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How Driver Risk Perception Affects Operating Speeds

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Abstract

Excessive speed is one of the primary safety hazards facing highway users. However, in many cases operating speeds exceed design speeds, and drivers generally ignore posted speed limits. The main objective of this research was to identify roadway elements and roadside features that could influence driver operating speeds in rural two-lane roads without compromising safety.
Virtual Reality video simulations were employed and drivers recorded the influence of these elements on their judgments about the appropriate driving speed. The driver/participants viewed 22 models projected on a large screen in a darkened room, simulating the windshield of a vehicle.
The viewing sessions simultaneously accommodated significant numbers of subjects and gathered their feedback through electronic audience response systems. The response feedback was modeled through use of a fuzzy set system allowing the inspection of interrelationships of many different design parameters. The arithmetic mean score for discomfort for each scenario ranged from 4.3 to 8.1, representing large variation among scenarios. Our results show that simulating the driving environment using visualization was effective in generating feedback, thus avoiding the expensive and time-consuming process of individually ‘processing’ subjects through a driving simulator.

Keywords – audience response system, cross section design, driver behavior, operating speeds, roadside elements

1. Introduction

Roadway designs most often require the evaluation and balancing of a diverse set of issues and concerns that include safety, mobility, capacity, environmental aspects, and community preferences. Transportation agencies frequently are called on to balance these issues and conduct a trade off analysis in order to deliver the desired project. One of the most fundamental elements in roadway design is the design speed; a fact that was emphasized in the 2001 Policy for Geometric Design of Highways and Streets (Green Book) indicating that this is a choice that determines the various geometric components [1].

Driver expectations and prior experiences contribute to the operating speed of a roadway and therefore, the relationship between operating and design speeds is a crucial consideration that has the potential to significantly influence the resulting roadway design.

However, current practices fail to emphasize this relationship and designers often overlook it, creating inconsistencies in design. The heavy reliance on signing to enforce lower operating speeds while the roadway geometrics encourage travel at higher speeds is a good example of current practices and of this overlooked relationship.

In the last decade, emphasis has been placed on designing roadways in a manner where the driver will be capable of understanding the roadway requirements and operate at the desirable speeds.

This approach relies on specific roadway design elements to encourage driving at the intended operating speeds with a minimal requirement for street furniture and signage to encourage compliance with these speeds. The roadway design elements that can be used in these designs are features of horizontal and vertical curvature, cross section widths and the presence and type/height of barrier. All of these elements are all in the driver's natural visual scan of the road ahead.

This concept represents a roadway design philosophy that relies on the roadway design itself to "enforce" operating speeds.

The concept of designing roadways that encourage drivers to operate at desirable speeds is central to safety concerns, since several safety issues stem from the inconsistencies between design and operating speeds and speed limits. Even though this could be viewed as a speed management approach where the objective is simply to reduce speeds, it also results in a properly designed roadway where the appropriate operating speed is attained. Thus, a "self-explaining" look for each road category could be achieved.

The concept of the "self-explaining, self-enforcing" road, where a road is designed for a specific purpose or function, is the most appropriate approach for designing roadways that require little or no signing to achieve a desired operating speed. Each road addresses safety in an efficient way for all users by implementing an aesthetic approach to "explain" the road function and enforce speeds.

This approach also allows designers to establish speed limits close to the desired operating speeds and thus potentially reduce speed differences along the roadway.

Even though this concept seems to be capable of achieving the desired matching of design and operating speeds, there is little knowledge of which and to what extent these highway design elements could effectively influence driver behavior and thus the drivers' choice of operating speeds.

Quantitative research is lacking in key areas, such as driver response to overall highway configurations, as opposed to several other specific, single design elements [2].

A fundamental concept for developing a safe roadway design is to avoid conflicting messages to the driver regarding their appropriate operating speed, i.e. roadway design encourages high speed while speed limit signs indicate lower legal speeds. For example, reducing speed limits along the same roadway without providing any changes to the cross section could lead to confusion.

The absence of visual clues other than the posted speed limit does not enforce the need to reduce speeds. Moreover, drivers tend to ignore speed limit signs [3].

The primary objective of this research is to identify design elements that have the potential to influence drivers' perception to achieve the appropriate operating speeds. A secondary, and future, objective is the estimation of the potential magnitude of these influences for each element that has an influence. Virtual Reality video simulations were employed and drivers recorded their judgment of the appropriateness of the driving sped based on the scenario projected.

This study evaluated the use of various means to induce lower operating speeds and subsequently affect the driver behavior without compromising safety.

This work could be considered as pioneering the concept of group-based design protocols for developing roadways where design speed will match the intended operating speed.

Moreover, this approach has not been used before in identifying driver reactions to roadway designs.

2. Literature review

A driver should be able to understand the roadway requirements regarding the appropriate operating speed as well as be able to identify the locations where changes are required. Prior driving experience typically forms a driver's expectancy and influences the driver's readiness to complete a required task.

It can be hypothesized that drivers frequently associate wide, open roadways with high speeds and narrower, curvy roadways with lower speeds. Roadway designers should consider these aspects in their designs in order to develop a design that addresses both safety and mobility while matching the intended and actual operating speeds. The desirable product form such an approach is the development of a consistent speed environment that conforms to driver expectations and avoids abrupt changes in operating speeds. The design speed chosen by highway designers via the Green Book does not in practice correspond to the travel speeds chosen by drivers regardless of the posted speed limit [4].

The current practice in the USA for most of the state and local agencies for setting speed limits is based on the 85th percentile of operating speeds. In order to influence operating speeds, speed limits are often posted lower. The simplistic approach of using only speed limit signs to communicate the speed change to the driver may violate driver expectancy if it is not accompanied by other visual clues. Therefore, simply lowering the speed limit without any other accompanying changes will not cause drivers to adjust their speeds accordingly. It is therefore apparent that there is a need to use other methods to achieve this objective. Such methods include traffic calming devices, reduced lane widths, planting trees or shrubs, or changing the type and color of pavement.

All of these devices may convey a stronger message to the driver than the speed limit sign alone.

The "optical" narrowing of the roadway that has been used in Europe is another potential means of reducing operating speeds [5]. This approach creates the optical illusion that the available roadway is narrower. Tools that have been implemented include the lack of centerline striping, the use of shrubs or hedges by the side of the road, the painting of wider edge lines, and the narrowing of the lane without affecting the combined width of paved shoulder and lane. The effectiveness of any of these tools on driver behavior and safety has not yet been fully evaluated. The advantage of optically narrowing travel lanes, as opposed to physically narrowing, is that the total available roadway width is preserved, and thus the driver's options for correcting potential errors remain unaffected.

The effects of roadside features on driver operating speeds were recently examined [6]. The study examined a roadway section entering a small municipality that was scheduled for widening and straightening. However, this design had the potential to increase approach and through town speeds.

Light poles at the side of the road, shrubs lining the roadway, and colored pavement were features considered and simulated.

The results showed that light poles had no effect on reducing speed and in some cases had the opposite effect; colored pavement had the most consistent effect; and shrubbery along the roadside had inconsistent effects.

A possible explanation for the inconsistencies regarding the shrubbery could be the fact that the simulator could not depict shrubbery closer than six feet from the simulator, which meant that its effect on drivers could be different in the real world if shrubbery is closer than six feet from the roadway. Therefore, it is possible that shrubbery could have a greater effect in speed moderation in the real world.

The visual complexity surrounding a roadway can also have an impact on drivers' levels of attention and alertness [7]. The basic assumption is that tree plantings along the side of the road can affect the complexity of the roadway environment and therefore different amounts and types of trees should have differing effects on drivers.

These effects could also be different based on the location of the roadway, i.e. urban, rural or suburban. The Texas Transportation Institute's Driving Environment Simulator was used to examine these assumptions [8]. The results indicated that the presence of trees has a positive effect on drivers' perception of safety; that trees contribute to a perception of roadway edge; and this effect is stronger in urban than suburban scenarios. A greater speed variation was also noted when trees were not present.

The effect of combined roadside features on driver operating speeds has not been extensively examined.

There are a few studies indicating that plantings along the roadside have the potential to impact driver speed, however additional research is needed. In particular, the interaction effects of design elements must be considered. For example, it has been shown that vertical and horizontal road curvature influences driver perceptions in a compound way: vertical crests exaggerate the driver's perception of speed on a road with a given horizontal turn radius [9].

Even though this is currently confined to the relationship between vertical and horizontal curvature [10], it is unlikely that nonlinear compounding only occurs with respect to these two factors.

All factors could be assumed to have an effect on others. This means that testing highway profiles or design elements in isolation is not likely to yield a realistic approximation of driver perception. It is therefore imperative to present and evaluate the complete visual scenario to the driver in order to properly model the drivers' and understand their relationships and effects between elements and driver perception.

3. Research approach

The main objective of this research is to identify design elements and their combinations that effectively influence driver behavior and impact operating speeds.

To proceed with this objective, roadway environments were simulated to depict these different design elements and their combinations. It was important to determine the elements to be considered as well as their values from the outset of the research. The research team determined that only two-lane rural roadways would be tested in this phase due to the larger mileage of such roadways in Kentucky. A preliminary list of roadway elements was developed that included roadway width (lane and shoulder width), clear zone width (including the shoulder width), barrier type, vertical and horizontal curvature, and plant intensity. An expert panel consisting of roadway designers, safety engineers, and landscape architects reviewed this list and through facilitated discussions a list of potential values for these elements was generated (Table 1).

Tab. 1 – Values for design elements

Design element	Values
Roadway width (ft)	<16/16-18/>18
Clear zone width (ft)	10/15/20
Vertical curvature (ft)	Level/Rolling (3-6%)/Mountainous
Horizontal curve (ft)	500/750/1000
Plant intensity	Grass/Low plants/Light shrubs/Heavy shrubs/Heavy trees
Barrier type	None/Cable/Steel/Wood/Stone/Rock wall

It is apparent that it is impossible to test all these values due to the large number of potential design combinations. Therefore, selected combinations were used to develop the visualization models.

The general approach was to select some typical scenarios and then vary specific elements. For example, a two-lane facility with 12-foot lanes, 10-foot shoulders, wide clear zones, and medium horizontal and vertical curvature was one of the scenarios and could be used as the baseline for comparisons. The same geometry could be then used to evaluate the various elements identified above and measure their potential to influence driver behavior.

The scenarios to be modeled were developed with the use of the virtual reality simulation software *Virtual Nature Studio*.

A total of 22 visualizations were generated during this rendering process that provided a variety of conditions and create a well spread sample from among all potential designs. The density of coverage, i.e. the ratio of actual to possible design combinations, is relatively low because with six input parameters and from three to six input classifications for each parameter, there is a very large number of possible designs--over 2,500. The 22 scenarios provided combinations of roads where each design element value was used at least a few times.

Each scenario was simulated for 22 seconds and it was recycled for continued viewing until all participants recorded their scores. Average time for completing one sample cycle was about 30 seconds.

All models were developed with the same virtual “operating” speed to allow for estimating the effect of the roadway features on the drivers’ perception of comfort.

Participants were solicited among the research personnel of the Kentucky Transportation Center and 15 members participated in the process. The team’s Structured Public Involvement, or SPI^{TM}, protocol was followed [11].

The simulated scenarios were projected on a large screen in a darkened room, simulating the windshield of a vehicle. The scenarios were presented randomly to discourage potential comparisons between scenarios. Participants were asked to score their level of discomfort for driving on the roadway on a 1-10 integer scale.

The response scale was intended to correspond with suitability of the driving speed for the scenario shown on the scale where 1 indicates that the speed is too slow and 10 indicates that it is too fast for the scenario shown. The fact that this is a subjective rating of the scenario presented does not reduce the value of the analysis, since the procedure followed allows for estimating a range of responses and determines their statistical distribution. These distributions can be used to evaluate agreement (small deviation) and thus reduce any bias due to subjective rankings. This was the case for most of the scenarios presented.

The *SharpeDecisions®* electronic polling system was used due to our previous experience indicating that this system has many advantages for focus group and public evaluations. The process is anonymous and simultaneous and therefore there is no opportunity for social or peer pressures to alter the valuation of each individual in the audience, so scores or opinions held by one individual cannot influence other responses. The process is fast; within 30 seconds after viewing, scores for each scenario were gathered.

To analyze the scores obtained, a fuzzy set-based modeling approach was considered appropriate for this application. Fuzzy set-based modeling has a long history of application in mechanical and electrical control systems [12].

In recent years fuzzy set-based modeling has been applied in the transportation field to a wide range of perception questions, including performance of variable message highway signs [13] and car-truck interactions [14].

The application of the fuzzy modeling on these areas is similar to our research since in both cases it is necessary to estimate answers based on a relatively small sample size under conditions of high uncertainty. Standard statistical models are not appropriate for this problem because they require values for the entire experiment, which in this case would be expensive, infeasible or even impossible to acquire. Moreover statistical techniques based on the General Linear Models (regression and correlation) are not ideally suited to handle nonlinear, compounded system responses.

An approach that has been implemented in similar analysis is the CAVE method where a fuzzy set-based algorithms was applied to estimate aspects of a group-based visual analysis [15]. CAVE has been used to evaluate several other elements in highway including public satisfaction with rural highway designs [16].

This is, however, the first application to perceptions of operating speed. The approach relies on group scoring of visualizations or images based on a Likert scale expressing a reaction criterion (preference, comfort, and so on).

The advantage of the method is that it requires only a small proportion of all potential scenarios to be scored, since it has the ability to built models of interactions among the various variables and allow for filling in the gaps from visualizations that were tested. The selected visualizations are comprised of a range of design elements and should reflect a diverse group of conditions in order to allow for a meaningful extrapolation of the relationships among the various design elements. The model to be constructed uses the scores of the group and creates an “output” of fuzzy sets.

The corresponding scenario becomes the “input.” All scenarios are used to populate the data for these known input-output points, which are used as the “anchors” to allow for the development of relationships between these points.

The fuzzy set modeling process can then “fill in” the gaps in a fashion analogous to, although not identical with, linear interpolation. Each point is affected by all of the other dimensions, i.e. response to roadway width is not independent of clear zone width, shoulder type, curvature or any other input variable.

A knowledge base is built containing the samples (known points) and surface (estimations for the output values corresponding to other, untested, combinations of inputs). The complete surface can be used to identify the relationships among the variables and identify the elements that have a potential influence on affecting operating speeds.

This provides an understanding of the combined effects of all design elements even for those that were not tested visually but could have an influence on drivers’ behavior.

In effect, additional design simulations are performed by simply varying the input design variables, one at a time, from their minimum values stepwise through to their maxima, and documenting the perception value associated with this change.

4. Survey results

The results of the simulated 22 scenarios presented a large variation regarding the level of comfort of the scenario presented.

The arithmetic mean scores ranged from 4.3 to 8.1, representing variation on the "discomfort" evaluation scale.

The lowest score was noted for a roadway with 23 feet of roadway width, 20 feet clear zone, tall trees, stone wall, horizontal curve of 1,000 feet and grade of 3% while the highest was noted for a roadway with 13 foot roadway width, 10 feet clear zone, low plants, steel guardrail, curve with a 250 foot radius, and 3% grade.

Considering that these highway designs were presented at the same virtual speed, this represents a large difference in perceived driver comfort.

The standard deviation results show that some scenarios generated stronger perceptual agreement than others. The smallest deviation was 1.0 (roadway with 500 foot curve, 3% grade, 16 foot roadway width, 10 foot clear zone, no barrier and heavy trees) and the largest 2.6 (roadway with 250 foot curve, 3% grade. 19 foot roadway width, 15 foot clear zone, no barrier and light shrubs).

The *FuzzyKnowledgeBuilder®* software was used to generate a model of driver perception of speed relative to highway design [17]*(23)*.

A sample of 5 to 10% of all possible combinations is typically required to create a reliable model.

The available 22 scenarios could cover a universe of 220-440 possible design combinations; a reasonable fraction of the total universe possible with these six parameters of over 2,500 combinations.

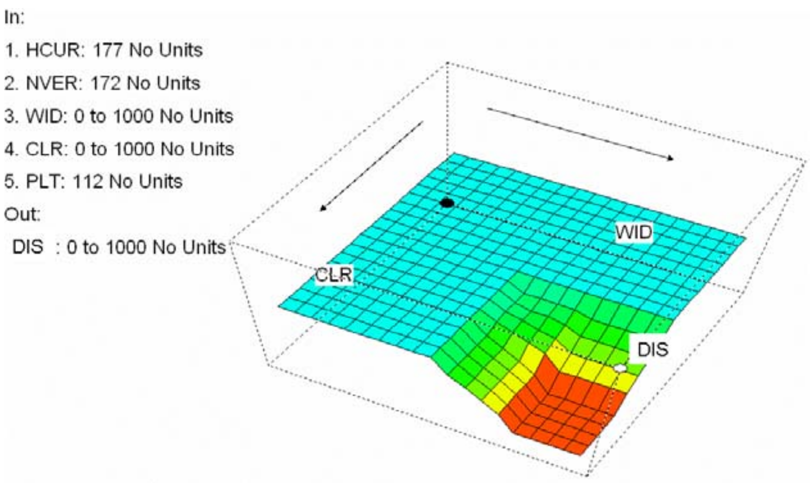

Fig. 1 – 3-D example of variable interaction

Therefore, to increase the validity of the findings, it was considered appropriate to prioritize the design parameters in a manner that was judged that they could most likely influence driver's discomfort. The initial modeling parameters were chosen to be horizontal and vertical curvature, roadway width, clear zone, and plant type. These five parameters yielded a total of 405 possible design combinations, and therefore the available sample of 22 scenarios was able to produce a responsive model.

The software provides a three dimensional interpretation of the interaction of the variables, where three are fixed and the interaction between the other two is shown as the area of the surface.

An example is shown in Fig. 1 where the horizontal curvature is high (1,000 ft radius), the vertical grade is low (less than 3%) and there are no plants at the side of the road.

The surface indicates the effects of roadway width and clear zone on the drivers' discomfort. The higher portion (blue shades) of the surface represent greater discomfort (DIS) on the vertical scale. The arrow progressing to the right depicts increasing roadway width (WID) while the arrow to the left shows increasing clear zone width (CLR).

The example shown here indicates that driver discomfort is moderate at combinations of narrow roadway widths and clear zone widths.

Once the widths become greater, the discomfort is reduced and for the extreme cases it is very low (bottom right hand corner).

To evaluate the effect of the plant presence on the level of discomfort of the driver, another surface can be created where the horizontal and vertical values remain the same and the plant intensity increases.

Fig 2 shows this scenario for low plant intensity (plants less than 3 feet tall). The discomfort level has been raised in general and especially for the extreme cases.

To further evaluate the effect of the same plant intensity on roads with narrower horizontal curves (500 ft radius) and greater grades (6%), a third surface is produced (Fig 3). This one shows that the comfort level for the narrower roadway with and clear zone widths is raised while for the wider combinations it remains the same.

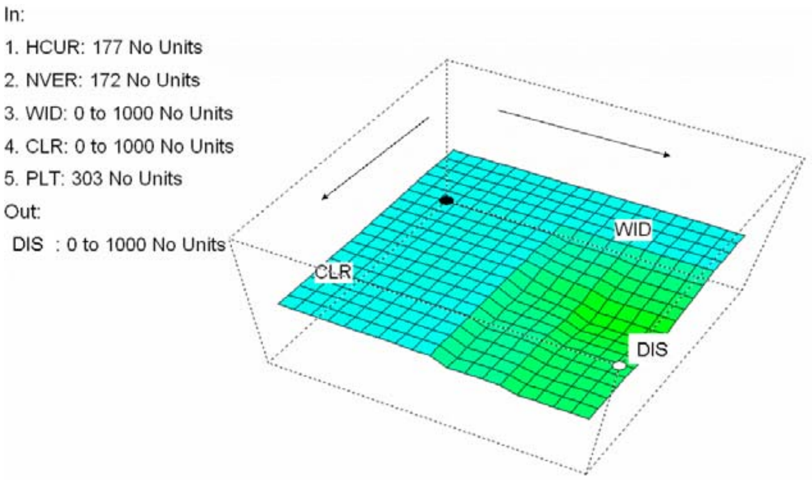

Fig. 2 – 3-D example of variable interaction

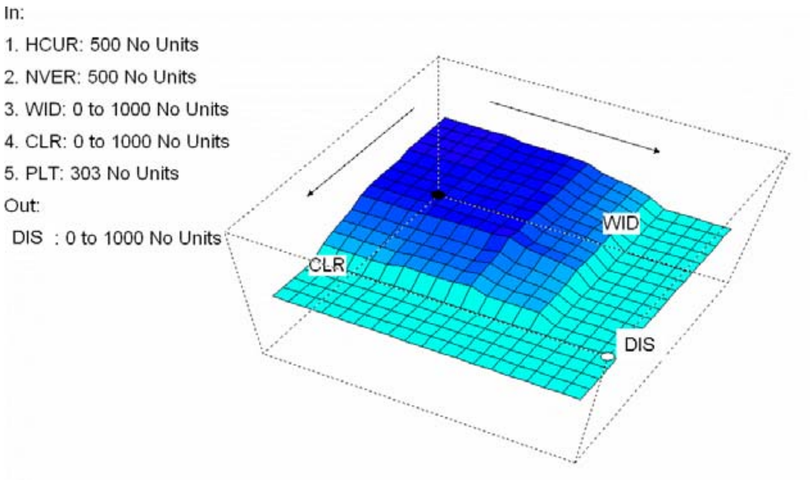

Fig. 3 – 3-D example of variable interaction

Therefore, a conclusion that can be drawn here is that the presence of low plants has very little effect on flat roads but once the geometry changes either horizontally or vertically, there is an effect from the presence of plants on the driver's discomfort and by extension on their operating speeds.

Similar surfaces were obtained for different combinations of the five parameters that allowed for a preliminary identification of the specific parameters that potentially could impact the drivers' operating speed through changes of roadway design. The following observations were made:

- For flat, wide and straight roads, the plant intensity was largely irrelevant and the discomfort was low.
- For roads with low grade (3%) and medium horizontal curves (500 ft), there was a response to the increasing plant density especially for roads with narrower road and clear zone widths.
- For roads with low grade (3%) and sharp horizontal curves (250 ft), there was a response to the increasing plant density especially for roads with narrower road and clear zone widths. However, this was only apparent for plants lower than 5 ft and above these values the results were counterintuitive.
- For roads with medium grade (6%) and medium horizontal curves (500 ft), there was a small response to the increasing plant density especially for roads with narrower road and clear zone widths. For wider roads and clear zones, this trend was not apparent and it appeared that either the type of barrier type could have an impact on the discomfort or that for these roads the increase of the plant density did not have any effect.
- For roads with high grade (9%) and flat horizontal curves (1,000 ft), the only trend observed was a decrease in discomfort as the clear zone became wider. This was independent of the plant intensity or road width.
- For roads with high grade (9%) and sharp horizontal curves (250 ft), there was a decrease in discomfort with wider clear zones. The increase of plant intensity created some noise on the responses and obscured any clear results.

In general, it was observed that the increase of plant intensity from none to moderate shrubbery (up to 5 feet tall) generally increased the discomfort for all scenarios of horizontal curvatures as long as vertical curvature remained low (<6%). Higher values of grade obscured the impact of increasing plant intensity and may indicate the potential of interaction from the sixth variable that was not included in the model.

For steeper roads, it seems that the presence of wider clear zone has a greater impact on the reduction of the discomfort level than the roadway width. At high values for both horizontal and vertical curves, the results seem to be spotty and this may be due to the lack of adequate sample of scenarios for these conditions.

5. Conclusions

The main aim of this research was to identify the design elements and their values that have an impact of drivers' operating speed. An additional objective was to also investigate the feasibility of the modeling approach. On this end, the results show

a) that the problem is tractable using the variables presented here, and
b) that the approach of simulating the driving environment using visualization was effective in generating feedback. This second point may be of great significance, since the approach developed allows researchers to avoid the expensive and time-consuming process of individually 'processing' subjects through a driving simulator.

The primary aim was to investigate which design elements, among the six considered, exerted the most influence and under which conditions.

The preliminary analysis conducted showed some promising results regarding the influence of these design elements and their interactions. However, the available number of scenarios did not allow for a complete evaluation of all elements.

The model was able to identify the interactions of five variables but the number of scenarios developed does not allow for considering the influence of the sixth variable—barrier type. It is possible that there is some influence of this variable as well and this may explain the presence of some of the counterintuitive trends observed. This highlights the need, in our view, to consider as many factors as possible simultaneously. Even with five factors, we suspect the sixth, as yet unmodeled, may be interactive with them.

In general, the results indicate that there is an influence of the plant density on the driver's discomfort, i.e. operating speed, which could be used in roadway designs aiming to influence these speeds. The plant intensity showed some influence that was more apparent for narrower roadways with narrower clear zone widths and for roadways with sharper horizontal curves and low grades. However, this trend was not uniform and showed some unexpected results that are attributed to either the inability of the modeling process to account for all variables examined or the scarcity of samples for certain combinations. It is anticipated that this problem will be resolved with the additional scenarios to be simulated in the next phase of the research.

A key component of such experiments is the number of visualizations that can be shown and evaluated effectively by the participants. Previous experience with large public forums suggests that a maximum of 30 or so can be evaluated effectively. This still allows time for a reasonable data-gathering meeting of approximately 90 minutes for scenarios as those presented here. This also provides adequate time for collecting responses that could assist in determining reasons for low and high preferences that might not be apparently obvious to designers and engineers during the initial design phase, but that reflect accurately the cultural values and preferences of the drivers using the highway.

An issue that has not been addressed is the similarity of the scenarios presented to real life situations. The specific scenarios used here were developed with an understanding of creating conditions that are typical and likely to be encountered by a driver. However, in order to allow for a robust model, there were scenarios that were tested that may not currently exist in real life designs. The software used here is fairly sophisticated and elaborate in generating these animations and allowed for the development of fairly realistic scenarios. It should be emphasized though that the complexity of the real world could not be exactly duplicated in the laboratory.

The next phase of this project will identify roadway sections where several of the combinations tested are present and collect real time speeds in order to evaluate their impact on operating speeds.

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