# Using SHRP 2 Naturalistic Driving Data to Estimate Operating Speeds on Freeway Entrance and Exit Ramps

February 2020 | Final Report


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16. Abstract

Current geometric design guidelines provide information to designers on appropriate design speeds for freeway entrance and exit ramps. These guidelines are based on practices dating back several decades. Recent research projects have examined various aspects of freeway ramp design, but the available field data driving the conclusions in those projects is often limited. These studies are usually able to collect data on only a small number of sites or drivers, and typically take spot speeds at key locations along ramps rather than compiling comprehensive speed profiles. The Second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study (NDS) dataset provides a new opportunity for analyzing detailed driving data to critically review and potentially update existing design guidelines. This study examined driving data on freeway ramps—speed profiles along with selected driver and vehicle variables—from the SHRP 2 NDS and compared that data to the design characteristics of the ramps traveled during the study. The objective of the comparison was to develop models for calculating operating speeds at key locations along freeway ramps. The resulting models were further compared to similar models from recent research. Potential topics for future research were also identified.

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# Abstract

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# 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 dating back several decades; however, it is not well known how accurately the speeds suggested by existing design guidance reflect current driving behavior. Various aspects of freeway ramp design have been examined in recent and current research projects, but the available field data driving the conclusions in those projects is often limited. These studies are usually able to collect data on only a small number of sites or drivers, the dataset typically contains spot speeds at key locations along ramps rather than comprehensive speed profiles, and little information about the corresponding driver behavior is known. The Second Strategic Highway Research Program (SHRP 2) Naturalistic Driving Study (NDS) dataset, collected during the study by the Virginia Tech Transportation Institute (VTTI) provides a new opportunity to analyze detailed driving data in order to critically review and potentially update existing design guidelines. This study examined SHRP 2 NDS driving data on freeway ramps—speed profiles along with selected driver and vehicle variables—and compared that data to the design characteristics of the ramps traveled during the study.

The objective of the comparison was to develop models for calculating operating speeds at key locations along freeway ramps. The resulting models were further compared to similar models from recent research. Potential topics for future research were also identified.

# Background

## Freeway Ramp Operating Speed

A number of factors can influence a driver's selected operating speed when traversing a freeway ramp, and the effects of some of those factors have been studied in previous research. In fact, a number of existing models 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 ramp's geometric design characteristics than other influences related to traffic volumes.

A focused analysis of vehicle speeds on loop ramps was conducted in National Cooperative Highway Research Program (NCHRP) Project 3-105 [*1*]. Field data showed that models based on Highway Safety Manual (HSM) methodology tended to overestimate vehicle speeds on the controlling curves (i.e., sharpest curves) of loop ramps by the following magnitudes:

- Entrance ramp: 4.2 km/h (2.6 mph) at the midpoint, 2.9 km/h (1.8 mph) at the point of tangency (PT).
- Exit ramp: 17.1 km/h (10.6 mph) at the point of curvature (PC), 3.5 km/h (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:

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

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

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

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

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).

In NCHRP Project 17-45, Bonneson et al. [*2*] developed crash prediction methodologies for freeways and interchanges. The methodologies were recently incorporated into the HSM as a supplement (Chapter 18 – Predictive Method for Freeways, and Chapter 19 – Predictive Method for Ramps) [*3*] to the original three-volume edition published in 2010 [*4*]. The general form of the Safety Performance Function (SPF) for estimating the crash frequency for a ramp is as follows:

$$N = L_r \times \exp\left[a + b \times \ln(c\, AADT_r) + d\,(c \times AADT_r)\right] \quad (5)$$

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 and property damage only 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, the average entry speed increases, and 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 1. The speed profile models are implemented in the spreadsheet-based Enhanced Interchange Safety Analysis Tool (ISATe). Bonneson et al. [*2*] noted 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.

**Table 1. Input Data for Ramp Curve Speed Prediction Procedures in ISATe [2]**

| 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<br>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 Xi 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 Ri is equal to the radius of the central circular portion of the curve.

The NCHRP 17-45 research team developed separate seven-step procedures for entrance ramps and exit ramps, as follows:

1. Gather the needed input data identified in Table 1.
2. Compute the limiting speed ($v_{max,i}$) for each curve on the ramp.
3. Calculate the entry speed ($v_{ent,1}$) on the first curve.
4. Calculate the exit speed ($v_{ext,1}$) on the first curve.
5. Calculate the entry speed ($v_{ent,2}$) on the second curve, based on the previous curve.
6. Calculate the exit speed ($v_{ext,2}$) on the second curve, based on the previous curve.
7. Calculate the entry and exit speeds ($v_{ent,i}$, $v_{ext,i}$) on subsequent curves, by repeating Steps 5 and 6.

The equations that correspond to each step are provided in Table 2.

Table 2. Equations Used in NCHRP 17-45 Seven-Step Speed Prediction Model [2]

| Step | Entrance Ramp | Exit Ramp |
|---|---|---|
| **2** | $v_{max,i} = 3.24\ (32.2\ R_i)^{0.30}$ | Same as Entrance Ramp |
| **3** | $v_{ent,1} = ([1.47\ V_{xroad}]^3 + 495 \times 5280\ X_1)^{1/3}$ <br> $\leq 1.47\ V_{frwy}$ | $v_{ent,1} = 1.47\ V_{frwy} - 0.034 \times 5280\ X_1$ <br> $\geq 1.47\ V_{xroad}$ |
| **4** | $v_{ext,1} = (V^3_{ent,1} + 495 \times 5280\ L_{c,1})^{1/3}$ <br> $\leq v_{max,1}$ and $\leq 1.47\ V_{frwy}$ | $v_{ext,1} = v_{ent,1} - 0.034 \times 5280\ L_{c,1}$ <br> $\leq v_{max,1}$ and $\geq 1.47\ V_{xroad}$ |
| **5** | $v_{ent,i} = (\ V^3_{ext,i\text{-}1} + 495 \times 5280\ [X_i - X_{i\text{-}1} - L_{c,i\text{-}1}]\ )^{1/3}$ <br> $\leq 1.47\ V_{frwy}$ | $v_{ent,i} = v_{ext,i\text{-}1} - 0.034 \times 5280\ (X_1 - X_{i\text{-}1} - L_{c,i\text{-}1})$ <br> $\geq 1.47\ V_{xroad}$ |
| **6** | $v_{ext,i} = (V^3_{ent,i} + 495 \times 5280\ L_{c,i})^{1/3}$ <br> $\leq v_{max,i}$ and $\leq 1.47\ V_{frwy}$ | $v_{ext,i} = v_{ent,i} - 0.034 \times 5280\ L_{c,i}$ <br> $\leq v_{max,i}$ and $\geq 1.47\ V_{xroad}$ |
| **7** | Same as Steps 5 and 6 | Same as Steps 5 and 6 |

Notes:

1 All curve speeds are in ft/s. All other variables are in the units described in Table 1.

2 The boundary condition of Entrance Ramp Steps 3 and 5 indicates that the value computed ($v_{ent}$) cannot exceed the average freeway speed ($V_{frwy}$).

3 The boundary conditions of Entrance Ramp Steps 4 and 6 indicate that the value computed ($v_{ext}$) cannot exceed the limiting curve speed ($v_{max,i}$) or the average freeway speed ($V_{frwy}$).

4 The boundary condition of Exit Ramp Steps 3 and 5 indicates that the value computed ($v_{ent}$) cannot be less than the average speed at the point where the ramp connects to the crossroad ($V_{xroad}$).

5 The boundary conditions of Exit Ramp Steps 4 and 6 indicate that the value computed ($v_{ext}$) cannot exceed the limiting curve speed ($v_{max,i}$) and should not be less than the average speed at the point where the ramp connects to the crossroad ($V_{xroad}$).

# Data Collection

The process for collecting speed and other vehicle data on freeway ramps has traditionally used one or more of the following methods: instrumented vehicles, lidar profiles, and road sensor spot-speeds. Each method has its advantages and disadvantages, which are summarized in Appendix A. 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 SHRP 2 NDS dataset is a source of "big data," comprising data from more than 3,000 participants in six states. In total, it contains as much as 3,500 years of time series data [*5*]. 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 taken of 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 [*6*, *7*].

The SHRP 2 NDS used an expanded version of the instrumented vehicle method described in Appendix A. At the beginning of participation, data acquisition systems (DAS) and sensor equipment were installed in the personal vehicles of each of the thousands of participant drivers in order to record their everyday driving activity in a real-world environment.

We explored the trip density maps in the SHRP 2 NDS InSight database [*8*] to identify a robust sample of ramps from which to collect speeds and other travel data. We reviewed available data for the six participating states (FL, IN, NC, NY, PA, WA) in the database, looking for ramps on which 50–200 unique participants had made trips. We 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, we used the aerial mapping tool Google Earth as a supplemental source of information, viewing the same locations simultaneously in InSight and Google Earth. This allowed us to obtain the GPS coordinates of the ramps, document the context of each ramp (e.g., urban/rural and residential/commercial), and confirm the ramp type and the entry and exit routes for each ramp.

We ultimately identified 1,686 ramps with 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 8 trips by each participant per ramp. We then 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. We removed all ramps that did not lead to or from an interstate highway, all 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. We also retained only one ramp per interchange. At the end of this process, a site list of 100 ramps remained, with 10,895 unique participant/ramp combinations (see Table 3). For this study, unique participant-ramp combinations better represent real-world data; their use provides a better mix of participants than measuring the same driver in the same vehicle on the same ramp for multiple trips. We sent this list of sites to SHRP 2 data administrators to request a selection of SHRP 2 NDS time series data variables for trips taken on those ramps. Specifically, we requested detailed time series data for the first traversal made by each unique participant on each of the selected ramps.

**Table 3. Number of Unique Participant/Ramp Combinations in the Dataset**

| State | Curve Configuration | Diamond Configuration | Loop Configuration | Direction of Travel – Entrance | Direction of Travel – 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 |

The SHRP 2 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. Following are variables that were included in the requested data 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)
- Steering wheel position
- Distance
- Accelerator pedal position
- Brake pedal position
- Anti-lock brake system activation
- Electronic stability control
- Traction control

We intended to use the SHRP 2 Roadway Information Database (RID) to obtain the desired site characteristics data for each of the ramps on the study site list. Unfortunately, we discovered that the ramp dataset is quite limited in RID. Of the 1,686 ramps that we 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 those ramps, but decided that it would be better to use a more representative set of ramps, so we opted to explore other methods of obtaining the ramps' design and geometric data.

Ultimately, we 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 ramp features, including physical measurements. We subdivided each ramp into curve and tangent segments, and 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; a simple straight-line length was projected with the ruler tool and the corresponding distance was recorded in the database. The ruler tool also allowed us 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. We 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 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.

# Data Analysis and Results

At this point, the dataset was analyzed and we determined what additions and changes would be needed. Before evaluating the impact of the ramp characteristics on the operating speed of the traveling vehicles, we considered some important questions that needed to be answered:

- Which time series speed variable should be used?
- Are the radii obtained from aerial photography the best method of estimating the ramp curvature?
- Is there a way to infer superelevation on the roadway from the data available?
- What is the best way to determine where on the ramp the time series data are occurring (i.e., locating the vehicle)?

Analysis of the time series data provided answers to these questions, with particular attention given to the last question.

## Time Series Speed Data

In speaking with the database managers at VTTI, we learned that the Network Speed time series variable was generally more reliable than the GPS Speed variable, so Network Speed was chosen as the speed variable of choice. Although the network speed data had fewer blank cells than the GPS speed data, the blank cells still had to be filled for later data analysis. Linear interpolation was applied to fill in the missing speed values.

## Using Time Series Data to Find Radius and Superelevation

Although the radius of each curved segment was found using the aerial mapping tool Google Earth, we wanted to see if the radii could be inferred from the time series data. The SHRP 2 NDS time series data contained information on vehicle yaw rate, which is directly related to how sharply a vehicle turns, with a higher rate indicating a sharper turn. The radius of a curve can be calculated from yaw rate as follows:

$$Radius = \frac{Velocity}{Yaw\ Rate} \qquad (6)$$

with radius measured in ft, velocity in ft/s, and yaw rate in rad/sec.

Unfortunately, in many cases, the radius calculated from the time series data differed from the radius obtained in Google Earth, and the calculated radius was also different between vehicles on the same ramp. One likely reason for this difference is that the calculated radius relies on the movement of the vehicle rather than the actual roadway, so it can be affected by the vehicle's position relative to the middle of the lane or the vehicle's steering wheel angle as it varies throughout the curve. These variations led us to use the radius measured from Google Earth in subsequent calculations and analyses.

Next, we explored the time series data for the possibility of measuring the superelevation rate of the traveled ramps, using the basic curve formula shown below [9]:

$$f = \frac{V^2}{15R} - 0.01e \qquad (7)$$

Where: f = side friction factor;

V = vehicle speed, mph;

R = radius driven, ft; and

e = superelevation rate, percent.

We wanted to use this formula by substituting the y-acceleration (f), speed (V), and inferred radii (R) from the time series data to estimate the superelevation found in the middle third of each curve (where superelevation should be highest). However, similar to the process for calculating radius, we concluded that there was not sufficient precision to overcome the variation in the data introduced by differences in driver behavior and sensor limitations.

## Using Time Series Data to Locate Vehicle on a Ramp

One of the primary challenges in working with the time series data was locating the vehicle on the ramp. When collecting data in the field, there is a high level of certainty about where the vehicle is during data collection, as it can be physically observed and measured. This makes evaluating the impact of ramp geometrics relatively easy, as the geometrics can be known for each point. However, the precise location of the vehicle is much harder to determine when using time series data.

The time series data did not contain GPS tracking data, so we looked to alternative methods for determining vehicle location. As part of the request for time series data from VTTI, we requested that each trip's dataset contain 2 seconds of time series data before the vehicle entered the link corresponding to the LinkID of the ramp and 2 seconds of time series data after the vehicle entered the subsequent link. Ideally, every vehicle on a given ramp would be at the same location at the start of the third second of time series data and that location would be the start of the ramp as measured using aerial mapping. To that end, we calculated cumulative distance traveled beginning with the 21st line of time series data, which was 2.1 seconds into the trip, or the first line of data in which the vehicle was supposed to be on the ramp. We also calculated the distance incrementally so that the distance traveled every tenth of a second was calculated. However, the time series data contained two primary sources of uncertainty for determining a vehicle's location:

1. Disagreement on the beginning of the ramp between the LinkIDs from the SHRP 2 dataset and the measurements obtained from Google Earth, and
2. Disagreement between individual trips on where the ramp and ramp segments began.

A possible source of both of these disagreements in the data is the limitation of accuracy in the instruments used in the SHRP 2 data collection. Automotive-grade GPS devices, such as those used in SHRP 2, have a possible margin for error of up to 30 ft. That means there could be as much as 60 ft of disagreement between the locations identified by any two vehicles for the start of a given LinkID. Ideally, resolving one of these two disagreements would explain any dissimilarities between where the vehicle was and where the vehicle should have been on the ramp, given the starting location and distance traveled. The latter disagreement was difficult to resolve due to differences in individual drivers' behavior and unknown levels of additional sensor error. We measured differences in the distance traveled (by as much as 30 m [100 ft]) between vehicles on the same ramp, meaning that the distance traveled could not, by itself, identify where the ramp began and ended. The former disagreement could be mitigated using clues from the time series data. We subsequently explored the existing data for options to resolve these problems.

Because the location of the vehicle could not be determined via the calculated distance alone, we used the yaw rate, in degrees per second, to compare the distance required to travel one degree on the circumference of the circle being driven by the vehicle, given the vehicle's speed, to the distance it would take to travel one degree on a circle with a predetermined radius. From the yaw rate, the change in deflected angle was measured for each vehicle, as seen in Figure 1. However, the sensors for yaw rate lacked the necessary precision, leading to large fluctuations in the measured deflected angle from one reading to the next. To mitigate this, we calculated a moving average of the yaw rate for use in the distance calculation.

To ultimately locate the vehicle, we divided the calculated distance traveled by the vehicle (in feet per 0.1 second) by the vehicle's yaw rate (in degrees per 0.1 second) to find the distance that it would take the vehicle to travel one degree on the circumference of the driven circle (feet per degree), as shown in Column 5 in the example in Figure 2. We also calculated the distance it would take to travel one degree on the circle of each ramp radius measured from Google Earth, as shown in Column 7 in Figure 2. We then compared the two, setting up two columns in a spreadsheet to identify transitional areas between segments. One of these columns identified the transition from a curve to a tangent and the other identified the transition from a tangent to a curve (Columns 9 and 10, respectively, in Figure 2**)**. The calculations in these two columns would identify such a change based on a predefined "threshold of turning" that indicated a vehicle was changing from a tangent section to a curve section, or vice-versa. In the example shown in Figure 2, where the vehicle is moving from a tangent segment (Segment 1) to a curve segment (Segment 2) on an entrance ramp, the threshold of turning is 3.0. The formula in Column 8 divides Column 5 by Column 7 to show the multiplier between the vehicle's average distance per degree and the distance per degree of the curve. That multiplier falls below a value of 3.0 at a time stamp value of 130, which is when the vehicle is estimated to enter the curve, reflected in Column 10 of Figure 2. Figure 3 shows the assumed location of the vehicle from Figure 2 at that point.

| System.Time_Stamp | Filled Yaw Rate (degrees/second) | Yaw Rate Moving Average | Sum Deflected Angle (degrees) | Angle Change (degrees) | Absolute Angle Change (degrees) |
|---|---|---|---|---|---|
| 74 | -0.3252 | 0.0296 | -52.9373 | 0.0030 | 0.0030 |
| 75 | -0.3252 | -0.0887 | -52.9461 | -0.0089 | 0.0089 |
| 76 | -0.3252 | -0.1183 | -52.9579 | -0.0118 | 0.0118 |
| 77 | -0.3252 | -0.1478 | -52.9727 | -0.0148 | 0.0148 |
| 78 | -0.3252 | -0.2069 | -52.9934 | -0.0207 | 0.0207 |
| 79 | 0.0000 | -0.2365 | -53.0171 | -0.0237 | 0.0237 |
| 80 | 0.0000 | -0.2365 | -53.0407 | -0.0237 | 0.0237 |
| 81 | 0.0000 | -0.2365 | -53.0644 | -0.0237 | 0.0237 |
| 82 | -0.3252 | -0.2365 | -53.0880 | -0.0237 | 0.0237 |
| 83 | -0.3252 | -0.2069 | -53.1087 | -0.0207 | 0.0207 |
| 84 | -0.3252 | -0.2069 | -53.1294 | -0.0207 | 0.0207 |
| 85 | -0.3252 | -0.2365 | -53.1531 | -0.0237 | 0.0237 |
| 86 | -0.3252 | -0.2956 | -53.1826 | -0.0296 | 0.0296 |
| 87 | -0.3252 | -0.3548 | -53.2181 | -0.0355 | 0.0355 |
| 88 | 0.0000 | -0.3843 | -53.2565 | -0.0384 | 0.0384 |

**Figure 1. Example yaw rate and angle measure calculations.**

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| System.Time_Stamp | Incremental Distance (ft) | Absolute Angle Change (deg) | Feet/ Degree Calculated | Feet/ Degree Moving Avg | Feet/ Degree Segment 1 | Feet/ Degree Segment 2 | Calculation for Threshold of Turning | Curve to Tangent Location | Tangent to Curve Location |
| 109 | 5.140 | 0.050 | 102.278 | 113.651 | 999999 | 8.447 | 13.454 | 0 | 0 |
| 110 | 5.158 | 0.067 | 77.547 | 102.223 | 999999 | 8.447 | 12.101 | 0 | 0 |
| 111 | 5.177 | 0.090 | 57.409 | 83.793 | 999999 | 8.447 | 9.919 | 0 | 0 |
| 112 | 5.195 | 0.087 | 59.564 | 70.375 | 999999 | 8.447 | 8.331 | 0 | 0 |
| 113 | 5.213 | 0.108 | 48.311 | 62.127 | 999999 | 8.447 | 7.355 | 0 | 0 |
| 114 | 5.231 | 0.099 | 52.821 | 55.640 | 999999 | 8.447 | 6.587 | 0 | 0 |
| 115 | 5.250 | 0.120 | 43.844 | 50.355 | 999999 | 8.447 | 5.961 | 0 | 0 |
| 116 | 5.268 | 0.129 | 40.962 | 47.473 | 999999 | 8.447 | 5.620 | 0 | 0 |
| 117 | 5.286 | 0.123 | 43.084 | 46.770 | 999999 | 8.447 | 5.537 | 0 | 0 |
| 118 | 5.286 | 0.126 | 42.071 | 45.135 | 999999 | 8.447 | 5.343 | 0 | 0 |
| 119 | 5.286 | 0.120 | 44.148 | 44.613 | 999999 | 8.447 | 5.281 | 0 | 0 |
| 120 | 5.286 | 0.120 | 44.148 | 43.270 | 999999 | 8.447 | 5.122 | 0 | 0 |
| 121 | 5.286 | 0.115 | 45.847 | 42.818 | 999999 | 8.447 | 5.069 | 0 | 0 |
| 122 | 5.286 | 0.106 | 49.667 | 42.007 | 999999 | 8.447 | 4.973 | 0 | 0 |
| 123 | 5.286 | 0.127 | 41.582 | 40.462 | 999999 | 8.447 | 4.790 | 0 | 0 |
| 124 | 5.286 | 0.124 | 42.572 | 38.743 | 999999 | 8.447 | 4.586 | 0 | 0 |
| 125 | 5.286 | 0.139 | 38.043 | 36.623 | 999999 | 8.447 | 4.335 | 0 | 0 |
| 126 | 5.286 | 0.136 | 38.870 | 34.388 | 999999 | 8.447 | 4.071 | 0 | 0 |
| 127 | 5.304 | 0.166 | 32.039 | 31.925 | 999999 | 8.447 | 3.779 | 0 | 0 |
| 128 | 5.323 | 0.204 | 26.092 | 28.955 | 999999 | 8.447 | 3.428 | 0 | 0 |
| 129 | 5.341 | 0.231 | 23.161 | 26.613 | 999999 | 8.447 | 3.150 | 0 | 0 |
| 130 | 5.359 | 0.257 | 20.836 | 24.055 | 999999 | 8.447 | 2.848 | 0 | Segment 2 begins |
| 131 | 5.377 | 0.275 | 19.558 | 21.769 | 999999 | 8.447 | 2.577 | 0 | 0 |
| 132 | 5.377 | 0.287 | 18.752 | 19.316 | 999999 | 8.447 | 2.287 | 0 | 0 |
| 133 | 5.377 | 0.316 | 16.999 | 17.450 | 999999 | 8.447 | 2.066 | 0 | 0 |
| 134 | 5.377 | 0.340 | 15.816 | 16.105 | 999999 | 8.447 | 1.907 | 0 | 0 |

**Figure 2. Example of a vehicle traveling through a segment change on an individual ramp.**

Determining the appropriate threshold of turning was crucial to determining the location of the transition point from one segment to the next. This threshold was set specifically for each ramp in order to match the segment length calculated from the time series data to the segment length already known from aerial photography. In doing this, we could be more confident about identifying the appropriate segment, particularly when there was high consistency among ramps at a certain threshold. Once the beginning point of one ramp segment was located, the others could be found using the measurements taken from Google Earth. Additional detail about the procedures for this process are provided in a paper submitted for the 2019 TRB Annual Meeting [*10*].

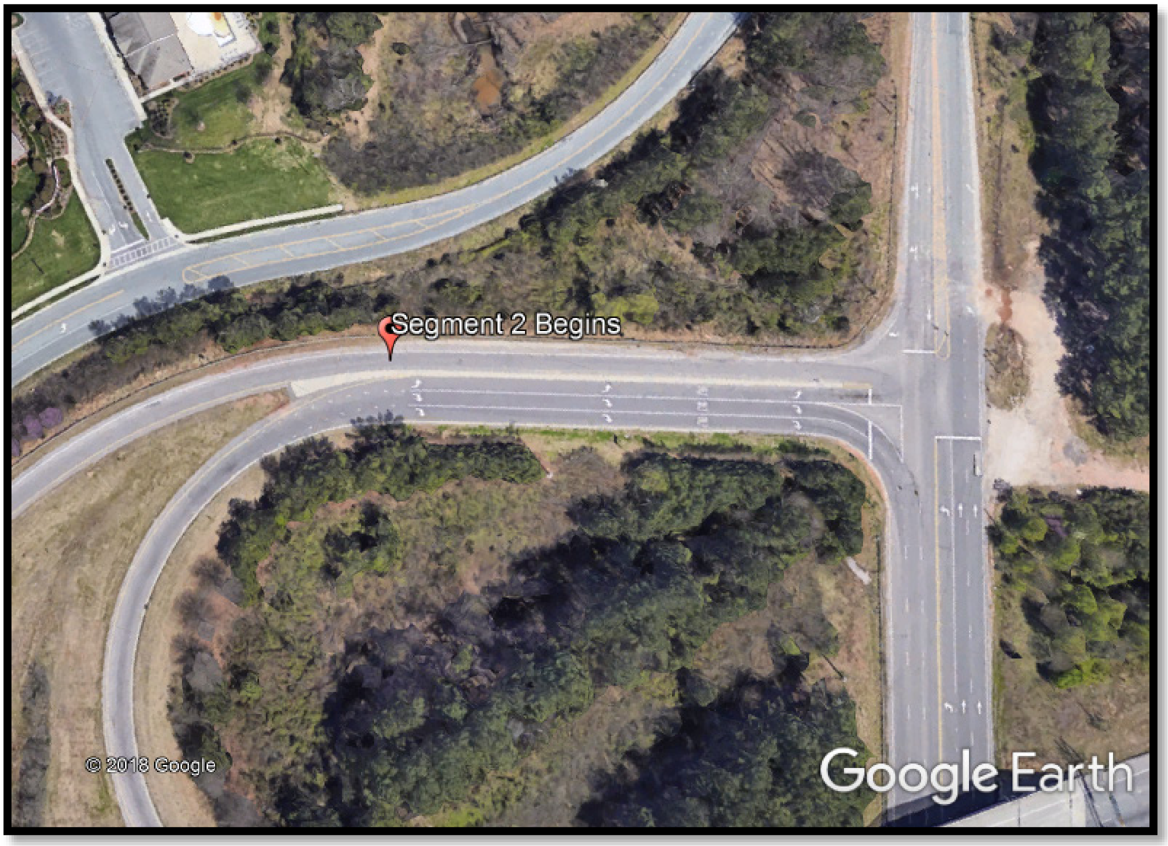


**Figure 3. Assumed position of example vehicle during segment change.**

## Findings from Data Analysis

To provide a measure of consistency with other previous and ongoing projects, we 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 data was divided into curve data and tangent data for separate analysis of individual ramp segments. For this analysis, we chose the SAS software program (specifically the general linear model procedure) to perform the calculations and provide output on the relationships between the speeds of vehicles and the associated site characteristics. Additional details can be found in a separate paper we submitted to the 2019 TRB Annual Meeting based on this research [*11*].

Initial analyses provided results that confirmed a suspected outcome: 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 the effect on operating speed, was deemed to be statistically significant in the SAS results. To produce more meaningful results, we prioritized the list of available variables and removed lower-priority variables that were correlated with high-priority variables. High-priority variables were directly related to geometric design or traffic control devices. Using a smaller set of variables, we then focused on combinations of those 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 curved segments, the variables included in the selected model were the radius (ranging from 144 to 5,220 ft for entrance ramps, and 148 to 4,393 ft for exit ramps), the square of the radius, the freeway speed limit (ranging from 55 to 70 mph), the form of traffic control at the crossroad terminal (free-flow, traffic signal, stop, or yield), and the percentage of the entire ramp that the vehicle traversed. Separate models were produced for entrance and exit ramps. For entrance ramps, a traffic signal was considered the baseline crossroad traffic control and adjustment was made only if the crossroad terminal was free-flow. For exit ramps, stop control was considered the baseline, with adjustments for free-flow or traffic signal control. The speed models for curved ramp segments are as follows:

$$v_{curve,ent} = 0.51v_{fwy} + 56.5R - 41.5R^2 + 0.68TC_{FF} - 1.07 \quad (8)$$

$$v_{curve,exit} = 0.20v_{fwy} + 79.9R - 61.1R^2 - 0.154\text{Ramp}_{pct} + 11.75TC_{FF} + 10.17TC_{SIG} + 12.30 \quad (9)$$

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).
- $\text{Ramp}_{pct}$ = 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 were 0.454 and 0.505, respectively. Equations 8 and 9 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 on the second half of a curve, depending on the type and length of the next segment. 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 (1.1 km), above which the $R^2$ 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 on entrance ramps.

Ramp percentage was included in analyses for both the entrance ramp model and exit ramp model, but 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 main lanes; 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, a variable was introduced 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:

$$v_{tangent,ent} = 0.84 v_{PT} + 0.081\, Seg_{pct} - 2.29\, Next_C - 4.05\, Prev_C + 10.78 \quad (10)$$

$$v_{tangent,exit} = 0.98 v_{PT} - 0.115\, Seg_{pct} + 2.31\, Next_C + 0.83\, Prev_C + 0.60 \quad (11)$$

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. The coefficients of $Next_C$ and $Prev_C$ indicate that, on an entrance ramp tangent, the vehicle's speed is expected to be slower when either the previous or the following segment is curved. On an exit ramp tangent, the speed is expected to be slightly higher when either the previous segment or the following segment is curved.

Note that $v_{PT}$ 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.

## Speed Profile on the Ramp Proper

Using the previous models for individual segments as a basis, we explored the possibility of modeling speeds over an entire ramp. Ultimately, we 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:

$$v_{curve} = \beta_0 + \beta_1 v_{PC} + \beta_2 R + \beta_3 R^2 + \beta_4 TC_{Sig} + \beta_5 TC_{FF} + \beta_6 Pre_C + \beta_7 Pre_N + \beta_8 Next_C + \beta_9 Next_N \quad (12)$$

$$v_{tangent} = \beta_0 + \beta_1 v_{PT} + \beta_2 TC_{Sig} + \beta_3 TC_{FF} + \beta_4 Pre_C + \beta_5 Pre_N + \beta_6 Next_C + \beta_8 Next_N \quad (13)$$

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, it is necessary to 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 use of calibrated coefficient estimates for each point on the ramp is also required. Using the available data, we 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 through Table 7). 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.

**Table 4. Estimates of Coefficients for Speed Profile Model – Entrance Curves**

| | $V_{PC}$ | $V_{PT}$ | R | $R^2$ | $TC_{Sig}$ | $TC_{FF}$ | $Pre_C$ | $Pre_N$ | $Next_C$ | $Next_N$ | Int |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{25}$ | 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 |

**Table 5. Estimates of Coefficients for Speed Profile Model – Entrance Tangents**

| | $V_{PC}$ | $V_{PT}$ | R | $R^2$ | $TC_{Sig}$ | $TC_{FF}$ | $Pre_C$ | $Pre_N$ | $Next_C$ | $Next_N$ | Int |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{25}$ | - | 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 |

**Table 6. Estimates of Coefficients for Speed Profile Model – Exit Curves**

| | $V_{PC}$ | $V_{PT}$ | R | $R^2$ | $TC_{Sig}$ | $TC_{FF}$ | $Pre_C$ | $Pre_N$ | $Next_C$ | $Next_N$ | Int |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{25}$ | 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 |

**Table 7. Estimates of Coefficients for Speed Profile Model – Exit Tangents**

| | $V_{PC}$ | $V_{PT}$ | R | $R^2$ | $TC_{Sig}$ | $TC_{FF}$ | $Pre_C$ | $Pre_N$ | $Next_C$ | $Next_N$ | Int |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $V_{25}$ | - | 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 |

### Comparison of Results with Other Models

Using the models described in the Background section of this report (i.e., the NCHRP 17-45 model and the NCHRP 3-105 model) for comparison, we developed an example entrance ramp and exit ramp to apply each SHRP 2-data-based model developed in this project (i.e., the segments model described in Equations 8 through 11, and the speed profile model described in Equations 12 and 13 and Table 4–7). We then compared and interpreted the results. Each model uses a unique combination of variables, so the comparison of results provides insights into the influences of those variables on operating speed. Appendix B provides tables that list each of the variables used in each model as well as the outputs from each model. Appendix C contains a list of the ramp characteristics as well as the results from the exit ramp model comparison. Results from the entrance ramp comparison are shown in Figure 4.

A key consideration in the comparison among models is that each model produces different outputs:

- The segments model developed in this project produces an average operating speed for each curve and an operating speed at each desired location along each tangent. In this comparison, tangent speeds were calculated for each quarter-point of the segment.
- The speed profile model in this project produces an operating speed at the quarter-points of each curve segment and each tangent segment.
- The NCHRP 17-45 model produces a speed at the beginning and end of each curve.
- The NCHRP 3-105 model produces a speed at the midpoint and at the freeway end (i.e., end of the curve on an entrance ramp and the beginning of a curve on an exit ramp) of each controlling curve. The 3-105 model was designed specifically for the controlling curve on a loop ramp; for this comparison, the 3-105 model was applied to each curve on the ramp to generate results that could be compared to the other models.

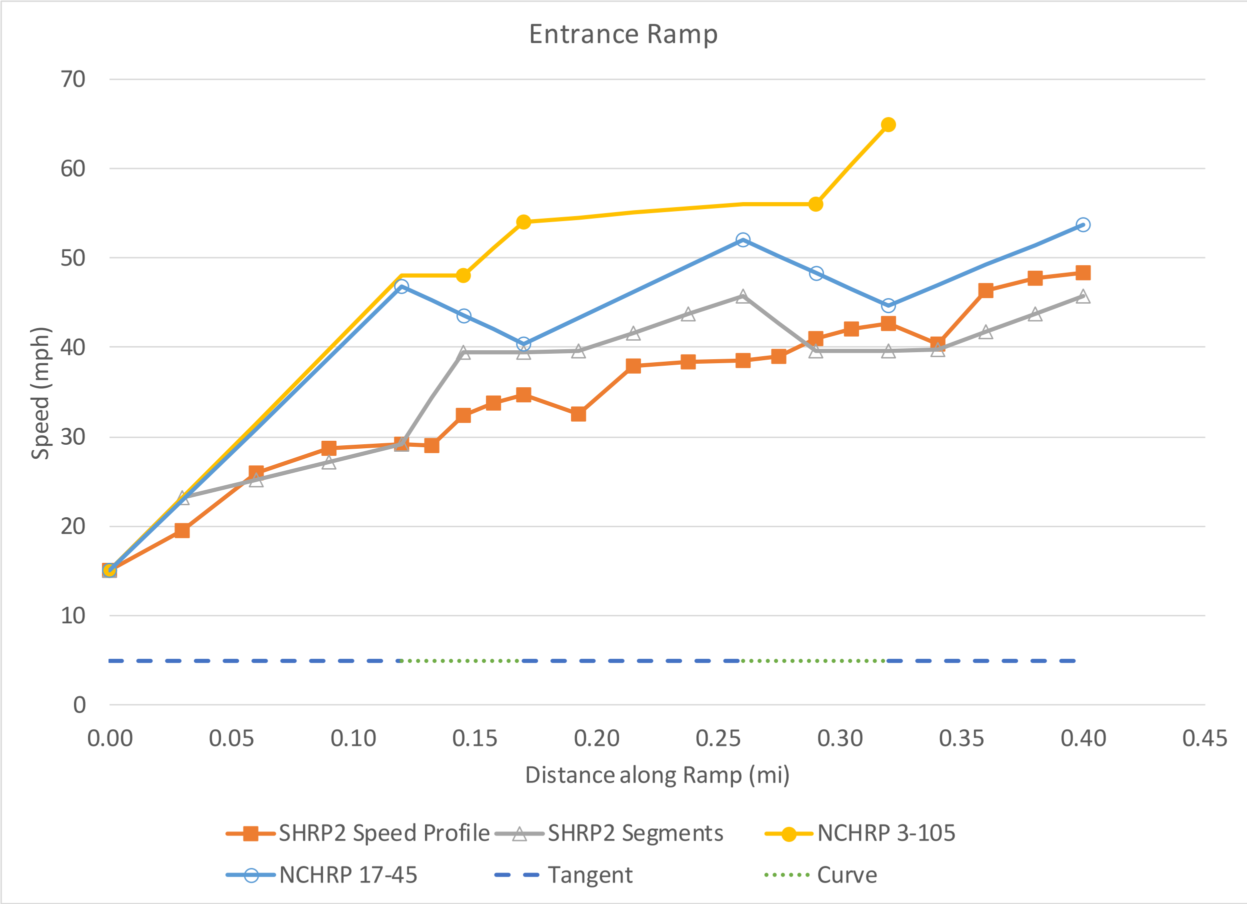


**Figure 4. Results from each model for example entrance ramp.**

Results of the entrance ramp model comparison in Figure 4 show that the SHRP 2 speed profile model produced a plot with realistic speeds that steadily increase or level out throughout the entirety of the ramp, with the exception of the first quarter-point of the second and third tangent sections. The equations in the speed profile model produced a decrease in speed at those points, which may reflect the speeds obtained in the SHRP 2 data but may not be consistent with the broader driving population, as the expectation would be that drivers on an entrance ramp would accelerate at the beginning of a tangent section. The SHRP 2 segments model produced a plot with larger speed changes between curves and tangents, which reflects a limitation of the curve equations that produce a single average for the segment and are not tied to the speed of the previous segment; these are limitations that we worked to address in developing the speed profile model.

The NCHRP 3-105 model is limited in that it does not calculate speeds on tangents, so the plot for that model ends at the end of the final curve, and speeds on earlier tangents are calculated as averages between points of known speeds. The 3-105 model also produced higher values for the calculated operating speed than the other models, which would be beneficial for facilitating merging, but may not accurately reflect acceleration behavior on a ramp with more than one curve.

The NCHRP 17-45 model produced results similar to those found in the SHRP 2 speed profile model for much of the ramp after the beginning of the first curve, though the 17-45 model calculates fewer points along the ramp and requires the use of average speeds along tangents. The resulting plot has more acceleration and deceleration activity, as measured in magnitude of speed change and/or in rate of change, along the ramp than the SHRP 2 speed profile model. Inclusion of tangent points in the 17-45 model may produce a smoother curve for the first and second tangents.

### Summary

The results from the analyses provide models for predicting operating speed on freeway ramps. The SHRP 2-data-based models developed in this project consider entrance and exit ramps separately, with separate components for curves and tangents. The segments model, which produces an average speed for each curve and a speed for any desired point on each tangent, considers crossroad traffic control, curve radius, freeway speed, the speed at the end of the previous curve segment, the type of the previous segment and next segment, and the distance traveled through a particular segment and/or the entire ramp. The speed profile model, which produces speeds at every quarter-point of each curve and tangent segment, considers crossroad traffic control, curve radius, the speed at the end of the previous segment, the type of the previous segment, and the type of the next segment. Use of the speed profile model provides a more detailed set of speeds for curves than the segments model and also consistently includes consideration of the speed on the previous segment as a factor.

These SHRP 2-data-based models were founded on data from many more vehicles and at more locations than was possible under previous research using traditional data collection methods. These models may be used on both existing and planned ramps, and the use of these predicted speeds in the design process for planned ramps may result in designs that more closely reflect driver behavior. The results from this research do not, by themselves, lead directly to specific recommendations for revisions to existing policies, such as the AASHTO *Green Book*. But, in conjunction with other recent and ongoing research efforts, such as those described in the Background, they may suggest that the process for determining freeway ramp design speed could be revised to consider new sources of operating speed data. Design speeds more directly related to known operating speeds have a greater potential to reinforce driver expectations, potentially reducing crashes and improving safety.

## Conclusions and Recommendations

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

- The SHRP 2 NDS database contains a vast amount of data and opens the door to "big data" research methods that would be impractical otherwise. Despite having more potential than traditional data collection methods, the SHRP 2 NDS dataset also comes with unique challenges that must be addressed, such as less certainty about the location of the vehicle and a decreased ability to regulate the quality of the data compared to direct data collection via traditional methods.

- The uncertainty associated with some variables in the SHRP 2 NDS dataset led to a degree of high noise level in the raw data that made it impossible to identify either the superelevation of the ramps or the radius.
- The SHRP 2 NDS time series dataset 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 SHRP 2 NDS provided a robust data source with regard to the amount and detail of data available compared to what is available in the data typically collected through traditional 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. A future research study could further explore the optimal number of speed readings that provide a balance between a robust dataset and significant results.
- Of the variables examined for this study, curve radius, as expected, 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 on freeway ramps are influenced more by where they are going than where they have been 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.
- Compared to existing AASHTO policy on selecting freeway ramp design speed, the models developed in this project can contribute to a process that more thoroughly integrates driver behavior into the speeds that can be expected on a given ramp, as they are based on a much higher magnitude of driving data (i.e., more vehicles, more types of vehicles, and more locations) than available in previous research. Developing such a process would be an objective of a future research project.

# Additional Products

The Education and Workforce Development (EWD) and Technology Transfer (T2) products created as part of this project can be downloaded from the Safe-D website here. The final project dataset is located in the Safe-D Collection of the VTTI Dataverse.

## Education and Workforce Development Products

This project incorporated the research activities for the Ph.D. dissertation of the Principal Investigator (Marcus Brewer), and it provided the opportunity for a master's student (Jayson Stibbe) to develop a proposal for his own thesis. Stibbe's thesis has been completed and Brewer's dissertation is in development; both will be published according to the requirements of the Zachry Department of Civil Engineering at Texas A&M University.

## Technology Transfer Products

In addition to the final research report, the dissertation, and the master's thesis, researchers submitted two technical papers to the 2019 TRB Annual Meeting for presentation and publication in the *Transportation Research Record*. Paper #19-05389, "Processing SHRP 2 Time-Series Data to Facilitate Analysis of Relationships Between Speed and Roadway Characteristics," discusses details of the data collection and reduction process; it was accepted for presentation at the Annual Meeting and inclusion in the meeting compendium [*10*]. Paper #19-05395, "Investigation of Design Speed Characteristics on Freeway Ramps Using SHRP 2 Naturalistic Driving Data," provides an overview of the entire project, focusing on activities and findings not contained in Paper #19-05389; this overview paper was accepted for presentation at the Annual Meeting and publication in the *Transportation Research Record* [***Error! Bookmark not defined.***].

The research team will also consider other venues, such as the ASCE *Journal of Transportation Engineering* and similar professional conferences and publication series for future submissions and technology transfer. As appropriate, the principal investigator will also share any suggested revisions to the AASHTO *Green Book* with AASHTO's Technical Committee on Geometric Design, either by correspondence or by presentation at a future committee meeting, in conjunction with similar ongoing research.

## Data Products

Data files generated as a result of this project's activities have been uploaded to the Safe-D Dataverse and can be found at this link: https://doi.org/10.15787/VTT1/K11ULD. Data files included in the Dataverse from this project include:

- Four text files containing the site characteristics and speed variables data for trips on entrance and exit ramps used in the study. Each file is a text version of the spreadsheet used in the project analyses, and each file can be opened in Microsoft Excel as a tab-delimited file to facilitate use and analysis. The four files are as follows:

- EntranceRamps1.txt: The file contains all of the entrance ramp data that can be included in a single Microsoft Excel workbook (.xlsx) within its limit of 1,048,576 rows.
- EntranceRamps2.txt: The file contains all of the entrance ramp data that could not be included in EntranceRamps1 due to file size restrictions.
- ExitRamps1.txt: The file contains all of the exit ramp data that can be included in a single Microsoft Excel workbook (.xlsx) within its limit of 1,048,576 rows.
- EntranceRamps2.txt: The file contains all of the exit ramp data that could not be included in ExitRamps1 due to file size restrictions.

- RampList.txt: A text file containing a list of the ramps selected for use in the study. The list includes descriptors such as city and state, LinkID, origin and destination routes, and lat/long coordinates. The list also contains the site characteristics variables that were used in the analysis of the trip data in the EntranceRamps and ExitRamps files.
- Data Dictionary: A Microsoft Word file containing a brief project description, the data scope, and a Data Specification table that lists each of the variables used in the analysis, along with a brief description of each variable, its units of measurement, and the range of values for that variable within the database.

# Appendix A: Discussion of Data Collection Methods

The use of SHRP 2 NDS data represents a potential for a tremendous improvement in the methods by which data are collected for these types of projects. Traditionally, speed-distance data are collected through one or more of the following methods: instrumented vehicles, lidar profiles, or road sensor spot-speeds. For freeway ramps, which often have substantial curvature and have lengths of a half-mile or more, the data collection process typically requires multiple methods in combination to compile a meaningful dataset.

Lidar guns, commonly referred to as laser guns, can measure vehicles' speed and distance, 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 will still require 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 A1) 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 include 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.

**Figure A1. Example of road tubes installation.**

(Image Credit: Marcus Brewer)

Field observational measurements as described above can capture speed and position changes on a macroscopic level. Only observations made in-vehicle 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. Primarily, the computer records basic driving data such as speed, brake and throttle position, and steering wheel angle, though numerous other data variables can be collected and recorded as well, depending on the sensors and cameras used in a particular system.

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.

The NDS study used an expanded version of the instrumented vehicle method described in Appendix A, in that it installed DAS and sensor equipment in the personal vehicles of each of the thousands of participant drivers and recorded their everyday driving activity. Examples and schematics of some of the sensor installations are shown in Figure A2 and Figure A3 [*12*]. The

DAS continuously recorded data whenever the participant's vehicle was in operation, enabling an exposure-based approach that documented conditions prior to crash events and other incidents. The central computer, or main unit, encrypted and recorded all data on a removable hard drive that was replaced every 4–6 months. The camera units shown in Figure A2 recorded images in many directions: the forward view from the front windshield; the view of the driver; the view of the left, right, and rear side of the vehicle; and the view of the vehicle's instrument panel.

PHOTOS: SHRP 2


(*Left:*) A forward radar unit, mounted near the license plate, is among the data-gathering devices installed in participant vehicles.

(*Right:*) A head unit, attached near the rear-view mirror, comprises cameras recording four different fields of view. It also receives data from accelerometers and a passive alcohol sensor.

**Figure A2. Radar and camera units used in the SHRP 2 Naturalistic Driving Study.**

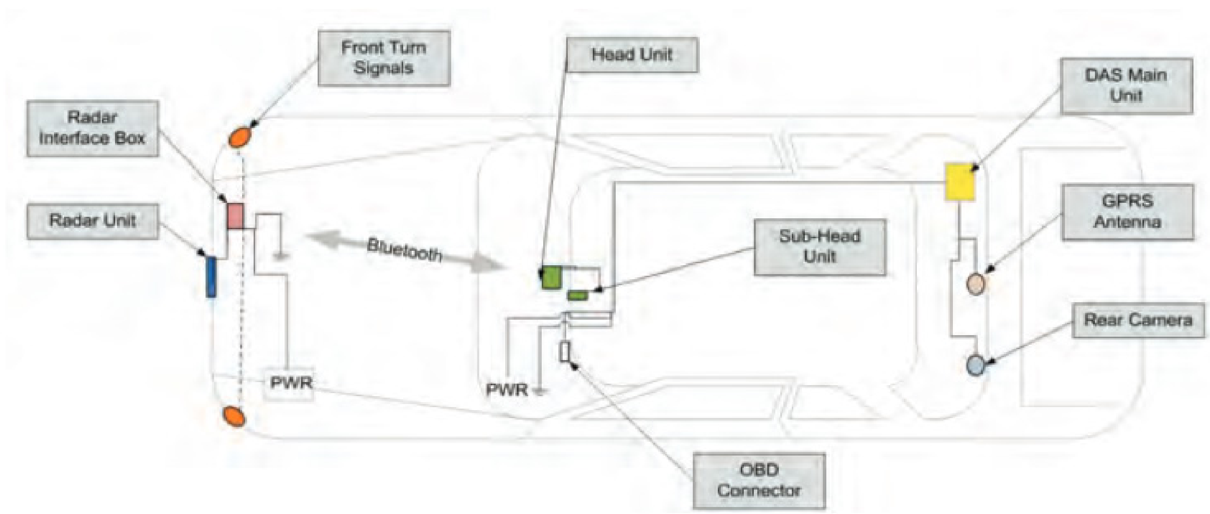


**Figure A3. Schematic view of data acquisition system used in SHRP 2 NDS.**

A fifth camera took still images of the vehicle's interior at intervals of a few seconds to document passengers in the vehicle, though the images were blurred to prevent recognition of those passengers by others [*12*]. The result of the data acquisition process is an in-vehicle system that continuously records several dozen channels of data, including:

- Multiple videos
- Machine vision
- GPS: latitude, longitude, elevation, time, velocity
- Lane tracker
- Accelerometer data (3-axis)
- Rate sensors (3-axis)
- Vehicle speed

- Other vehicle network data
- X and Y positions
- X and Y velocities
- Accelerator pedal
- Brake pedal
- Automatic braking system
- Gear position
- Steering wheel angle

While analyzing the circumstances surrounding a crash is valuable and indeed was one of the primary motives behind the development of this database [*5*], the SHRP 2 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, such as freeway ramp operations.

# Appendix B: Summary of Variables Used in Compared Models

Table B1 and Table B2 provide a summary of the input and output variables for each of the four models compared in the project:

- SHRP 2 Segments – the model for curve and tangent segments developed in this project based on SHRP 2 data, described in Equations 8 through 11.
- SHRP 2 Speed Profile – the speed profile model for segment quarter-points developed in this project based on SHRP 2 data, described in Equations 12 and 13 and Table 4.
- NCHRP 3-105 – the model developed in NCHRP Project 3-105, described in Equations 1 through 4.
- NCHRP 17-45 – the model developed in NCHRP Project 17-45, described in Table B1 and Table B2.

**Table B1. Variables in Each Entrance Ramp Model**

| Variable | SHRP 2 Segments | SHRP 2 Speed Profile | NCHRP 3-105 | NCHRP 17-45 |
|---|---|---|---|---|
| Traffic control at crossroad | ✓ | ✓ | | |
| Distance traveled through the ramp | ✓ | | | |
| Distance traveled through each segment | ✓ | | | |
| Radius of each curve | ✓ | ✓ | ✓ | ✓ |
| Freeway speed limit or operating speed | ✓ | | | ✓ |
| Speed at beginning of each curve | | ✓ | | ✓ |
| Speed at end of each curve | ✓ | ✓ | | |
| Type of previous segment (curve, tangent, or none) | ✓ | ✓ | | |
| Type of next segment (curve, tangent, or none) | ✓ | ✓ | | |
| Presence of a second lane | | | ✓ | |
| Lane width | | | ✓ | |
| Outside shoulder width | | | ✓ | |
| Inside shoulder width | | | ✓ | |
| Indicator variable for truck | | | ✓ | |
| Speed at crossroad | | | | ✓ |
| Milepoint at beginning of each curve | | | | ✓ |
| Length of each curve | | | | ✓ |
| *Average speed on each curve | ✓ | | | |
| *Speed profile on each tangent | ✓ | | | |
| *Speed at the quarter point of each segment (curves and tangents) | | ✓ | | |
| *Speed at midpoint of controlling curve | | | ✓ | |
| *Speed at end of controlling curve | | | ✓ | |
| *Speed at beginning and end of each curve | | | | ✓ |

**NOTE:** * indicates output variable of the model

**Table B2. Variables in Each Exit Ramp Model**

| Variable | SHRP 2 Segments | SHRP 2 Speed Profile | NCHRP 3-105 | NCHRP 17-45 |
|---|---|---|---|---|
| Traffic control at crossroad | ✓ | ✓ | | |
| Distance traveled through the ramp | ✓ | | | |
| Distance traveled through each segment | ✓ | | | |
| Radius of each curve | ✓ | ✓ | ✓ | ✓ |
| Freeway speed limit or operating speed | ✓ | | | ✓ |
| Speed at beginning of each curve | | ✓ | | ✓ |
| Speed at end of each curve | ✓ | ✓ | | |
| Type of previous segment (curve, tangent, or none) | ✓ | ✓ | | |
| Type of next segment (curve, tangent, or none) | ✓ | ✓ | | |
| Presence of a second lane | | | ✓ | |
| Indicator variable for simple curve radius | | | ✓ | |
| Outside shoulder width | | | ✓ | |
| Type of freeway speed-change lane | | | ✓ | |
| Indicator variable for truck | | | ✓ | |
| Speed at crossroad | | | | ✓ |
| Milepoint at beginning of each curve | | | | ✓ |
| Length of each curve | | | | ✓ |
| *Average speed on each curve | ✓ | | | |
| *Speed profile on each tangent | ✓ | | | |
| *Speed at the quarter point of each segment (curves and tangents) | | ✓ | | |
| *Speed at midpoint of controlling curve | | | ✓ | |
| *Speed at end of controlling curve | | | ✓ | |
| *Speed at beginning and end of each curve | | | | ✓ |

**NOTE:** * indicates output variable of the model

# Appendix C: Characteristics of Example Ramps and Results from Exit Ramp Model Comparison

The example ramps had the following characteristics:

- Freeway speed = 70 mph
- Crossroad traffic control = traffic signal (crossroad speed = 15 mph)
- Single travel lane with width = 12 ft
- Inside and outside shoulder width = 10 ft
- Ramp length of 0.40 mi, with a sequence of five segments on the ramp, beginning with a tangent and alternating between curve and tangent:
  - Entrance ramp:
    - Segment 1 Tangent: length = 0.12 mi
    - Segment 2 Curve: length = 0.05 mi, radius = 500 ft
    - Segment 3 Tangent: length = 0.09 mi
    - Segment 4 Curve: length = 0.06 mi, radius = 700 ft
    - Segment 5 Tangent: length = 0.08 mi
  - Exit ramp:
    - Segment 1 Tangent: length = 0.12 mi
    - Segment 2 Curve: length = 0.06 mi, radius = 700 ft
    - Segment 3 Tangent: length = 0.08 mi
    - Segment 4 Curve: length = 0.05 mi, radius = 500 ft
    - Segment 5 Tangent: length = 0.09 mi

Applying these ramp characteristics to each model produces operating speed calculations that are represented in Figure 4 and Table 4 through Table 7 for the entrance ramp and for the exit ramp, respectively.

Results in Figure C1 show the SHRP 2 speed profile model producing a plot with realistic speeds that are steadily decreasing throughout the entirety of the ramp, with minor variations in speed changes between curves and tangents. The SHRP 2 segments model has similar speeds at the beginning and end of the ramp, but the predicted speeds on the first curve and second tangent are much lower; similar to the entrance ramp segments model, the segments model for exit ramps produces only a single speed for a curve and does not have the previous segment's speed as a constraint, which results in a speed plot that has sizeable speed changes between tangents and curves, and duplicates the same speed profile for each curve.

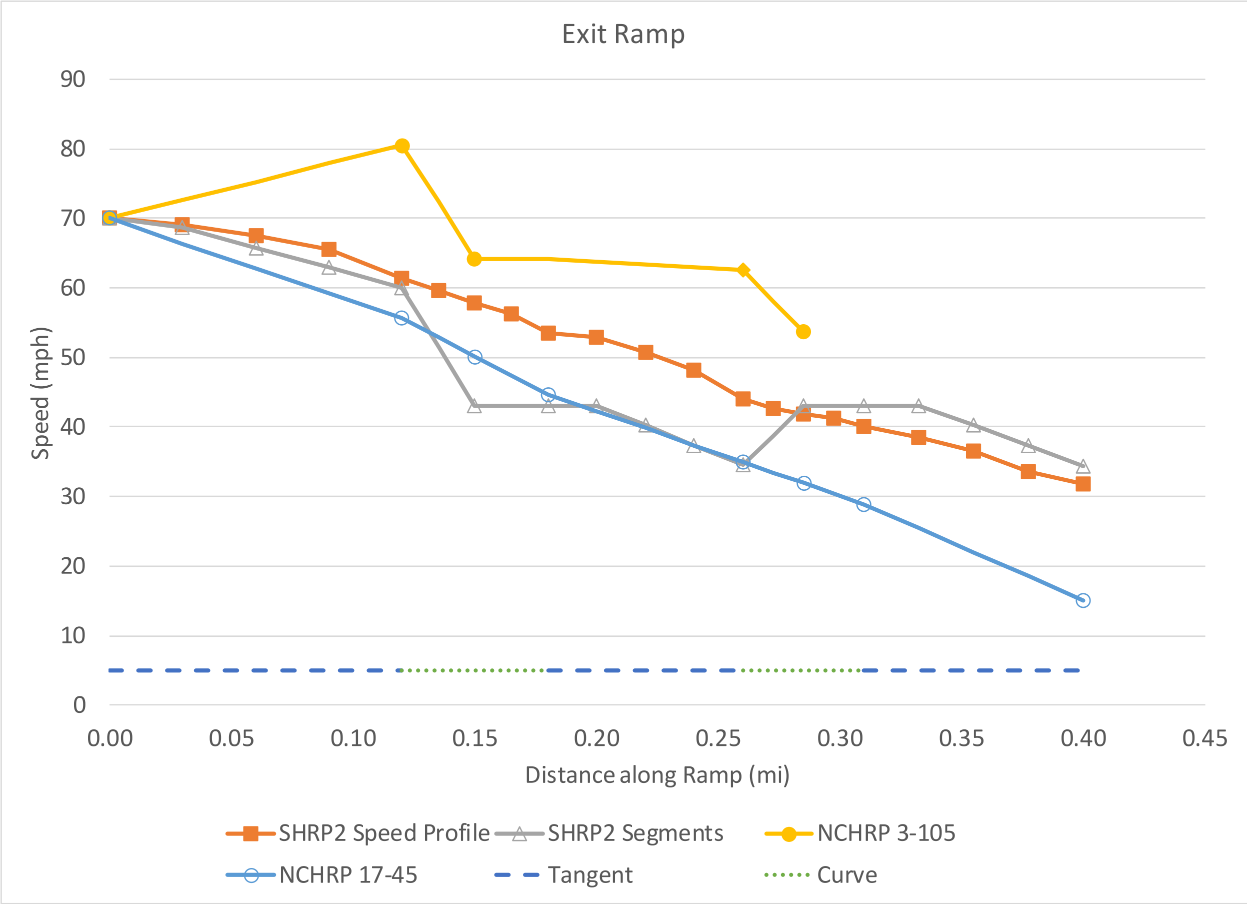


**Figure C1. Results from each model for example exit ramp.**

The NCHRP 3-105 model for exit ramps has the same limitation as the model for entrance ramps; it does not calculate speeds on tangents, so the plot for that model ends at the end of the final curve, and speeds on earlier tangents are calculated as averages between points of known speeds. Because the 3-105 model is primarily intended to calculate the speed on the controlling curve of a loop ramp, the use of the model on multiple curves on the same ramp may introduce some unintended effects that produce results noticeably different from the other three models plotted in Figure C1.

The NCHRP 17-45 model produced a plot that shows steady decreases in speed throughout the ramp, similar to the SHRP 2 speed profile model, but the speeds produced by the 17-45 model are consistently lower. The differences in deceleration rate between the two models reflect the speed data on which the models are based, but agreement between the shape of the two plots, which would be consistent with a steady, controlled deceleration throughout the ramp, suggests that the two models can provide similar bases for evaluating speeds on exit ramps.

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