade direction, full superelevation was established approximately 100-ft into the curve, but then the superelevation dropped back to below 8% (0.08) within 50-ft and continued at less than 8% (0.08) for the remainder of the curve. In the area of station 1769 (approximately 200-ft into the curve), the superelevation was significantly

Figure 7.

"AS - BUILT" SUPERELEVATIONS GOING DOWNGRADE- ALLEGHENY MOUNTAIN SITE

(Note: + indicates superelevation, - indicates adverse crown
Downgrade is in direction of decreasing stations)

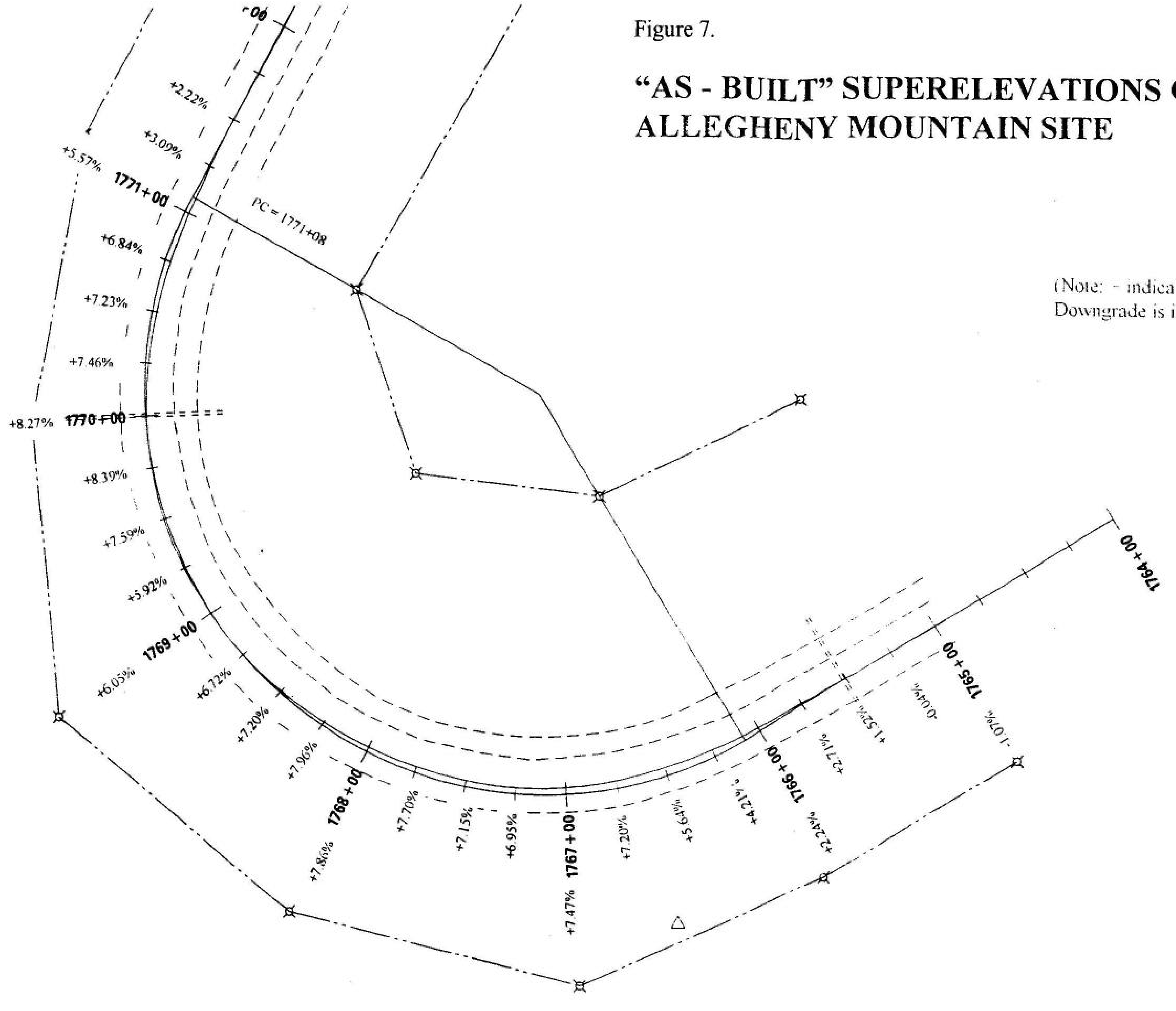
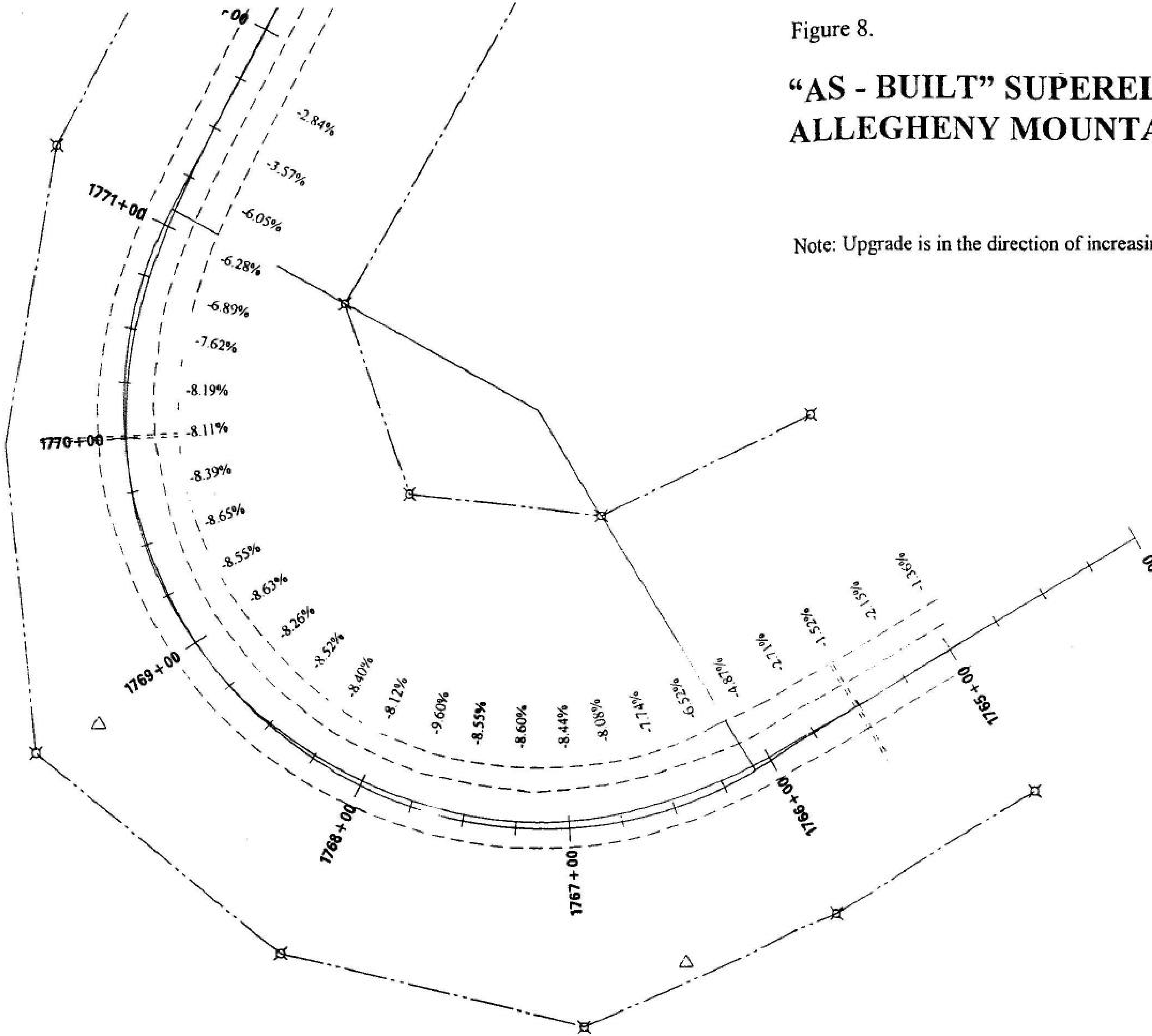


Figure 8.

"AS - BUILT" SUPERELEVATIONS GOING UPGRADE-ALLEGHENY MOUNTAIN SITE

Note: Upgrade is in the direction of increasing stations.



lower than design, and at 1769+25 was less than 6% (0.06). According to the theory presented in this report, additional superelevation is required for safe operation on downgrades, therefore less superelevation than originally designed may have an adverse effect on truck operations.

In the upgrade direction, the superelevation was greater than that specified in the design. Again, according to the theory presented in this report, less superelevation will be required on upgrades, since part of the gravitational force will act in concert with the centripetal force. Therefore, this may also have an adverse effect on truck operations. Part of the problem is likely attributable to the difficulty of constructing of superelevation on steep downgrades.

CHAPTER 5 – HUMAN FACTORS ISSUES

Based on the information gathered during the course of this study, including the informal discussions with truck drivers, a number of human factors issues associated with the problem of trucks on steep grades with sharp curves were identified. These are summarized below, in no particular order.

Drivers may perceive more hazard due to the downslope curve combination, drop-offs in the near roadside area, and the long downgrade. Thus, they may be more likely to panic brake, particularly when lateral acceleration reaches 0.2g’s.

Cross slopes that were formerly 16 percent but reconstructed to 8 percent can potentially violate driver expectancy for regular users, particularly if other curves in the area are still superelevated at a rate of 16 percent. However, for particularly sharp curves, the superelevation rates at neighboring curves may be irrelevant. Furthermore, the truck drivers indicated that they did not notice any difference in the banking of the curve before and after the climbing lane project on Allegheny Mountain.

US 33 in Pendleton County has a significant amount of ‘through” traffic (long distance travelers, including many from outside the region). Such motorists may traverse these curves at speeds very near the maximum possible speed because of the desire to improve travel time. Truck driver reports of aggressive driving behavior by passenger cars and trucks (e.g., passing in no passing zones) is indicative of attempts to improve travel time.

Truck drivers generally seemed to respect the grade on the east side of Allegheny Mountain and expressed no concern over the first curve east of the summit. However, as brakes heat up in negotiating the grade, they mentioned two curves near the base of the mountain where rigs often leave the road.

Several of the "local" drivers noted that some of the trucks from outside the region are not equipped with engine retarders. They felt that these drivers were a particular safety hazard and suggested laws that required this equipment. Perhaps, for facilities such as US 33, where steep downgrades combine with sharp horizontal curvature to make speed selection and management the most critical element of driving, trucks should be required to have the appropriate speed management equipment, including engine retarders.

The improved cross-section (e.g., wider shoulders, lined ditches, modern rock cuts) of the rebuilt sections creates the perception of a higher type facility than actually exists. Consequently, passenger car speeds may have increased subsequent to the improvements. Although there is no "before" data on which to evaluate, an increase in speed may explain the increase in crash rate.

Although they could be under other circumstances, these particular high-superelevation-rate sites were not a problem under winter conditions. This statement is supported by both the crash records and truck driver comments.

CHAPTER 6 – CONCLUSIONS, RECOMMENDATIONS AND IMPLEMENTATION

This project has involved a review of the literature, examination of several roadway sites and an analytical assessment. A number of findings were identified and recommendations developed. These are presented below.

On downgrades, a portion of the available friction is consumed in maintaining a steady speed (counteracting the downhill force). This leaves less than the maximum (or ideal) friction available for side friction demands. This is not a significant problem under normal steady speed conditions. However, the available side friction is severely reduced by braking for deceleration. Furthermore, the downgrade adds to the lateral acceleration. These two theoretical models support the use of additional superelevation on sharp curves on steep downgrades.

In addition, review of the literature relative to human factors, geometric design, and large trucks indicated that the margin of safety in such situations is small. If intentional countermeasures are not taken, a safety problem will likely result.

Other conclusions and recommendations, not derived from the analytical models, are identified below.

High superelevation rates ($0.08=e=0.16$) make curves more forgiving. The high superelevation rate does not permit a significant increase in speeds to improve travel time, but can accommodate drivers making errors in safe speed selection for the curve/grade combination.

The improved cross section associated with the reconstruction projects may increase speeds. Reducing the superelevation in combination with these increased speeds creates a difficult situation for passenger car operators. A before-after study of the effects of improved cross section design on vehicle speeds on rebuilt sections of two-lane, two-way roadways in mountainous terrain should be conducted.

The significant increase in passenger car crashes where the superelevation rate has been reduced is at least partially attributable to violation of driver expectancy, namely (1) the lower superelevation rate and (2) the improved cross section design. The lower superelevation rate does not totally explain the increase in accident rates; however, the reduction in "e" accentuates the problems caused by the increase in speed due to improved cross section. Consequently, reducing the superelevation of existing curves is not good highway design practice unless there is another more compelling safety reason that requires the reduction of superelevation. .

None of the sharp curves on steep downgrades studied used spiral transitions. This is a possible contributing factor to the crash problem. Including spiral transitions should be a consideration in the design of similar curves in the future.

Pavement widths adequate for large trucks must be provided in sharp curves. This will reduce stone and earth being tracked onto the pavement and will reduce the hazards associated with pavement edge drop-offs.

Paved shoulders are an important safety appurtenance on sharp curves on steep grades because they provide a good surface for truck tires that leave the traveled way in turns due to their larger swept path. Paved shoulders also reduce the amount of stone in the traveled way.

Before using the models developed in this research in the geometric design of roadways, the models need to be critically reviewed and further enhanced. For example, additional investigation of the situation is needed to account for any other phenomena which either reduce side friction or increase lateral acceleration, e.g., truck loading condition. Other issues may be identified in a peer review by researchers and practitioners in the field of geometric design. Once these things are accomplished, the final step would be to formulate and guidelines relative to how to handle superelevation of sharp curves on steep downgrades.

Note that in July 2001, an expert panel made up of researchers, state highway agency designers, and a Federal Highway Administration representative, met to review and discuss the preliminary results described herein. That review and the follow-on work subsequently performed will be described in a forthcoming Phase II report.

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