INVESTIGATION OF DESIGN SPEED CHARACTERISTICS ON FREEWAY RAMPS USING SHRP2 NATURALISTIC DRIVING DATA

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ABSTRACT

Freeway ramp design guidance has existed in the United States for many decades, coinciding with the advent of the nation's freeway network and the Interstate Highway system. Some principles associated with ramp design are largely unchanged since their inception, and a review of those principles in the context of today's drivers and vehicles is beneficial for identifying potential updates to existing guidance. The process of collecting the necessary data may consist of a variety of methods, each with limitations on the number of ramps, vehicles, and trips that can be studied. A current research project is exploring the feasibility of using data from the SHRP2 Naturalistic Driving Study (NDS) to identify relationships between ramp design speed characteristics and drivers' choice of operating speed on those ramps. The NDS data provides a dataset that is unprecedented in its size and detail, but its suitability for this type of analysis is largely unknown. This paper summarizes the activities and findings on the current research project, including basic models for estimating vehicle speeds on freeway ramps based on the NDS data; these models may be used in conjunction with other ongoing related research efforts to suggest material for potential updates to existing ramp design guidance.

INTRODUCTION

Current geometric design guidelines provide information to designers on appropriate design speeds for freeway entrance and exit ramps. These guidelines are based on practices from decades past; however, the profession would benefit from better knowledge on how well existing design guidance reflects current driving behavior. Recent and current research projects have looked at various aspects of freeway ramp design, but the available field data driving the conclusions in those projects are often limited. These studies are usually able to collect data on a constrained sample of sites or drivers; sometimes the dataset contains spot speeds at key locations along ramps rather than comprehensive speed profiles, and little information about the corresponding driver behavior is known. The SHRP2 Naturalistic Driving Study data provides a new opportunity to analyze detailed driving data in order to critically review and potentially update existing design guidelines. A current research project sponsored by the Safety through Disruption University Transportation Center (SAFE-D UTC) (*1*) examines driving data on freeway ramps from the SHRP2 NDS – speed profiles along with selected driver and vehicle variables – and compares that data to the design characteristics of the ramps traveled during the study.

The objective of the comparison is to identify relationships between the factors used to select freeway ramp design speed (e.g., radius, superelevation, etc.) and the actual speeds of drivers traveling on those ramps and their associated behaviors (e.g., brake/accelerator use, steering wheel angle, etc.). The findings from the comparison will then be further compared to the findings from recent research to identify similarities, differences, and potential topics for future research or considerations for changes to existing design guidance. This paper summarizes the research conducted on the SAFE-D project and describes the research team's key findings to date in developing basic models for estimating operating speed on freeway ramps.

PREVIOUS RESEARCH AND EXISTING GUIDANCE

Current Policies

There are a variety of policies that speak to the selection of design speed on freeway ramps. Various guidance documents contain directives or information on the subject, and many of them have a basis in the information provided by the American Association of State Highway and Transportation Officials (AASHTO), which is contained primarily in their document *A Policy on the Geometric Design of Highways and Streets* (*2*) (commonly called "the *Green Book*").

A review of AASHTO's current policy on selecting appropriate ramp design speeds first requires a review of AASHTO's definition of design speed and the basic concepts of design speed most pertinent to ramp design speed. AASHTO defines design speed in Section 2.3.6 of the 2011 *Green Book* (*2*) as follows:

> *"Design speed is a selected speed used to determine the various geometric design features of the roadway. The selected design speed should be a logical one with respect to the anticipated operating speed, topography, the adjacent land use, and the functional classification of the highway. In selection of design speed, every effort should be made to attain a desired combination of safety, mobility, and efficiency within the constraints of environmental quality, economics, aesthetics, and social or political impacts. Once the design speed is selected, all of the pertinent highway features should be related to it to obtain a balanced design. Above-minimum design criteria for specific design elements should be used, where practical, particularly on high-speed facilities. On lower speed facilities, use of above-minimum design criteria may encourage travel at speeds higher than the design speed. Some design features, such as curvature, superelevation, and sight distance, are directly related to, and vary appreciably with, design speed. Other features, such as widths of lanes and shoulders and clearances to walls and rails, are not directly related to design speed, but they do affect vehicle speeds. Thus, when a change is made in design speed, many elements of the highway design will change accordingly."*

AASHTO policy continues to explain that the selected design speed should be consistent with the speeds that drivers are likely to expect on a given highway facility and should fit the travel desires and habits of all drivers expected to use the particular facility. It is also desirable that the running speed of a large proportion of drivers be lower than the design speed.

Referring specifically to guidance on selecting a design speed for ramps, Section 10.9.6 of the 2011 AASHTO *Green Book* states that it is desirable for ramp design speeds to approximate the low-volume running speed on the intersecting highways, but this is not always practical. This statement means that lower design speeds may be selected but they should not be less than the lower range of speeds shown in *Green Book* Table 10-1 (see TABLE 1). AASHTO policy provides further guidance on selecting appropriate design speed values from *Green Book* Table 10-1 based on various conditions and ramp types.

The *Green Book* also states that the guide values for ramp design speed in *Green Book* Table 10-1 only apply to the sharpest or controlling ramp curve, which is usually on the ramp proper, and that the speed values in *Green Book* Table 10-1 do not pertain to the ramp terminals. The three segments of a ramp (crossroad terminal, ramp proper, and freeway terminal) should be evaluated in combination to determine appropriate design speeds and superelevation rates for the given ramp configuration. Additional design speed guidance is provided specifically related to loop ramps and semidirect connections.

While the *Green Book* provides guidance on ramp design speed and factors related to it, individual state DOTs may have guidelines that differ from or add to the material found in the *Green Book*. To gain an appreciation for the differences that might exist, researchers conducted an online search of state DOT design manuals as part of the activities for the current NCHRP

Project 15-56 (*3*). Rather than reviewing design manuals for all 50 states, the research team reviewed a representative sample of design manuals from 20 states, including:

- Arizona
- California
- Colorado
- Florida
- Georgia
- Illinois
- Kansas
- Kentucky
- Maryland
- Massachusetts
- Michigan
- Minnesota
- Missouri
- New Jersey
- North Carolina
- Ohio
- Pennsylvania
- Texas
- Virginia
- Washington

Of these 20 states, 16 had design manuals that contained sections or chapters corresponding to the relevant material in the *Green Book*. Eleven states provided guidance that was nominally the same as the *Green Book* and/or specifically referred the reader to the *Green Book*. In the remaining five states, much of their guidance was also very similar to the *Green Book* but contained some unique features as well. In the manuals from Illinois and Washington, the table that corresponds to *Green Book* Table 10-1 contained ramp design speed values that were all in multiples of 5 mph (e.g., the mainline design speed of 55 mph has an upper-range ramp design speed of 50 mph, not 48 mph, as shown in TABLE 1) and some other values are different from *Green Book* values. Other differences between the *Green Book* and existing state guidance included:

- The Florida manual advised that minimum acceleration/deceleration lengths are provided with a minimum length of taper, but those values correspond to *Green Book* values.
- The California manual based minimum deceleration lengths on the radius of the controlling curve.
- The Georgia manual stated that ramp design speed should be no less than 10 mph below the design speed of the mainline.

Freeway Ramp Operating Speed

A number of factors can influence the operating speed a driver chooses when traveling through a freeway ramp, and effects of some of those factors have been studied in previous research. In fact, a number of models in the literature predict ramp speed from the traffic volume along a given ramp or mainline; the most useful models for this study focus on free-flow speeds, which provide a better appreciation for the effects of the geometric design characteristics of the ramp rather than other influences related to traffic volumes.

A focused analysis of vehicle speeds on loop ramps was conducted in NCHRP Project 3-105 (*4*). Field data showed that models based on *Highway Safety Manual* (HSM) (*5*) methodology tended to overestimate vehicle speeds on the controlling curves (i.e., sharpest curves) of loop ramps by the following magnitudes:

- Entrance ramp: 2.6 mph at the midpoint, 1.8 mph at the PT.
- Exit ramp: 10.6 mph at the PC, 2.2 mph at the midpoint.

The aforementioned analysis was based on 15 entrance ramp sites and 13 exit ramp sites. The following models were developed to provide more accurate estimates of ramp speeds:

$$v_{ent,c,MC} = 8.359 + 1.978\, I_{l2} + 0.040\, R + 0.313\, W_{l} + 0.912\, W_{os} + 0.682\, W_{is} - 4.333\, I_{tk} \qquad (1)$$

$$v_{ent,c,PT} = 16.276 + 1.444\, I_{l2} + 0.054\, R + 1.079\, W_{os} - 4.051\, I_{tk} \qquad (2)$$

$$v_{ext,c,PC} = 17.515 + 0.090\, R - 5.967\, I_{tk} \qquad (3)$$

$$v_{ext,c,MC} = 9.512 + 1.241\, I_{l2\text{-}3} + 0.053\, R + 1.008\, W_{os} - 4.873\, I_{tk} + 3.551\, I_{rs} + 2.911\, I_{d} + 3.975\, I_{p} + 4.334\, I_{w} \qquad (4)$$

Where:

- $v_{ent,c,MC}$ = average passenger car speed at the midpoint of the entrance ramp controlling curve, mph.
- $v_{ent,c,PT}$ = average passenger car speed at the PT of the entrance ramp controlling curve, mph.
- $v_{ext,c,PC}$ = average passenger car speed at the PC of the exit ramp controlling curve, mph.
- $v_{ext,c,MC}$ = average passenger car speed at the midpoint of the exit ramp controlling curve, mph.
- I_{l2} = indicator variable for lane 2 (= 1 if predicting speed in the outside lane, 0 otherwise).
- $I_{l2\text{-}3}$ = indicator variable for lanes 2 and 3 (= 1 if predicting speed in the middle or outside lanes, 0 otherwise).
- R = radius (measured to the inside of the traveled way), ft.
- W_l = lane width, ft.
- W_{os} = outside (left) shoulder width, ft.
- W_{is} = inside (right) shoulder width, ft.
- I_{tk} = indicator variable for trucks (= 1 if predicting truck speed, 0 otherwise).
- I_{rs} = indicator variable for curve radius type (= 1 if simple, 0 if compound).
- I_d = indicator variable for drop speed-change lane (= 1 if present, 0 otherwise).
- I_p = indicator variable for parallel speed-change lane (= 1 if present, 0 otherwise).
- I_w = indicator variable for weaving speed-change lane (= 1 if present, 0 otherwise).

These models can be incorporated into a framework like that in the HSM to estimate a more accurate speed profile for a loop ramp.

Venglar et al. (*6*) developed a ramp speed profile model to aid in setting advisory speeds for exit ramps. While forming their model, the researchers on that project used only speed data from passenger cars with leading and lagging headways of at least 10 seconds and trucks with leading and lagging headways of at least 7 and 3 seconds, respectively, to focus on free-flowing vehicles. The researchers found that the most influential factors on operating speed were horizontal curvature and the distance to the nearest intersection downstream. They also found that vertical geometric features did not significantly alter driver speed behavior. Their model is described as follows:

$$v_c = -20.872 - 0.758DC + 9.864 \ln(Z) \qquad (5)$$

Where:

- v_c = average passenger car speed in free-flow conditions, mph.
- DC = degree of horizontal curvature.
- Z = distance to the first downstream at-grade signalized or stop-controlled intersection, ft.

Venglar et al. also suggested applying a multiplier of 0.95 to Equation 5 to estimate the average truck speed, and then using the average truck speed to set the advisory speed on an exit ramp.

In NCHRP Project 17-45, Bonneson et al. (*7*) produced crash prediction methodologies for freeways and interchanges, which were incorporated into the HSM as a supplement (*8*) to the original three-volume edition published in 2010 (*5*). The general form of the Safety Performance Function (SPF) for estimating the crash frequency for a ramp is as follows:

$$N = L_r \times \exp\left[a + b \times \ln(c\ AADT_r) + d\ (c \times AADT_r)\right] \qquad (6)$$

Where:

- N = crash frequency per year on the ramp.
- L_r = ramp length (mi).
- $AADT_r$ = average annual daily traffic volume on the ramp (veh/day).
- a, b, c, d = regression coefficients.

The SPF uses different regression coefficients for one-lane and two-lane ramps, for fatal-and-injury (FI) and property damage only (PDO) crashes, and for multiple- and single-vehicle crashes. The crash modification factors (CMFs) developed for use with the SPFs account for the following factors on ramp segments:

- Horizontal curvature
- Lane width
- Right shoulder width
- Left shoulder width
- Right-side barrier
- Left-side barrier
- Lane addition or drop
- Ramp speed-change lane

For horizontal curvature, the base condition is a tangent ramp proper, and the CMF value is a function of the radius of curvature, the average entry speed for the curve, and the proportion of the ramp proper with a curvilinear alignment. The CMF value predicts an increase in crashes as the radius of curvature decreases, as the average entry speed increases, and as the proportion of the ramp proper with a curvilinear alignment increases.

The NCHRP 17-45 curve speed prediction model, used with the horizontal curvature CMF, was based on data from five interchange loop ramp curves and 20 rural two-lane highway curves. The speed profile models included in the HSM methodology are applied in the direction of travel and account for the variables listed in TABLE 2. The speed profile models are implemented in the spreadsheet-based Enhanced Interchange Safety Analysis Tool (ISATe); Bonneson et al. noted, however, that these speed models were not developed for predicting vehicle speeds in the context of operational or design analyses. When applied, the speed profile models included in the HSM methodology yield average entry and exit speeds for each curve on a ramp. The NCHRP 17-45 research team developed separate seven-step procedures for entrance ramps and exit ramps.

Data Collection Methods

The process for collecting speed and other vehicle data on freeway ramps has traditionally required multiple methods to compile a meaningful dataset (e.g., instrumented vehicles, lidar profiles, road sensor spot-speeds). Each method has its advantages and disadvantages.

Lidar (Light Detection and Ranging) guns, commonly referred to as laser guns, can measure speed and distance of vehicles, which allows researchers to, for example, determine the speed profile of vehicles along an entrance ramp and speed change lane, specifying where drivers begin to accelerate, reach their merge speed, and merge into the mainline freeway from the acceleration lane. Lidar speed-distance profiles can generate a dataset on a robust number of drivers (perhaps 100 to 200 drivers during a given study period of one day or less) at a site, but the number of sites that can be reasonably collected on a typical research project would be limited to perhaps a dozen. Another limitation is line of sight, especially for loop ramps and other curves; researchers cannot collect data on vehicles that they cannot target with the laser, so obstructions such as signs, other vehicles, and luminaire poles can affect the ability to obtain a continuous profile or to record every vehicle. Furthermore, on horizontal curves, the angle at which the lidar tracks the vehicle continuously changes, and the further away from 180 degrees that angle is, the more potential error is introduced into the data, due to parallax or cosine error. Mathematical methods or multiple lidar guns may help mitigate that effect, but it still requires detailed data reduction and post-processing procedures to assemble a complete speed-distance profile for each vehicle.

When spot speeds provide sufficient detail for analysis, road sensors (e.g., road tubes, piezometric sensors, side-fire radar, etc.) may also be used to collect speed data for many hundreds of vehicles. One advantage to these sensors is that they can be installed and then left to run largely unattended, compared to other methods that require one or more staff members to be present to either operate the equipment or observe the operations at the study site. As a result, data on many more vehicles can be collected in total, including every vehicle that travels through the sensor area during the study period. These sensors (see FIGURE 1) typically record not only a time-stamped speed measurement but also the classification of each vehicle.

For in-lane traffic counter sensors such as tubes or piezometric sensors, two key drawbacks are: the need for personnel to physically enter the travel lanes to install and remove the sensors, and the potential effect on driver behavior if too many sensors are installed in a short distance. Installing such sensors requires coordination of temporary traffic control with the appropriate road agency, and the sensors must be observed on a regular basis to ensure that they remain installed at the desired locations. A drawback of road sensors is that they can be installed only at specific points, which means that the resulting data lacks the detail of how speed changes as drivers travel through each study area, such as curve and tangent sections along a ramp.

Field observational measurements as described above can capture speed and position changes on a macroscopic level. Only in-vehicle observations can ascertain the driver's subtle changes in speed in response to ramp design and traffic conditions. Instrumented vehicles can collect data to document these responses as well as the simultaneous characteristics of the vehicle for a given situation. These vehicles typically contain multiple integrated systems to record various data relating the driver's behaviors, the external driving situation, and the dynamic vehicle performance. For vehicles outfitted with such equipment, all on-board equipment is managed by a data acquisition system (DAS), which is responsible for integrating the many streams of data that can be collected through the vehicle (see FIGURE 2). Primarily, the computer records basic driving data such as brake and throttle position and steering wheel angle. These data are gathered through sensors located on the pedals and steering column. Accelerometers record roll, pitch, and yaw rates. A radar unit or similar equipment is mounted on the front of the vehicle to enable the collection of headway data and to simply note the presence or absence of a lead vehicle; a global positioning system (GPS) provides accurate, real-time data on the exact position of the vehicle, enabling the calculation of location, distance traveled, and velocity. Fully equipped vehicles contain an array of video cameras to provide information on such external factors as weather conditions and ambient traffic, as well as in-vehicle driver behaviors. Video cameras can be placed facing the driver's head (e.g., at the rear view mirror and on the A-pillar of the car) to monitor head turns and glance direction.

Much of the effort of collecting this type of microscopic driver behavior data comes in the data reduction and analysis phase. The instruments in the vehicle collect data at rates many times per second (e.g., 30 Hz). These methods result in large data files that must be error-checked and reduced for analysis. In addition, the video data from the on-board cameras must be manually reviewed and categorized. This instrumentation allows collection of a rich data set that must be carefully categorized and interpreted. Unfortunately, for a typical project, this very detailed dataset describes the activities of a small number of drivers (often 20 or fewer) in a single vehicle, often at predefined locations, because the project cannot afford the time or resources to collect data for more drivers, at more locations, and/or in more vehicles.

Features of the SHRP2 NDS Dataset

Each of the aforementioned methods has a tradeoff between detail and sample size, providing an incomplete picture of how well drivers' chosen speed profiles match design speeds under current guidelines; however, a recently developed resource provides an opportunity to combine some of the benefits from those methods. The Strategic Highway Research Program 2 Naturalistic Driving Study (SHRP2 NDS) dataset is a source of "big data" that contains data from more than 3,000 participants in six states. In total, it contains as much as 3,500 human-years of time series data (*9*). Since the conclusion of the study in 2013, safety researchers have used the data to analyze crashes and near-crash events. The time series data from this study, supplemented by the videos that recorded the drivers and their surrounding environments, has allowed researchers to gain a more thorough understanding of these events by examining the environment both inside and outside of the vehicle (*10*, *11*). While analyzing the circumstances surrounding a crash is valuable and indeed was one of the primary motives behind the development of this database (*9*), the SHRP2 NDS dataset provides an unprecedented resource to analyze detailed driving data for a large sample of drivers on a wide variety of roadway segments during normal operations.

DATA COLLECTION

Researchers explored the trip density maps in the SHRP2 NDS InSight database (*12*) to identify a robust sample of ramps from which to collect speeds and other travel data. The researchers reviewed available data available for the six participating states (FL, IN, NC, NY, PA, WA) in the database, looking for ramps on which between 50 and 200 unique participants had made trips. Researchers also used InSight as a primary tool in determining the configuration of a ramp (i.e., diamond, loop, curve, direct, semidirect, or outer) and documenting whether each site was an entrance or exit ramp.

While collecting information from the InSight trip density maps, the researchers used the aerial mapping tool Google Earth (example shown in FIGURE 3) as a supplemental source of information, viewing the same locations simultaneously in InSight and Google Earth. This allowed them to obtain the GPS coordinates of the ramps, document the type of environment of each ramp (e.g., urban/rural and residential/commercial), and confirm the ramp type and the origin and destination routes for each ramp.

When finished, the researchers had identified 1,686 ramps that had the desired level of trip data, with at least 130 ramps taken from each of the six participating states. Altogether, the 1,686 identified ramps had nearly 1.4 million recorded individual trips, with an average of about eight trips by each participant per ramp. This resulted in more than 173,000 unique participant-ramp combinations. For this study, unique participant-ramp combinations are the better representation of real-world data; their use provides a better mix of participants, rather than measuring the same driver in the same vehicle on the same ramp for multiple trips.

With this as a starting point for the study database, the researchers used a series of filters and qualifiers to reduce the database to a more manageable size, both in terms of processing and analyzing the data and in what was practically attainable for project resources. Researchers removed from consideration all ramps that did not lead to or from an Interstate highway, metered ramps, connectors, ramps that had fewer than 200 total trips by participants, and ramps that spanned more than one LinkID in the InSight database. Researchers also retained only one ramp per interchange. At the end of this process, the researchers compiled a candidate site list of 100 ramps, with 10,895 unique participant/ramp combinations (see TABLE 3). Researchers sent this list of sites to the SHRP2 data administrators to request a selection of SHRP2 NDS time series data variables for trips taken on those ramps. Researchers requested the detailed time series data for the first traversal made by each unique participant on each of the selected ramps.

The SHRP2 time series data were recorded every 0.1 second by the sensors in each participant's vehicle, along with the vehicle's corresponding distance along the ramp and GPS coordinates. The time series data requested by the research team contained the following key variables for each trip:

- Speed from GPS.
- Speed from vehicle network.
- Acceleration on x-, y-, and z-axes.
- Yaw rate, z-axis.
- Pitch rate, y-axis.
- Roll rate, x-axis.
- Lane width.
- Lane confidence (right- and left-side).

Researchers also requested additional time series data variables to explore their potential usefulness in analysis. The SHRP2 administrators cautioned that these variables were available for some trips and missing in others and may have limited applicability, but the research team wanted to request the data in the event that the variables provided additional useful information for analysis. The requested variables included:

- Steering wheel position.
- Distance.
- Accelerator pedal position.
- Brake pedal position.
- ABS Activation.
- Electronic stability control.
- Traction control.

To help ensure that the trip data contained the entire ramp and provided a readily identifiable frame of reference, researchers requested that each trip's dataset contain two seconds of time series data before the vehicle entered the link corresponding to the LinkID of the ramp and two seconds of time series data after the vehicle entered the subsequent link.

The researchers intended to use the SHRP2 Roadway Information Database (RID) to obtain the desired site characteristics data for each of the ramps on the study site list. Unfortunately, they discovered that while the RID contains extensive roadway data for many freeway curves traversed by participants in the NDS, alignment data that covers ramps is quite limited. Of the 1,686 ramps that researchers originally identified in InSight, fewer than 40 had corresponding alignment data in the RID, more than three-quarters of which were in Pennsylvania and New York. The project team briefly considered using all of these ramps, but decided that it would be better to use a more representative set of ramps that contained more unique participant/ramp combinations as described previously, and so the team opted to explore other methods of obtaining the design and geometric data of the ramps.

Ultimately, the researchers used Google Earth as the primary source of site characteristics. In addition to being used to confirm the ramp type (diamond/curve/loop) and classification (entrance/exit), Google Earth was used to more precisely describe features of the ramp, including physical measurements. Researchers subdivided each ramp into curve and tangent segments, and they used the ruler tool on Google Earth as a means of measuring the length of each segment of each ramp. The process of measuring tangent sections was straightforward by projecting a simple straight-line length with the ruler tool and recording the corresponding distance in the database. The ruler tool also contains the option of projecting a circle, which researchers used to determine the radius of each curve segment by fitting a circle to correspond to the center of the travel lane on the ramp within the segment. The radii of the projected circles were noted as the radii for the curve segments on the ramps and recorded in the site characteristics database. Researchers also recorded GPS coordinates from Google Earth for the start and end of each ramp section for the purpose of later use in linking speed data to specific ramp segments. The end result of these data reduction and processing activities was a series of spreadsheets containing the NDS data at intervals of 0.1 second combined with the associated site characteristics at the particular location that corresponded to that time interval; the spreadsheets were formatted to contain one row per time interval to facilitate analysis. Subsequent filtering of the data removed trips with sensor errors and other features that prevented the collection of a complete free-flow speed profile along the entirety of the ramp. Additional details on this procedure and other data processing methods used in this research can be found in another paper submitted for the 2019 TRB Annual Meeting (*13*).

DATA ANALYSIS AND FINDINGS

After reducing and processing the data, researchers began the analysis of the data. To provide a measure of consistency with other previous and ongoing projects, the researchers sought to create two primary types of models: a simple model that would predict speed on a specific ramp segment, and one that could be used to estimate speed at a given point anywhere on a ramp. To that end, the researchers divided the data into curve data and tangent data, for separate analysis of individual ramp segments. For this analysis, researchers chose the SAS program (specifically the GLM procedure) to perform the calculations and provide output on the relationships between the speeds of vehicles and the associated site characteristics.

Initial analyses provided results that confirmed a suspected outcome; that is, given the large volume of data (i.e., 10,834 trips along the 100 selected ramps, with a total of 1,731,753 individual speed readings) every variable contained in the early models, no matter how small its effect on operating speed, was deemed to be statistically significant in the results from SAS. To produce more meaningful results, researchers prioritized the list of available variables and removed lower-priority variables that were correlated with high-priority variables. High-priority variables focused on those that were directly related to geometric design or traffic control devices. Using a smaller set of variables, researchers then focused on combinations of remaining variables to produce models that had intuitive forms and coefficients, focusing on effects related to the design of the ramp.

Speed on Curved Ramp Segments

For speeds on curve segments, the variables that were ultimately included in the selected model were the radius, the square of the radius, the freeway speed limit, the form of traffic control at the crossroad terminal, and the percentage of the entire ramp that the vehicle has traversed.

Researchers produced separate models for entrance ramps and exit ramps. The speed models for curved ramp segments are shown in equations (7) and (8). For entrance ramps, a traffic signal is considered the baseline crossroad traffic control and adjustment is made only if the crossroad terminal is free-flow. For exit ramps, stop control is considered the baseline, with adjustments for free-flow or traffic signal control.

$$v_{curve,ent} = 0.51v_{fwy} + 56.5R - 41.5R^2 + 0.68TC_{FF} - 1.07 \quad (7)$$

$$v_{curve,exit} = 0.20v_{fwy} + 79.9R - 61.1R^2 - 0.154\text{Ramp}_{pct} + 11.75TC_{FF} + 10.17TC_{SIG} + 12.30 \quad (8)$$

Where:

- $v_{curve,ent}$ = estimated speed of vehicle on curved segment of entrance ramp, mph.
- $v_{curve,exit}$ = estimated speed of vehicle on curved segment of exit ramp, mph.
- v_{fwy} = speed limit of freeway, mph.
- R = radius of curve, miles.
- R^2 = square of the radius of curve, square miles.
- TC_{FF} = indicator variable for traffic control at crossroad terminal (= 1 if free-flowing, 0 otherwise).
- TC_{SIG} = indicator variable for traffic control at crossroad terminal (= 1 if signalized, 0 otherwise).
- Ramp_{pct} = percent of entire ramp already traveled at the beginning of the ramp segment.

The coefficient of determination for the entrance ramp speed and the exit ramp speed equations are 0.454 and 0.505, respectively. Equations 7 and 8 describe an average speed on the curve, as each equation produces one speed per segment. In reality, the speed a vehicle travels on a curve changes as the vehicle approaches, traverses, and departs the midpoint of the curve. On an entrance ramp, a vehicle typically has a pronounced acceleration coming out of a curve, while on an exit ramp a driver may not accelerate at all on the second half of a curve, depending on the type and length of the next segment of the ramp. Further development of the model will provide the capability to estimate speed at any point along the curve. The formulae produce logical results for radii up to approximately 0.7 mi, above which the radius-squared term begins to have an outsized effect and produces a decrease in speed as the radius increases.

For both entrance and exit ramps, the destination of the vehicle has an intuitive effect on subsequent speed. For entrance ramps, the speed limit of the freeway plays a larger role in the determination of operating speed than on exit ramps. Conversely, the crossroad traffic control has a larger effect for vehicles on exit ramps than entrance ramps.

Ramp percentage was included in analyses for both the entrance ramp model and exit ramp model, but it was significant only for exit ramps. This suggests that a vehicle's location on the ramp has a bigger impact on speed for exit ramps than entrance ramps. This is plausible because a vehicle entering a freeway might not have to accelerate to the value of the speed limit in order to merge into the mainlanes; however, an exiting vehicle does have to decelerate to a speed appropriate for the crossroad terminal traffic control and the driver of that vehicle will be more likely to adjust to that speed the closer the vehicle is to the end of the ramp.

Speed on Tangent Ramp Segments

Because tangent segments do not contain the same inherent influences on speed as curve segments, researchers introduced a variable to account for the speed the vehicle was traveling at the beginning of the segment. The inclusion of this variable led to models for predicting speed on tangent sections with much higher coefficients of determination than the models developed in earlier analyses. The models are as follows:

$$v_{tangent,ent} = 0.84 v_{PT} + 0.081\, Seg_{pct} - 2.29\ Next_C - 4.05\ Prev_C + 10.78 \quad (9)$$

$$v_{tangent,exit} = 0.98 v_{PT} - 0.115\, Seg_{pct} + 2.31\, Next_C + 0.83\, Prev_C + 0.60 \quad (10)$$

Where:

- $v_{tangent,ent}$ = estimated speed of vehicle on tangent segment of entrance ramp, mph.
- $v_{tangent,exit}$ = estimated speed of vehicle on tangent segment of exit ramp, mph.
- v_{PT} = vehicle speed at the point of tangency, mph.
- Seg_{pct} = percent of the tangent section already traveled by vehicle, percent.
- $Next_C$ = indicator variable for type of upcoming segment (= 1 if a curve, 0 otherwise).
- $Prev_C$ = indicator variable for type of previous segment (= 1 if a curve, 0 otherwise).

The models for entrance and exit tangents have coefficients of determination of 0.761 and 0.794, respectively. The inclusion of the variable Seg_{pct} in this model leads to the ability to estimate speed at any point on the tangent segment if the other variables are known. It also suggests that vehicle speed increases by an average of about 8 mph on entrance tangents and decreases by 11.5 mph on exit tangents. The coefficients of Seg_{Next} and Seg_{Prev} indicate that on an entrance ramp tangent, the vehicle's speed is expected to be slower when either the previous or the following segment are curved. On an exit ramp tangent, the speed is expected to be slightly higher when either the previous segment or the following segment are curved.

Note that the use of v_{PT} sets a baseline or threshold speed for the segment that is affected by the characteristics of the previous segment. This is logical in that the speed at the end of the previous curve is also the speed at the beginning of the tangent, but it does introduce effects on the tangent speed that are not part of the design of the tangent itself. If a tangent is the first segment on a ramp, then the v_{PT} term is equal to the speed at the end of the deceleration lane.

Similarly, the effects of the previous and next segment types are introduced to balance the strong effect of Seg_{pct} and define when a tangent is the first or last segment on a ramp. The presence of a curve before or after the tangent has an effect on how much the driver chooses to adjust speed on the tangent.

Speed Profile on the Ramp Proper

Using the previous models for individual segments as a basis, researchers wanted to explore the possibility of modeling speeds over an entire ramp. Ultimately, the research team focused on the quarter-points of each segment to provide reference points for this analysis; while that does not produce a true speed profile at any point along the ramp, it does provide an estimate that reflects expected changes in speed throughout the ramp. The following formulas for curved sections and tangent sections can be used in series to produce the desired speeds along a given ramp:

$$v_{curve} = \beta_0 + \beta_1 v_{PC} + \beta_2 R + \beta_3 R^2 + \beta_4 TC_{Sig} + \beta_5 TC_{FF} + \beta_6 Pre_C + \beta_7 Pre_N + \beta_8 Next_C + \beta_9 Next_N \quad (11)$$

$$v_{tangent} = \beta_0 + \beta_1 v_{PT} + \beta_2 TC_{Sig} + \beta_3 TC_{FF} + \beta_4 Pre_C + \beta_5 Pre_N + \beta_6 Next_C + \beta_8 Next_N \quad (12)$$

Where:

- v_{PC} = velocity at point of curvature, mph.
- v_{PT} = velocity at point of tangency, mph.

- R = radius of curve, miles.
- TC_{Sig} = indicator variable if the crossroad terminal is signalized (= 1 if yes, 0 if no).
- TC_{FF} = indicator variable if the ramp has a free-flow turn lane (= 1 if yes, 0 if no).
- Pre_C = indicator variable if the preceding ramp segment is a curve (= 1 if yes, 0 if no).
- Pre_N = indicator variable if the segment is the first ramp segment (= 1 if yes, 0 if no).
- $Next_C$ = indicator variable if the next ramp segment is a curve (= 1 if yes, 0 if no).
- $Next_N$ = indicator variable if the segment is the final ramp segment (= 1 if yes, 0 if no).

To use these models, the user must know the type (curve or tangent) and order of each of the ramp segments, the speed of the vehicle at the beginning of the ramp, the traffic control type at the intersection, and the radii of all curved segments. The user must also use calibrated coefficient estimates for each point on the ramp. Using the available data, researchers calculated beta coefficient estimates for the quarter points of both curve and tangent segments on both entrance and exit ramps (in all 16 coefficients, shown in TABLE 4). The exit ramp model has a baseline condition of stop-control at the crossroad terminal, while the entrance ramp model uses signal control as a baseline.

CONCLUSIONS

Based on the activities conducted as part of this research, the authors conclude the following:

- The SHRP2 NDS time-series data has the potential to be used in conjunction with other sources of data to provide realistic models of vehicle speed related to geometric design characteristics. The researchers developed an initial set of speed models that could be used as a resource for a more formal procedure.
- The NDS data also succeeded in providing a robust data source compared to the amount and detail of data that can typically be collected through previous methods; however, there is a caveat that a wealth of data can generate results that have statistical significance without a corresponding level of practical significance. In this case, every variable in the initial model was significant after analyzing more than 1.7 million speed readings, even though some variables' practical effects were minimal. This served as a reminder that the model development process in any statistical analysis must include a consideration of which variables and how much data provide the best opportunity to generate meaningful, implementable results.
- Of the variables examined for this study, curve radius was, as expected, a variable that had one of the greatest effects on ramp operating speed, and the effect was non-linear. As a result, speed increases at a diminishing rate as curve radius increases.
- The models suggest that drivers are influenced more by the destination than the origin in their selection of speed. On entrance ramps, the freeway speed limit plays a large role in speed prediction, while the type of traffic control at the crossroad terminal has a larger effect on exit ramps than on entrance ramps.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: Marcus Brewer, Jayson Stibbe; data collection: Marcus Brewer, Jayson Stibbe; analysis and interpretation of results: Marcus Brewer, Jayson Stibbe; draft manuscript preparation: Marcus Brewer, Jayson Stibbe. All authors reviewed the results and approved the final version of the manuscript.

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TABLE 1 Guide Values for Ramp Design Speed as Related to Highway Design Speed (*2*)

U.S. Customary										
Highway design speed (mph)	30	35	40	45	50	55	60	65	70	75
Ramp design speed (mph)										
Upper range (85%)	25	30	35	40	45	48	50	55	60	65
Middle range (70%)	20	25	30	33	35	40	45	45	50	55
Lower range (50%)	15	18	20	23	25	28	30	30	35	40
Corresponding minimum radius (ft)	See *Green Book* Table 3-7									

TABLE 2 Input Data for Ramp Curve Speed Prediction Procedures in ISATe (*7*)

Variable	Description	Default value	Applicable procedure
X_i	Milepost of the point of change from tangent to curve (PC) for curve *i* [1], mi	None	All
R_i	Radius of curve *i* [2], ft	None	All
$L_{C,i}$	Length of horizontal curve *i*, mi	None	All
V_{frwy}	Average traffic speed on freeway during off-peak periods of the typical day, mph	Estimate is equal to the speed limit	All
V_{xroad}	Average speed at point where ramp connects to crossroad, mph	15 – ramps with stop-, yield-, or signal-controlled crossroad ramp terminals 30 – all other ramps at service interchanges	Entrance ramp, exit ramp, connector ramp at service interchange

Notes:

1 If the curve is preceded by a spiral transition, then X_i *is* the average of the TS and SC mileposts, where TS is the milepost of the point of change from tangent to spiral and SC is the milepost of the point of change from spiral to curve.

2 If the curve has spiral transitions, then R_i is equal to the radius of the central circular portion of the curve.

TABLE 3 Number of Unique Participant/Ramp Combinations in the Dataset

	Configuration			Direction of Travel		
State	**Curve**	**Diamond**	**Loop**	**Entrance**	**Exit**	**Total**
FL	816	2049	624	1975	1514	3489
IN	0	150	51	201	0	201
NC	796	1770	993	1713	1846	3559
NY	475	391	527	875	518	1393
PA	406	523	84	164	849	1013
WA	398	842	0	369	871	1240
Total	2891	5725	2279	5297	5598	10895

TABLE 4 Estimates of Coefficients for Speed Profile Model

			Coefficients										
			V_{PC}	V_{PT}	R	R^2	TC_{Sig}	TC_{FF}	Pre_C	Pre_N	$Next_C$	$Next_N$	Int
Entrance	Curves	V_{25}	1.04		5.45	-3.76	0.00	-0.56	1.70	4.11	-1.66	-2.29	-1.85
		V_{50}	0.84		23.16	-19.12	0.00	-0.58	-0.92	2.87	-2.10	-0.17	5.76
		V_{75}	0.81		24.48	-18.90	0.00	-0.58	-0.99	3.39	-2.21	0.19	8.05
		V_{100}	0.78		16.53	-8.92	0.00	0.30	-1.96	4.22	-2.22	0.56	10.44
	Tangents	V_{25}		1.05			0.00	3.44	-7.65	0.00	0.61	0.00	3.13
		V_{50}		0.84			0.00	1.38	-4.46	0.00	-1.84	0.00	15.21
		V_{75}		0.79			0.00	1.44	-6.11	0.00	-3.21	0.00	20.11
		V_{100}		0.82			0.00	1.61	-6.75	0.00	-3.49	0.00	20.39
Exit	Curves	V_{25}	0.98		4.18	-3.48	1.15	2.03	0.00	0.73	-1.81	-1.05	-1.82
		V_{50}	0.92		5.10	-2.96	3.13	5.30	0.21	0.49	-2.53	-4.64	-2.15
		V_{75}	0.85		4.83	-2.51	4.33	6.56	0.51	0.50	-3.74	-9.74	-1.09
		V_{100}	0.78		0.00	0.00	3.23	8.70	0.00	0.00	-4.31	-11.72	2.27
	Tangents	V_{25}		1.02			1.25	1.49	0.50	0.00	0.69	0.00	-4.04
		V_{50}		0.97			2.05	2.18	-0.81	0.00	1.04	0.00	-3.58
		V_{75}		0.94			4.25	3.54	-1.99	0.00	2.02	0.00	-6.21
		V_{100}		0.89			10.25	10.78	-2.55	0.00	0.36	0.00	-11.68

FIGURE 1 Example of road tubes installation.

(Image Credit: Marcus Brewer)

FIGURE 2 Cameras, sensors, and data acquisition unit in an instrumented vehicle. (Image Credit: Marcus Brewer)

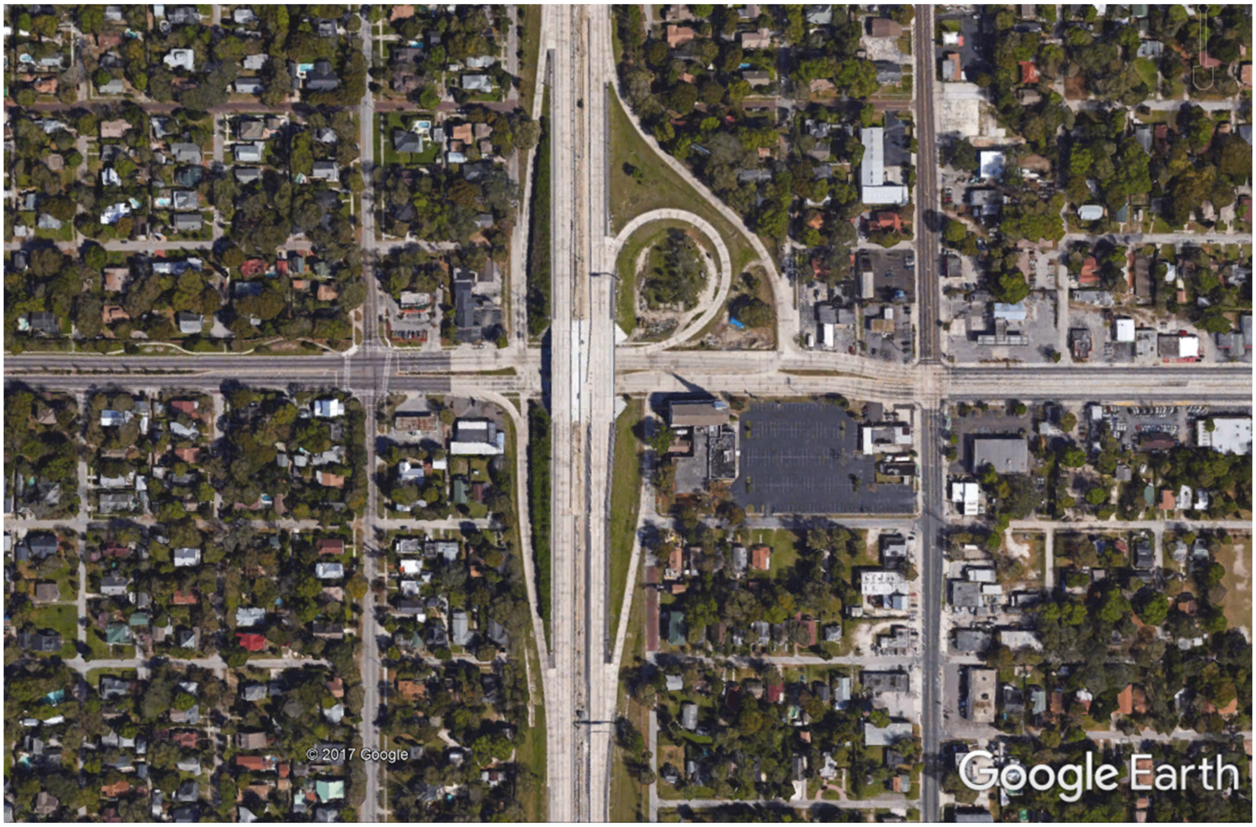

FIGURE 3 Screenshot of 5 ramps (1 loop, 1 curve, and 3 diamond) from Google Earth.