GAP AT START OF A PASSING MANEUVER AS A FUNCTION OF LEAD VEHICLE SIZE AND POSTED SPEED LIMIT FOR FREEWAYS

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ABSTRACT

An important factor in maintaining safe headway in high-speed driving is the perceived speed of a lead vehicle looming into the view of a driver. This may be the result of the lead vehicle traveling slowly or being stopped. This research effort measured the distance, or time gap, at the point when a vehicle's driver-side front tire crossed the centerline during a passing maneuver on a freeway. This "passing gap" was measured by having researchers record the behavior of a following vehicle during a passing maneuver using video and a LIDAR gun. Researchers recorded 1,118 passes during 41 hours of daytime data collection. Evaluations, using speed difference between the lead vehicle and the following vehicle, found posted speed limit to be significant as part of a two-way interaction term that consisted of posted speed limit and lead vehicle size. At 80 mph, the passing gap to either a sedan or an RV was similar. For 70 mph, the passing gap was significantly different; drivers were closer to the RV than the sedan when passing. The statistical analyses indicated drivers passed more closely to the larger-profile vehicle than the smaller-profile vehicle. For example, one of the analyses found drivers were 282 ft from the sedan and only 238 ft from the RV when they passed, a difference of 56 ft. The passing gap increases approximately 8 to 10 ft for each mile-per-hour increase in the speed difference between the lead vehicle and the following vehicle. Stated in another manner, the faster a driver approaches a vehicle, the greater the passing gap distance.

Keywords: freeway driving, passing gap, following distance

INTRODUCTION

An important factor in high-speed driving is the perceived speed of a lead vehicle looming into the view of a driver because it is traveling slowly or is stopped. Are the decisions made by a passing driver similar regardless of the speed of the lead vehicle, the speed of the passing vehicle, or size of the lead vehicle? If not, what driver or roadway characteristics influence the passing behavior?

To answer these questions, this research effort measured the distance at the point when the vehicle's driver-side front tire crossed the centerline during a passing maneuver on a freeway. This "passing gap" was measured by having staff record the behavior of a following vehicle during a passing maneuver. For this study passing gap was defined as being the distance between the rear of the lead vehicle and the front bumper of the following vehicle at the initiation of a pass. For the current effort, two instrumented vehicles of different sizes were used as probe vehicles moving in traffic. A video camera was used to record the area behind the instrumented vehicles, and a LIDAR (Light Detection and Ranging) instrument/gun was used to measure distance.

STUDY OBJECTIVES

The goal of a Texas Department of Transportation study (Fitzpatrick 2009) was to gain a better understanding of driver performance at high speeds. One of the objectives was to identify whether operating speed affects the following distance (or gaps) at passing. This paper reports on the measured passing gaps of vehicles on freeway sections with daytime posted speeds of 70 and 80 mph. If the passing gap distances were found to differ based upon the operating speed, differences in driver workload may be the cause. For this reason the following research questions were investigated:

- Is there a difference in passing gap between 70- and 80-mph daytime posted speed limit conditions?
- Do the following variables influence the passing gap:
    - speed of the lead vehicle,
    - speed of the following vehicle,
    - width of the lead vehicle,
    - type of the following vehicle (e.g., passenger car versus large truck),
    - roadway geometry (tangent, curve to left, or curve to right), or
    - traffic conditions (restricted, i.e., traffic conditions in the adjacent lane affect the ability to pass, or not restricted)?

LITERATURE REVIEW

As discussed by Olson and Farber (2003), driver judgment of the speed of other vehicles is generally less reliable than judgment of distance, especially when the other vehicle is moving directly toward or away from the observer. The cues drivers use to judge speed include the rate of increase or decrease in the angular size of the vehicle as it comes closer or moves farther away. Stated in another manner, if the object seems to be getting larger, it means the distance is closing.

When the path of the other vehicle is almost directly ahead of the observer, the primary closing rate cue—and perhaps the sole cue—is rate of change of image size. That is, if the object seems to be getting larger fast, that indicates a high closing speed. As noted by Olson and Farber, the difficulty is that this cue to closing speed depends not only on closing speed but also on separation distance. At large separation distances, the apparent size changes slowly and non linearly. Imagine that a stopped vehicle first comes into view when it is 1000 ft away. As the observer continues to travel closer to the stopped vehicle the image size changes as shown in Figure 1. The fact that it is a nonlinear relationship adds to the difficulty drivers have in making accurate estimates of closing speed especially at farther separation distances.

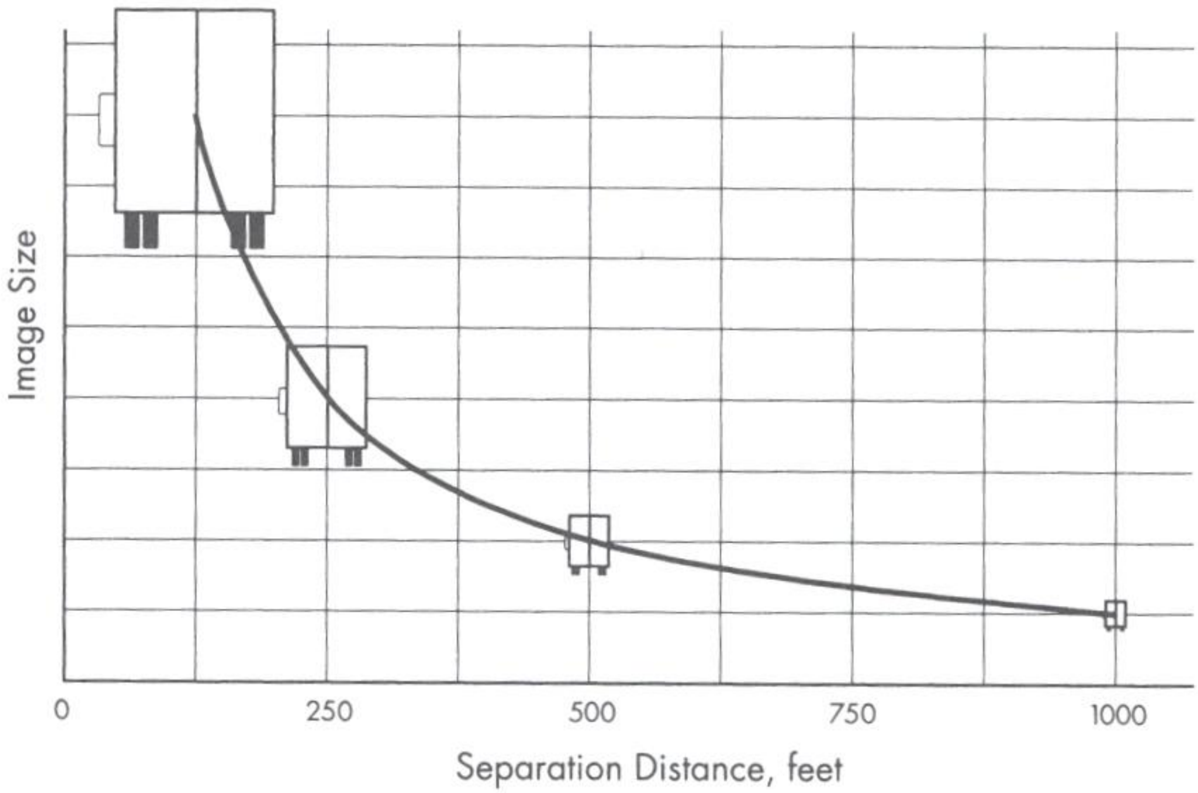


Figure 1. The Relationship between Viewing Distance and Image Size (Olson 2003).

Olson and Farber (2003) provide the following equation to estimate the distance at which drivers approaching a slower-moving vehicle can first begin to sense the closing rate:

$$D_{th} = (W\,V / 0.003)^{0.5} \quad (1)$$

Where:

D_{th} = threshold distance (ft),
W = width of the target vehicle (ft), and
V = closing rate (ft/sec).

Olson and Farber emphasize that the distance given by this equation is *not* the distance at which a driver can first determine that he or she is closing on a slower vehicle. The equation estimates the distance at which a driver overtaking a stationary or slower-moving vehicle first realizes how rapidly the spacing is closing, and that some response is required in the next few seconds.

Numerical examples are given in Table 1 for several combinations of vehicle widths and speeds. Note that the threshold distance increases with the speed but not proportionally. The time separations corresponding to the distances are also listed in Table 1. The result is that at higher speeds drivers have *less* time to respond even though they have more distance. Figure 1 illustrates that by the time a driver is close enough to a slower-moving or stopped vehicle to directly appreciate how rapidly the space is closing, the driver has limited time to respond. The situation becomes worse (i.e., time available is smaller) as closing speed increases and the size of the lead vehicle is smaller.

Past research has examined lead vehicle size. One naturalistic driving study conducted in Michigan (Sayer 2000) used participants who drove an instrumented passenger car, unaccompanied, as their personal vehicle for two to five weeks. One of the objectives of the study was to investigate how the driver's ability to see downstream traffic beyond the lead vehicle affects the driver's gap maintenance under optimal driving conditions (e.g., daytime, dry weather, free-flowing traffic). The results showed that passenger car drivers follow light trucks (defined as larger/taller vehicles that did not permit the following driver to see through them) at shorter distances than they follow passenger cars by an average of 19.6 ft.

The present study investigated gaps to a lead vehicle when beginning a pass on a freeway. The hypothesis was that this gap distance would depend on the speeds of the lead and passing vehicle as well as on the lead vehicle size. Based on the previous research described above we expected passing gaps to be shorter to large vehicles than to passenger cars. Further we expected passing gaps to be shorter at higher speeds because the driver judgment time of closing rate is constant and more distance is traveled in that fixed amount of time at higher speeds.

Table 1. Threshold Distance and Time Separation at Which Drivers Can First Judge Closing Rate with a Vehicle Directly Ahead (Olson 2003).

Target Vehicle Width (ft)	**45 mph**		**60 mph**		**75 mph**	
	Distance (ft)	**Time (sec)**	**Distance (ft)**	**Time (sec)**	**Distance (ft)**	**Time (sec)**
8 (tractor-trailer)	420	6.4	484	5.5	542	4.9
6 (passenger car, daytime)	363	5.5	420	4.8	469	4.3
5 (passenger car, nighttime)	332	5.0	383	4.4	428	3.9
2 (trailer, frame rail-mounted lights)	210	3.2	242	2.8	271	2.5

STUDY LOCATIONS

The route used in data collection included parts of I-10 and I-20 in West Texas:

- I-20 between Midland and Roscoe (70-mph section),
- I-20 between west of Odessa and the interchange of I-20 and I-10 (80-mph section), and
- I-10 between Sierra Blanca and Fort Stockton (80-mph section).

Data were collected in daylight hours only. The daytime posted speed limit was either 70 mph or 80 mph in the study section. For the 80-mph sections, the truck posted speed limit was 70 mph.

LEAD VEHICLES

Data were collected using two different vehicles to assess the effect of lead vehicle size—a large-profile vehicle and a small-profile vehicle. The large-profile vehicle was a Class C recreational vehicle (RV). A sedan (Dodge Caliber) was the small-profile vehicle. A photograph of the rear of each of the study vehicles is shown in Figure 2 along with the vehicle dimensions.

Dimensions	Sedan 2009 Dodge Caliber	RV C 25 Standard Motor Home
Length (ft)	14	25
Width (ft)	5.73	8.33
Height (ft)	5.03	12.00
Rear of Vehicle Area (ft^2)	28.82	99.96
Percent of (Rear of Vehicle Area) Largest Vehicle	29%	100%

Figure 2. Rear of Lead Vehicles.

DATA COLLECTION

Data collection consisted of a technician recording the distance to a following vehicle during a passing maneuver. Pilot tests of the data collection approach revealed that the lead vehicle would need to be driven at a speed less than the posted speed limit to ensure that passes would occur. The need to drive at less than the speed limit was especially important when the passenger car speed limit is 80 mph since the heavy-truck speed limit is 70 mph on those sections. The lead vehicle was operated at a target speed of 20 percent below the passenger car daytime speed limit. In the 70-mph sections the lead vehicle speed was about 56 mph, and in the 80-mph section the lead vehicle speed was typically 64 mph.

The distances to the following vehicle were collected using a LIDAR gun, which a researcher aimed out the rear window of the lead vehicle. The LIDAR gun can measure speed and distance to a vehicle three times per second. These data are then recorded on a laptop computer where comments regarding the following vehicle can be added to the file. A limitation with LIDAR is that it does not record measured speeds below 5 mph. Therefore, if the relative speed between the lead and following vehicles was less than 5 mph, no data would be recorded for the following vehicle. To avoid losing data for vehicles with less than a 5-mph speed difference, the researchers operated the LIDAR gun in distance mode only, which measured distance between the two vehicles even when relative speed was less than 5 mph. The relative speed and the following vehicle speed were then calculated using the distance and time measurements from the LIDAR and the known speed of the lead vehicle.

An onboard data acquisition system (DAS) was used to synchronize the lead vehicle speed from GPS data, and video feed from a rearward facing camera positioned in the lead vehicle. The video was used to classify the vehicle type of the passing vehicle as passenger car or heavy truck. It was also used to determine traffic conditions and roadway geometric characteristics. The data stream from the LIDAR gun could not be programmed into the system in time for this study; therefore, that data stream had to be manually matched to the DAS data through synchronizing clocks on the DAS and LIDAR computers. The video files also had the date and time captioned in text on the video frame.

Because the 80-mph sections had lower volumes, fewer passes typically occurred in an hour. Therefore, the study route was designed to spend more data collection time in the 80-mph sections. Also, to have greater opportunity to have higher volumes, and therefore more passing opportunities, data were collected on the weekends.

A total of 12 hours of data were available for the 70 mph sections and 29 hours for 80 mph sections.

DATA REDUCTION

Number of Passes

Table 2 lists the number of passes available for each lead vehicle type and posted speed limit combination. A total of 1118 vehicles making passes were videotaped as shown in the final row of Table 2. Not all of the passing gaps recorded on video could be used. A few of the passing gaps distances (about 1 percent) were not available because the vehicle changed lanes beyond the typical capability of the measuring device, which was about 700 ft. Distances for approximately another 15 percent of the gaps videotaped were not available because the researcher was occupied with recording information about a previous vehicle. Reviewing these passes on the video indicates that they were in the same general range as those vehicles whose distances were available. Approximately 83 percent of the passing gaps videotaped were available for the analyses, a total of 930 passes.

Data from Video and Supporting Files

The following data were obtained from watching the video, reviewing the timestamp captions on the video, and searching the dataset produced by the DAS:

- time when the driver-side front tire was centered over the roadway lane line (DWPtime) (see Figure 3(a) for an example),
- time when the passenger-side front tire was centered over the roadway lane line (PWPtime) (see Figure 3(b) for an example),
- lead vehicle speed,
- following vehicle type (car or heavy truck),
- traffic conditions (restrictions or no restrictions), and
- roadway geometry (curve to left, curve to right, or tangent).

Table 2. Number of Passes Observed during Study Period.

Data	**70 mph**				**80 mph**			
	Sedan		**RV**		**Sedan**		**RV**	
	Num	**%**	**Num**	**%**	**Num**	**%**	**Num**	**%**
Passes with distance collected (typically between 50 and 700 ft)	245	69%	211	91%	293	92%	182	86%
Passes within typical distance (e.g., within 50 to 700 ft) but distance measurement missed by technician	108	30%	20	9%	17	5%	25	12%
Passes beyond reading distance (typically >700 ft) where distance was not obtained	5	1%	1	0%	4	1%	4	2%
Passes too close to lead vehicle for measurement (<50 ft)	0	0%	0	0%	3	1%	0	0%
Total passes (by daytime posted speed limit and lead vehicle size)	358	100%	232	100%	317	100%	211	100%
Passes (by daytime posted speed limit)	590				528			
Passes (all conditions)	1118							

Data from LIDAR Files

The timestamp from the video when the following vehicle tire was on the lane line was used to identify the associated LIDAR readings for that vehicle. This video timestamp was recorded to the nearest second. The LIDAR readings typically had three distance readings for each second. The distances measured within the same second were averaged to provide the gap distance. This value was used as the distance between the lead vehicle and the following vehicle. It was also used to calculate the speed difference between the lead vehicle and the following vehicle.

(a) Driver-Side Front Tire Centered over the Roadway Lane Line

(b) Passenger-Side Front Tire Centered over the Roadway Lane Line

Figure 3. Examples of Video Views.

Traffic Conditions

The researchers judged whether other vehicles might have affected the decision of when to make a pass. An example of a situation when a traffic restriction was considered to be present was when vehicles passed both the lead vehicle (i.e., the vehicle with the research team) along with the following vehicle (i.e., the vehicle being measured). A situation when no restrictions were present was when there were no other vehicles in either lane within approximately 1000 ft of the lead and following vehicles.

Speed Difference between Lead and Following Vehicle

The speed of the lead vehicle was available from one of the input data streams to the DAS. The speed difference between the lead vehicle and the following vehicle was determined using the LIDAR readings. The calculations used the amount of time the following vehicle took to move the vehicle across the lane line during the passing maneuver, along with the distances measured by the LIDAR gun. The equation used to calculate the speed difference was:

$$SD = \frac{DWPgapL - PWPgapL}{PWPtime - DWPtime} \times \frac{3600\ sec/hour}{5280\ ft/mile} \quad (2)$$

Where:

SD = speed difference between the lead vehicle and following vehicle (mph),
DWPgapL = driver wheel passing gap measured by LIDAR gun (ft),
PWPgapL = passenger wheel passing gap measured by LIDAR gun (ft),
PWPtime = time when the passenger-side front tire is centered over the roadway lane line, and
DWPtime = time when the driver-side front tire is centered over the roadway lane line.

Following Vehicle Speed

The following vehicle speed was determined by adding the calculated speed difference from Equation 2 (between lead vehicle and following vehicle) to the lead vehicle speed.

$$FS = LS + SD \quad (3)$$

Where:

FS = speed of the following vehicle (mph),
LS = speed of the lead vehicle provided by the GPS unit (mph), and
SD = speed difference between the lead vehicle and following vehicle (mph).

Passing Gap Distance

To obtain the distance between the rear bumper of the lead vehicle and the front bumper of the following vehicle, the distance between the location of the LIDAR gun and the rear bumper of the lead vehicle had to be subtracted. The researcher was closer to the rear bumper in the RV as compared to in the sedan. When in the sedan, the LIDAR gun was 3 ft from the rear bumper. It was 1 ft from the rear bumper in the RV.

RESULTS

Potential Variables Influencing Passing Gap Distances

The following variables are available for investigating the influences on passing gap:

- daytime posted speed limit (70 or 80 mph),
- following vehicle speed (mph),
- lead vehicle speed (mph),
- lead vehicle size (sedan or RV),
- following vehicle type (passenger car or heavy truck),
- traffic conditions (restricted or not restricted),
- speed difference between the lead vehicle and following vehicle (mph),
- roadway geometry (tangent, curve to left, or curve to right).

The minimum driver-wheel passing gap measured was 31 ft, and the maximum in the dataset was 663 ft.

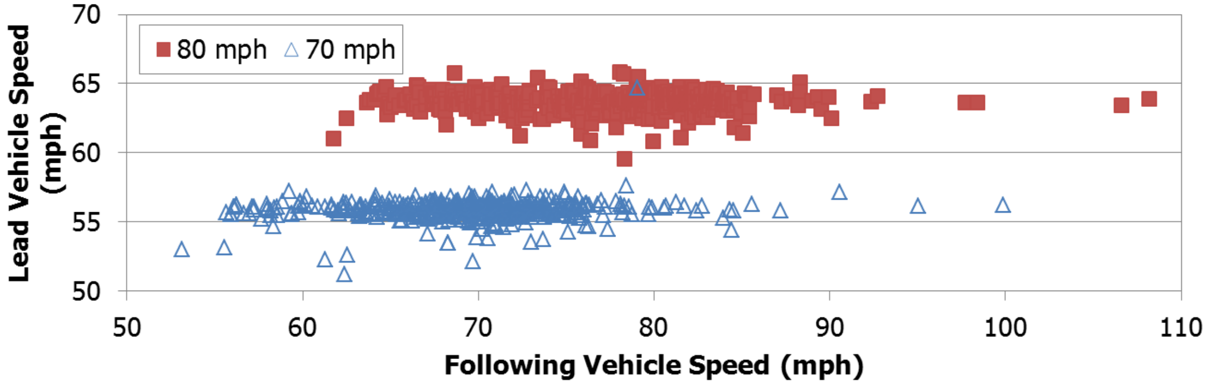
Figure 4 illustrates passing gap to speed data to provide an appreciation of potential relationships. Figure 4(a) shows the following vehicle speeds by lead vehicle speed. Recall the lead vehicle speed was set 20 percent below the posted speed limit via the vehicle's cruise control. The two groups of data shown illustrate the calculated following vehicle speeds for the two different posted speed limits. The spread of following vehicle speed was similar for both posted speed limit groups—about 50 mph. Typical speeds were centered about the posted speed limit.

Figure 4(b) shows the passing gaps (measured when the driver-side wheel of the passing vehicle crossed the lane line) as a function of following vehicle speed. The figure shows a wide dispersion of passing gap distances with a slight trend toward longer gaps at higher speeds. Note, however, that passing gaps of less than 100 ft were recorded for following vehicle speeds of up to 75 mph.

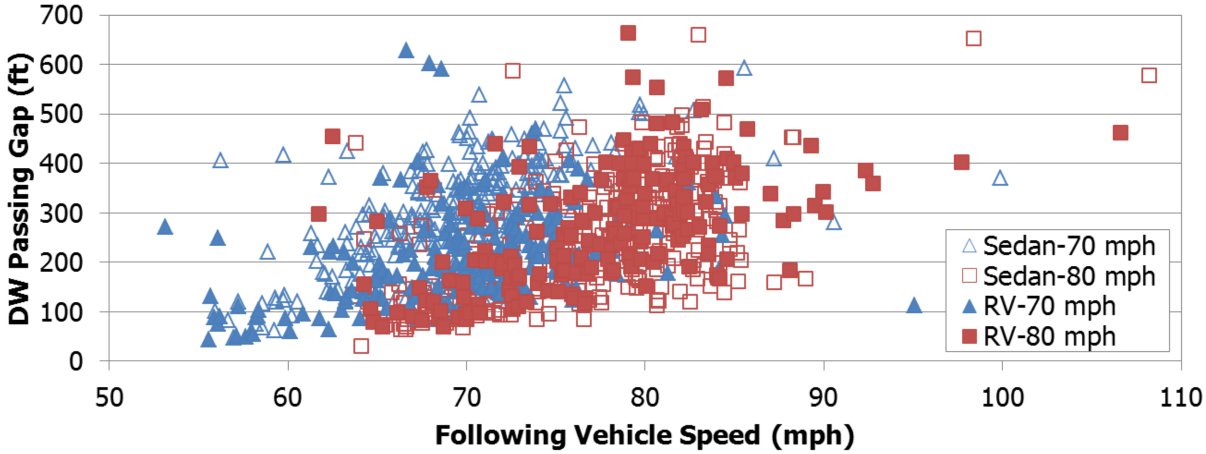
Figure 4(c) shows the passing gap as a function of the speed differential between the lead and following vehicle. Again, a wide dispersion in the data is evident with a slight trend toward larger gaps at higher-speed differentials.

Statistical Analysis

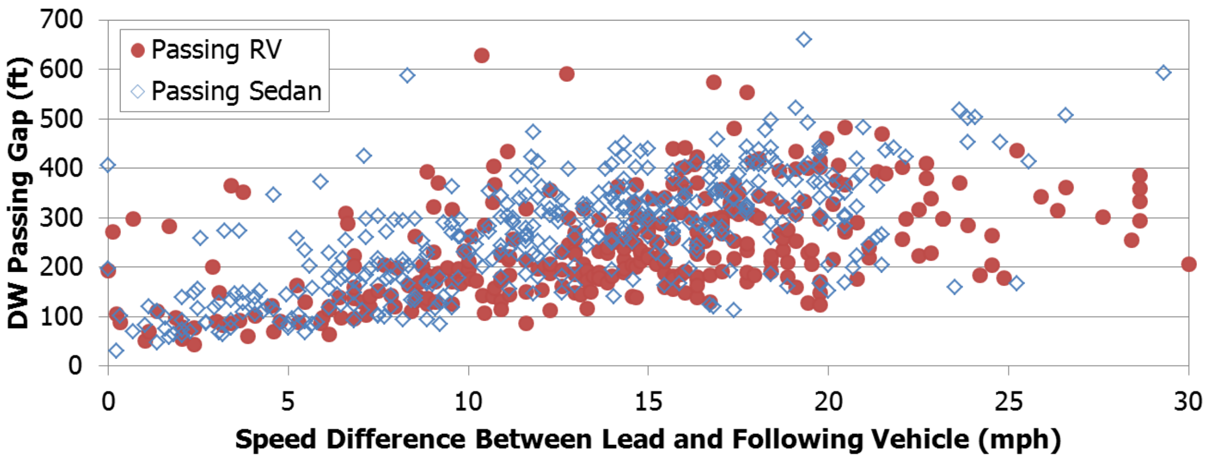
Researchers employed the Analysis of Covariance (ANACOVA) model to analyze the passing gap data because the set of candidate variables presumed to affect the passing gap includes both continuous and discrete variables. The JMP statistical package (SAS product) was used to run the ANACOVA. Analyses of the passing gap data began with considering which variables to include in the models. The speed measurements—following vehicle speed, lead vehicle speed, and speed difference—were all intercorrelated since following speed and speed difference were calculated based on the measured lead vehicle speed. Therefore, at most, two of the measurements could be included in the model. Models were tried with either speed difference only or with lead and following vehicle speeds.



(a) Lead Vehicle Speed by Following Vehicle Speed



(b) Driver-Wheel (DW) Passing Gap by Following Vehicle Speed



(c) Driver-Wheel Passing Gap by Speed Difference

Figure 4. Plots of Passing Gaps by Vehicle Speed.

Findings with Lead and Following Vehicle Speeds

Preliminary evaluations using lead and following vehicle speeds indicated relationships between variables were different depending upon the posted speed; in other words, there were significant two-way interactions between posted speed and other variables. The patterns of passing behavior were different for the two different posted speeds. Therefore, the dataset was split into a 70-mph dataset and an 80-mph dataset. For the 70 mph dataset, the following two-way interactions were also found to be statistically significant (see Table 3):

- following vehicle speed with lead vehicle size,
- following vehicle speed with traffic conditions, and
- lead vehicle size with traffic conditions.

The findings indicate that, overall, drivers will drive closer to a large-profile vehicle (the RV) than to a small-profile vehicle (sedan); although, there was a significant two-way interaction between lead vehicle size and traffic conditions. Table 4 provides the overall predicted mean passing gap of 224 ft to the RV and 311 ft to the sedan, a difference of 87 ft.

When traffic is present in the neighboring lane (i.e., restricted traffic conditions), drivers left a shorter distance to the RV (214 ft versus 233 ft, closer by a distance of 19 ft). Drivers left a slightly longer distance to the sedan, however, when traffic is not restricted (325 ft versus 297 ft, an increase distance of 28 ft). As illustrated by the letter coding in Table 4, the Tukey's Honestly Significant Difference (Tukey's HSD) multiple comparison analysis indicates the passing gap distance to the RV is significantly different than the distance to the sedan; however, the gap distances subdivided by the potential effects of traffic were not significantly different (since the levels were connected by the same letters). So even though the plot of the lines for non-restricted traffic and restricted traffic cross (see Figure 5), the Tukey HSD test did not find significant differences between the passing gap distances for the different traffic conditions. Given that drivers can modify their gap distance whether another vehicle is or is not located in the neighboring lane, it is logical that drivers are not adjusting their passing gap distance just because of the presence of other traffic. On the other hand, when traffic is restricted the difference in the passing gap distance between Sedan and RV is about 63 ft (297 ft versus 233 ft) while the difference is much larger (about 111 ft, 325 ft versus 214 ft) when traffic is not restricted.

The type of vehicle doing the passing was also significant. When cars are passing the lead vehicle, the predicted mean passing gap was 257 ft. Heavy trucks had a longer predicted mean passing gap of 278 ft. This finding indicates that heavy trucks began their passing maneuvers at a greater distance upstream regardless of the type of vehicle that was being passed.

The evaluations of the 80-mph data provided a fairly different result as compared to the 70-mph results. Only two variables were significant when main effects or when all potential two-way interaction terms are considered. The significant variables when examining the 80-mph data only are:

- following vehicle speed and
- lead vehicle speed.

Table 3. Model for Passing Gaps for 70-mph Data with Significant Interactions and Main Effects.

Response DWPgap
Summary of Fit

RSquare	0.446953
RSquare Adj	0.437055
Root Mean Square Error	84.34234
Mean of Response	263.8004
Observations (or Sum Wgts)	456

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	2569792.1	321224	45.1561
Error	447	3179792.8	7114	**Prob > F**
C. Total	455	5749584.8		<0.0001*

Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	446	3179774.8	7129.54	396.0855
Pure Error	1	18.0	18.00	**Prob > F**
Total Error	447	3179792.8		0.0401*
				Max RSq
				1.0000

Parameter Estimates

Term	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	508.73662	261.8408	1.94	0.0527
Following Vehicle Speed	10.315556	0.791687	13.03	<0.0001*
Lead Vehicle Speed	−17.16895	4.799714	−3.58	0.0004*
Lead Vehicle Size (RV)	−43.4789	5.081799	−8.56	<0.0001*
Following Vehicle Type (Car)	−10.11529	4.65739	−2.17	0.0304*
Traffic Conditions (Not Restricted)	2.1022392	5.383448	0.39	0.6964
(Following Vehicle Speed − 69.5964) * Lead Vehicle Size (RV)	−2.561884	0.697084	−3.68	0.0003*
(Following Vehicle Speed − 69.5964) * Traffic Conditions (Not Restricted)	−2.352683	0.763436	−3.08	0.0022*
Lead Vehicle Size (RV) * Traffic Conditions (Not Restricted)	−12.05865	5.187582	−2.32	0.0205*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Following Vehicle Speed	1	1	1207728.6	169.7767	<0.0001*
Lead Vehicle Speed	1	1	91022.4	12.7955	0.0004*
Lead Vehicle Size	1	1	520731.1	73.2019	<0.0001*
Following Vehicle Type	1	1	33555.4	4.7171	0.0304*
Traffic Conditions	1	1	1084.8	0.1525	0.6964
Following Vehicle Speed * Lead Vehicle Size	1	1	96081.7	13.5067	0.0003*
Following Vehicle Speed * Traffic Conditions	1	1	67557.4	9.4969	0.0022*
Lead Vehicle Size * Traffic Conditions	1	1	38437.8	5.4034	0.0205*

Table 4. Model for Passing Gaps for 70-mph Data Least Squares Mean Tables.

Lead Vehicle Size

Level	Least Sq. Mean	Std. Error	Mean
RV	223.98658	7.8175942	215.474
Sedan	310.94438	7.4441251	305.420

Following Vehicle

Level	Least Sq. Mean	Std. Error	Mean
Car	257.35019	6.0650040	266.889
Heavy Truck	277.58077	8.4545079	255.439

Traffic Conditions

Level	Least Sq. Mean	Std. Error	Mean
Not Restricted	269.56772	4.9845683	273.345
Restricted	265.36324	9.8993699	225.516

Lead Vehicle Size * Traffic Conditions

Level	Least Sq. Mean	Std. Error
RV, Not Restricted	214.03017	6.908830
RV, Restricted	233.94299	13.926771
Sedan, Not Restricted	325.10527	6.595450
Sedan, Restricted	296.78350	13.093616

LS Means Differences Tukey HSD

Level			Least Sq. Mean
Sedan, Not Restricted	A		325.10527
Sedan, Restricted	A		296.78350
RV, Restricted		B	233.94299
RV, Not Restricted		B	214.03017

Levels not connected by same letter are significantly different.

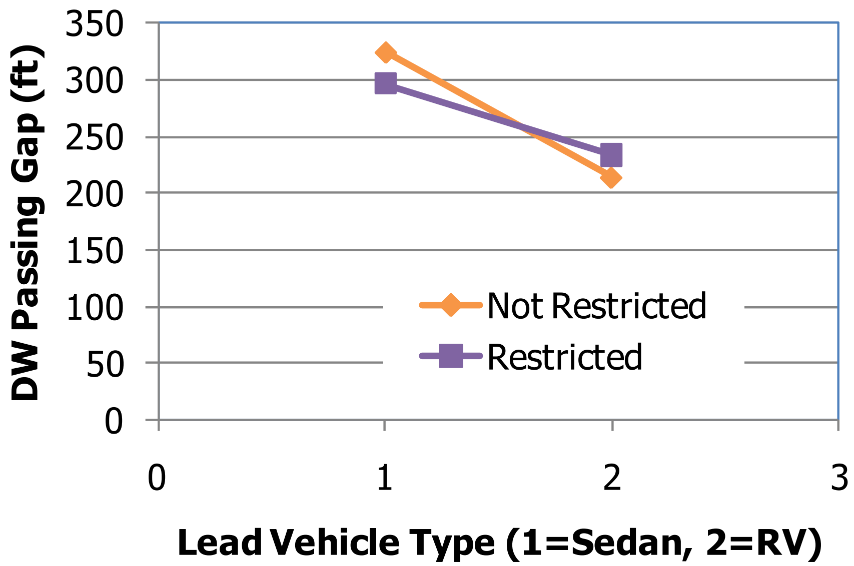


Figure 5. Lead Vehicle Size by Traffic Conditions, Shown as X Y Scatter.

Findings with Speed Difference

Investigations were also conducted using speed difference rather than the lead and following vehicle speeds as predictor variables. The speed difference variable combines these two variables into a single value. The analyses considered all possible two-way interactions along with the main effects. The following two-way interactions were significant:

- posted speed limit with lead vehicle size and
- speed difference with lead vehicle size.

Table 5 lists the results of the model for passing gaps while Table 6 provides the least square means results. Figure 6 illustrates the least square means results.

A method to gain a better understanding of the relationships revealed by the statistical analysis is to develop an equation using the coefficients for the parameters. Based on the model in Table 5, the equation to predict the passing gap distance is:

$$P{:}DWPgap = 127.09 + 9.81(SD) - 21.84(ILV) - 0.73(IPSL) - 27.32(IPSL)(ILV) - 1.89(ILV)(SD - 13.5548) \quad (4)$$

Where:

P:DWPgap	=	predicted driver wheel passing gap (ft);
SD	=	speed difference between the lead vehicle and following vehicle (mph);
ILV	=	indicator variable for lead vehicle size, ILV = 1 when lead vehicle is RV, 0 when lead vehicle is sedan; and
IPSL	=	indicator variable for posted speed limit, IPSL = 1 when posted speed limit is 70 mph, 0 when PSL is 80 mph.

The equation demonstrates the importance of the speed difference term. The term with the most potential to change the predicted gap distance is speed difference. The passing gap distance increases by approximately 10 ft and 8 ft, respectively, for Sedan and RV, for each additional mile-per-hour difference between the lead vehicle and the following vehicle.

The type of the following vehicle (car or heavy truck) was not significant in this analysis. Recall, however, that following vehicle type was significant when evaluating the effect of it along with following vehicle speed and lead vehicle speed based on only the 70-mph dataset.

The lead vehicle size is also influential, both as a main effect variable (coefficient of −21.84) and as part of a two-way interaction variable (coefficient of −27.32) with daytime posted speed limit. For example, passing an RV on a 70-mph section reduces the predicted passing gap by 49.89 ft (21.84 + 27.32 + 0.73 ft).

Table 5. Model with Significant Interactions and Main Effects Using Speed Difference and Both 70- and 80-mph Data.

Response DWPgap
Summary of Fit

RSquare	0.375966
RSquare Adj	0.372582
Root Mean Square Error	91.08311
Mean of Response	260.2112
Observations (or Sum Wgts)	928

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	4608372	921674	111.0969
Error	922	7649034	8296	**Prob > F**
C. Total	927	12257407		<0.0001*

Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	793	6613484.0	8339.83	1.0389
Pure Error	129	1035550.3	8027.52	**Prob > F**
Total Error	922	7649034.2		0.4011
				Max RSq
				0.9155

Parameter Estimates

Term	Estimate	Std. Error	t Ratio	Prob>|t|
Intercept	127.08777	7.383522	17.21	<0.0001*
Daytime Posted Speed Limit (70 mph)	−0.732899	3.03712	−0.24	0.8094
Speed Difference	9.806964	0.49091	19.98	<0.0001*
Lead Vehicle Size (RV)	−21.84217	3.047806	−7.17	<0.0001*
Daytime Posted Speed Limit (70 mph) * Lead Vehicle Size (RV)	−27.31723	3.03712	−8.99	<0.0001*
(Speed Difference − 13.5548) * Lead Vehicle Size (RV)	−1.888759	0.49091	−3.85	0.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Daytime Posted Speed Limit	1	1	483.1	0.0582	0.8094
Speed Difference	1	1	3310862.0	399.0850	<0.0001*
Lead Vehicle Size	1	1	426081.2	51.3590	<0.0001*
Daytime Posted Speed Limit * Lead Vehicle Size	1	1	671158.5	80.9002	<0.0001*
Speed Difference * Lead Vehicle Size	1	1	122807.5	14.8030	0.0001*

Table 6. Least Squares Mean Tables for Model with Speed Difference.

Daytime Posted Speed Limit

Level	Least Sq. Mean	Std. Error	Mean
70 mph	259.28669	4.2852412	263.800
80 mph	260.75249	4.3200872	256.744

Lead Vehicle Size

Level	Least Sq. Mean	Std. Error	Mean
RV	238.17742	4.6351172	240.860
Sedan	281.86175	3.9588103	274.364

Daytime Posted Speed Limit * Lead Vehicle Size

Level	Least Sq. Mean	Std. Error
70 mph, RV	210.12729	6.2898964
70 mph, Sedan	308.44609	5.8215437
80 mph, RV	266.22755	6.7814290
80 mph, Sedan	255.27742	5.3539549

LS Means Differences Tukey HSD

Level				Least Sq. Mean
70 mph, Sedan	A			308.44609
80 mph, RV		B		266.22755
80 mph, Sedan		B		255.27742
70 mph, RV			C	210.12729

Levels not connected by same letter are significantly different.

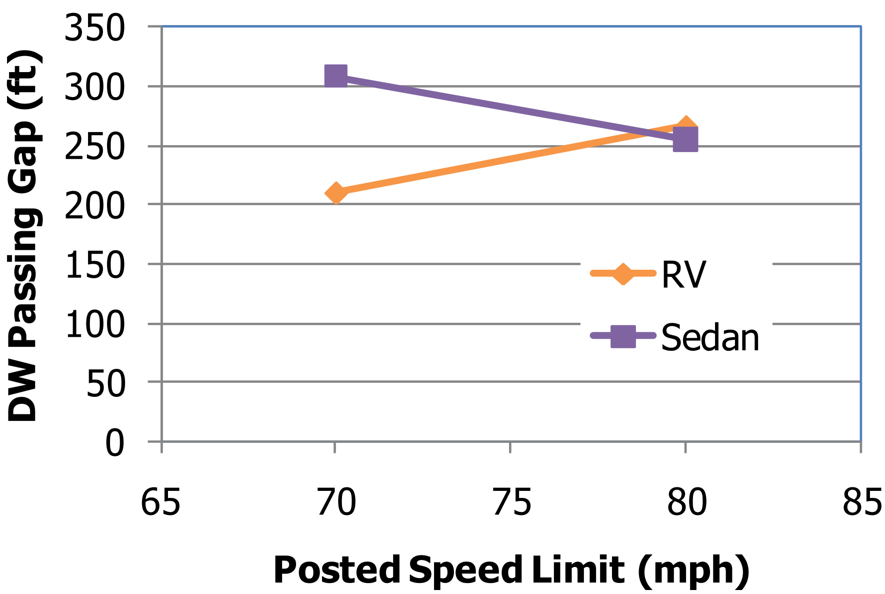


Figure 6. Posted Speed Limit by Lead Vehicle Size, Shown as X Y Scatter.

The size of the lead vehicle was a significant variable. Similar to the previous analysis, the findings were that drivers came closer to the larger vehicle (RV) as compared to the sedan. The predicted mean gap distance was 238 ft to the RV and 282 ft to the sedan. Drivers were 44 ft closer to the RV as compared to the sedan. The two-way interaction between posted speed limit and lead vehicle size reveals another interesting finding.

The posted speed limit was significant when crossed with the lead vehicle size. Figure 6 shows a plot that illustrates the relationship. The passing gap to an RV or to a sedan was similar for the vehicles in the 80-mph sections (266 and 255 ft, which the Tukey HSD found to be not significantly different; see Table 6). A different relationship was found for the vehicles in the 70-mph sections. Drivers in the 70-mph section drove closer to the RV (predicted mean distance of 210 ft) as compared to the sedan (predicted mean distance of 308 ft).

Another interaction was between speed difference and lead vehicle size. When the lead vehicle was the RV, the regression coefficient indicates that there was a 1.89-ft less change (compared to Sedan) in passing gap distance for each 1-mph change in speed difference.

COMPARISON WITH LITERATURE

Figure 7 lists the distance and time separation at which drivers can first judge closing rate with a vehicle directly ahead based on the methodology presented by Olson and Farber (2003) and using typical speed differences found in this research. Their method determined the threshold for detecting speed discrepancies in car-following studies. The distances in Figure 7 represent the value when drivers realize (based on previous research findings) that they need to take an action. These calculated distance separation, which range from 143 to 319 ft for the RV and 118 to 265 ft for the sedan, are generally much less than the typical passing gap distances found in this study (260 ft). In general, drivers in this Texas study were initiating their passing maneuvers before coming so close to the preceding vehicle that they "reach the point when they realize how rapidly the spacing is closing and that some response is required in the next few seconds" (Olson 2003).

The evaluations of the data from this passing gap study included identifying regression coefficients that can be used to predict the passing gap for various conditions. When the regression equation is used, a slightly different finding is determined for specific posted speed limit and vehicle type combinations as compared to the general findings that drivers are passing before reaching the point when a response is required. Drivers passing the sedan did so within the suggested distance separation; however, when drivers were passing the RV on the 70-mph section, they were within the distance suggested by Olson and Farber as needing a response. Drivers passing the RV in the 80 mph section were also very near the decision point.

Target Vehicle Width (ft)	**8.33 (Recreational Vehicle)**					**5.73 (Sedan)**				
Speed Difference (mph)	5	10	15	20	25	5	10	15	20	25
Olson and Farber (2003) Time Separation (sec)	19.5	13.8	11.2	9.7	8.7	16.1	11.4	9.3	8.1	7.2
Olson and Farber (2003) Distance Separation (ft)	143	202	247	285	319	118	167	205	237	265
Typical Passing Gaps Using Regression from This Study for 70 mph PSL (ft)	142	182	222	261	301	175	224	273	322	372
Typical Passing Gaps Using Regression from This Study for 80 mph PSL (ft)	170	210	250	289	329	176	225	274	323	372

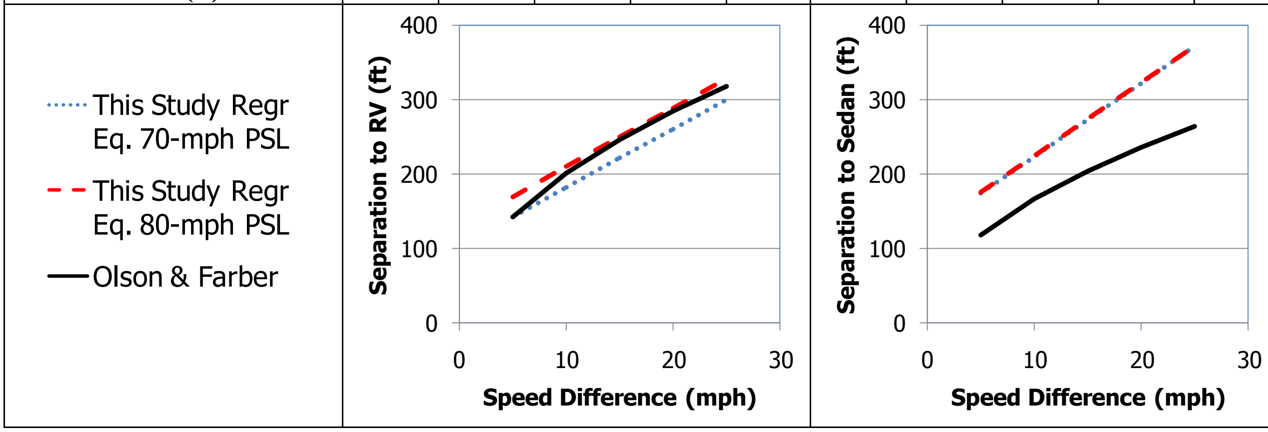


Figure 7. Distance and Time Separation at Which Drivers Can First Judge Closing Rate with a Vehicle Directly Ahead Using Equation from Olson and Farber (2003) and the Vehicle Size and Speed Differences Found in This Research.

CONCLUSIONS

Based on the results from the various analyses of the passing gap data, researchers drew the following conclusions:

- A total of 1118 passes were video recorded during 41 hours of data collection. The majority of the passes were within 663 ft of the lead vehicle. The average passing gap for all measurements was 260 ft.
- Evaluations that used speed difference between the lead vehicle and the following vehicle found posted speed limit to be significant as part of a two-way interaction term that consisted of posted speed limit and lead vehicle size. At 80 mph, the passing gap to either a sedan or an RV was similar. For 70 mph the passing gap was significantly different; drivers were closer to the RV than the sedan when passing.
- For the sedan, the passing gap increases by 10 ft for each mile-per-hour increase in the speed difference between the lead vehicle and the following vehicle while for RV, the passing gap increases by 8 ft. Stated in another manner, the faster a driver approaches a

vehicle, the greater the passing gap distance and the rate of passing gap increase is larger (by around 2 ft) for Sedan as compared to RV.
- The type of following vehicle (car or heavy truck) was not significant in the analysis that examined the effect of it along with speed difference. It was significant in the analysis that examined the effect of vehicle type along with following vehicle speed and lead vehicle speed (instead of speed difference) in the 70-mph dataset. Drivers of cars passed approximately 20 ft closer to the lead vehicle as compared to drivers of heavy trucks.
- The current study only measured passing gap when both vehicles were moving at relatively high speeds. A more serious safety threat is posed on high-speed roads when a lead vehicle is moving very slowly or is stopped. The stopping sight distance for 70 mph is 730 ft and for 80 mph is 910 ft. Clearly, these values are well beyond the average 260 ft gap observed for passing in this study.

The key finding from this effort follows:
- The statistical analyses indicated that drivers passed more closely to the larger-profile vehicle (RV) than the smaller-profile vehicle (sedan). For example, one of the analyses found that drivers were 282 ft from the sedan and only 238 ft from the RV when they passed, a difference of 56 ft. A comparison between the passing gap values predicted using the regression model developed within this research and the values determined using the Olson and Farber equation showed that only drivers on the 70-mph section passing an RV were within the distance suggested by Olson and Farber as needing a response although drivers on the 80 mph section were close to the Olson and Farber decision point. The reasons drivers were passing the RV so closely may deserve additional investigation.

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