Quantifying How Much Key Factors Influence Freeway Operational Speeds During Non-Congested Periods

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Key Words:

Freeway operating speed, posted speed limit

Abstract

An evaluation of speeds on Texas freeways used data from 243 roadway sensors located in Fort Worth representing operating speeds during daytime and clear weather conditions from 2015 to 2019. The initial evaluation explored how much average operating speeds increased when the posted speed limit (PSL) was raised from 60 to 65 mph, 60 to 70 mph, or 65 to 70 mph. The average operating speed increased between 2.4 to 4.0 mph for 5-mph increase in PSL or 2.9 mph for the 10-mph increase in PSL. The next evaluation identified variables associated with variations in average freeway speeds. The most significant amount of operating speed variation was associated with unidentified localized factors representing 33.8 percent of variability due to differences between detector locations. Yearly shifts in speeds at a given location were found to be the third most relevant source of speed variation (10.6 percent). Geometry was estimated to explain about 7.5 percent, speed limit 4.1 percent, and citations 3.6 percent of the speed variation in this dataset. Geometry, citations, and PSL represent the range of influence for engineering, law enforcement, and traffic management on operating speed. This study estimates that a strategy that entails modifying geometry, changing the PSL, and varying the level of law enforcement presence within the ranges included in this study may impact freeway operational speeds up to 6.2 mph (depending upon existing conditions along with the changes in the geometry, PSL, and enforcement).

Introduction

A highly complex transportation issue can be determining an appropriate posted speed limit (PSL). Determining the PSL involves engineering, human factors, and political and societal concerns. Drivers' operating speed can be used to set posted speed limits and posted speed limits are assumed to affect the speed selected by a driver. Several roadway-related factors are known or suspected to affect operating speed on freeways, such as vertical alignment, shoulder width, and ramp density. In addition, traffic conditions are a known influence on driver speed choice with slower speeds existing during more congested periods. The influence of the speed limit sign on operating speed, however, is not as well known. The primary goal of the evaluation presented in this paper was to investigate how much impact the posted speed limit sign has on freeway operating speeds including whether operating speeds change after a change in the posted speed limit.

Previous Research

The Transportation Research Board (TRB) *Modeling Operating Speed Synthesis Report* (*1*) documents several studies' findings regarding factors that influence driver's operating speeds with most focusing on two-lane rural highways with horizontal curvature being the prime influence. Much less knowledge is available regarding freeways. The TxDOT project (*2*) that supports the research in this paper investigated this gap.

Operating Speed and Roadway Factor Relationships for Freeways

Roadway geometric design variables with a known relationship to operating speed include access points (negatively associated), horizontal curve radius (positively associated), lane width (positively associated), median width (positively associated), number of lanes (positively associated), paved shoulder width (positively associated), and vertical grade (negatively associated) (*3*). Negatively associated indicates that as the value of the variable increases (e.g., steeper grades), operating speed decreases.

A 2015 TxDOT study (*4*) examined operating speeds on freeways and found an increase of about 2.2 mph for a 12-ft lane as compared to an 11-ft lane. The shoulder width was significant when the adjacent lane is 11 ft wide, but not when it is 12 ft wide which suggests that left shoulder width is more important with a reduced lane width. Operating speeds on Texas freeways are 2 mph lower during nighttime (with roadside lighting present) than during the day. Speeds were higher (by 1.5 mph) on the weekends (Saturday) than on the weekday studied (Wednesday).

The Highway Capacity Manual (HCM), version 6.0 (*5*), states in Exhibit 12-18 that the base free-flow speed under ideal conditions exceeds the speed limit by 5 mph for freeway segments with a PSL range of 55 to 75 mph as well as for multilane highway segments with a PSL of 45 to 70 mph. The HCM also provides additional information in Chapter 12 about adjusting the freeway free-flow speed using adjustment factors for lane width, right-side lateral clearance, and total ramp density.

Robertson et al. (*6*) developed suggested changes to the HCM freeway methodology to be able to consider freeways with free-flow speeds greater than 75 mph. The factors found to influence freeway operating speeds included posted speed limit, ramp density, truck percentage, differences between lanes (i.e., whether the vehicle was in the outside lane or the inside lane), median width, left shoulder width, and vehicle type (passenger car or truck).

Impacts from Increasing Regulatory Posted Speed Limit

Several studies are available regarding the impacts of increasing the regulatory speed limit. Hu (*7*) in 2017 reported that the average speed increased by 3.1 mph for passenger cars (4.1 percent) and 1.7 mph for large trucks (2.5 percent) when the PSL went from 75 to 80 mph on rural interstate roadways in Utah. Souleyrette et al. (*8*) in 2009 reported on implementing a 70-mph speed limit on most rural Iowa Interstates with mean and 85th percentile speed increases of about 2 mph. Utah Department of Transportation (UDOT) in 2009 (*9*) reported that overall, speeds increased between 2 and 3 mph on the sections with a 5-mph speed limit increase. Retting and Cheung (*10*) reported on the 2006 increase in daytime speed limit for passenger vehicles from 75 to 80 mph for West Texas freeways. They found passenger vehicle mean speeds were up by 4 mph on I-10 and 9 mph on I-20 relative to comparison roads.

Dixon et al. (*11*) in 1999 reviewed speed data for 12 rural multilane sites in Georgia in the 1990s to evaluate the effects of repealing the 55-mph national speed limit. They found that operating speeds were higher after the increase in the PSL with observed mean speeds being 3.2 mph higher when the posted speed increased from 55 mph to 65 mph.

The Transportation Research Board (TRB) Special Report 254 (*12*) in 1998 summarized several studies that examined the increase in operating speeds when the National Maximum Speed Limit (NMSL) went from 55 mph to 65 mph. Raising rural Interstate speed limits resulted in the following changes:

- Average speeds increased on the order of 4 mph or less for 10-mph increase in the speed limit.
- 85th percentile speeds also increased on the order of 4 mph or less for the 10-mph increase in the speed limit.

Musicant et al. (*13*) in 2016 analyzed information from several previous research studies where the speed limit in the before period was at least 50 mph. Their database included 108 entries where the speed limit was reduced for 52 locations and the speed limit was raised for 56 locations. Overall, they found that the direction of change in mean driving speed (up or down) is in line with the direction of change in the speed limit; however, the magnitude of change for driving speed is more moderate as compared to the magnitude of change in the PSL.

The magnitude of the change in operating speeds when there is an increase (or decrease) in posted speed is typically only a fraction of the amount of the actual speed limit change. Overall, the previous studies indicate for high-speed rural roadways, mean speeds are generally 3 to 5 mph higher for every 10-mph increase in speed limit above 55 mph, with smaller increases at higher speed limits.

Impacts from Decreasing Regulatory Posted Speed Limit

There are fewer previous research efforts documenting the change in operating speeds when the PSL is reduced for limited-access roads. TRB Special Report 254 (*12)* references a 1984 TRB study (*14*) on the effects of the national 55 mph speed limit and found that the lower limit reduced both travel speeds and fatalities, although driver speed compliance gradually eroded. Parker (*15*) in 1997 examined the effect of changes in speed limits on rural and urban nonlimited-access highways and found generally less than 2 mph change in driving speed regardless of the amount of change in PSL.

Musicant et al. (*13*) in 2016 analyzed information from several previous research studies and reported that when speed limit was reduced, the driving speed was reduced a moderate amount.

Study Approach

Research Questions

The following research questions guided the development and analysis of the freeway database:

- Research Question 1: Do freeway operating speeds change following an increase in PSLs?
- Research Question 2: What is the relationship between daytime operating speeds (average speeds) and the PSL value after accounting for other factors? Within this question is the interest to understand what factors are more influential (e.g., PSL, freeway geometry, other factors).
- Research Question 3: On Texas freeways, are operating speeds increasing over time?

Site Selection / Speed Data

The research team examined recent PSL changes within Tarrant County which includes Fort Worth. Fort Worth previously implemented environmental speed limits (ESL) in 2001 which were replaced in July 2015 based on speed studies conducted by the local TxDOT district. Researchers obtained operating speeds in May 2015 before the speed limits were changed in July. Because researchers also wanted to investigate whether freeway speeds are increasing over time, the data for May of subsequent years 2016-2019 were also gathered. Only one month per year was used to keep the database a manageable size. It was desired to include May 2020 data, but TxDOT lost these data due to a ransomware attack, so April 2020 data were obtained instead.

For the analysis, it was desired to obtain a robust speed dataset that has several locations with speed and volume data where the PSL was changed. TxDOT operates Traffic Management Centers (TMCs) in all large urban areas of Texas, including Fort Worth. The management is accomplished, in part, by roadway smart sensors (*16*). The smart sensors collect speed, volume, and occupancy (SVO) data and their data are stored locally in the field (at 20-second intervals) and then aggregated and archived in a regional data warehouse into five-minute intervals. Typically, two detector links are assigned to one detector (one in each direction).

The researchers reviewed the links and removed several for various reasons such as construction, being on ramps, or data availability. Detectors were also removed that had the following site characteristics because they represented a small number of sites compared to the rest of the database:

- Speed limit was 55 mph.
- The segment had 5 or 6 general-purpose lanes.
- The segment had one or more managed lanes.
- The next upstream or downstream ramp was a left-side ramp.

Ultimately, researchers used 243 detector links for the final dataset.

Developing Study Database

The research team assembled a merged database incorporating several data sources as discussed in the following sections.

Roadway Geometric Data and PSL Data

The roadway dataset included geometric data, PSL, and presence of construction. The geometric data included lane count, lane width, and characteristics of upstream and downstream ramps. The research team used aerial and street-level photographs to identify the locations of PSL signs. Once a PSL sign was identified in a street-level photograph, the historical street view feature was used to review previous years to determine if the PSL value changed in an earlier year. The detector-year was flagged as having construction when, in the opinion of the research team, the level of construction was believed to affect operating speed. Presence of construction was obtained from reviewing historical aerial and street-level photographs.

The PSLs present in the database included detectors that had 60 mph for all years, 65 mph for all years, 70 mph for all years, 60 mph in 2015 and 65 mph in other years, 60 mph in 2015 and 70 mph in other years, and 65 mph in 2015 and 70 mph in other years. A few detectors did not fit in those categories, such as having a speed limit change in 2017, and were removed.

Weather Data

The weather data file consisted of hourly records of precipitation (inches) and visibility (miles) readings at four weather stations in Tarrant County. The research team merged the hourly precipitation and visibility values into the speed database using the latitude and longitude coordinates for the detectors and the weather stations and the date and time variables. Each speed record was matched with the data from the closest weather station, or the next-closest weather station if the closest station was non-functional during the hour of interest.

Speed data were marked for removal if within the hour, more than 0 inches of rain occurred. The research team initially considered including speed data when a small amount of rain was present; however, a study in 2017 (*17*) found that free-flow speed decreased by 4.4 percent when rain between 0 and 0.20 in/h was present. Therefore, any 5-min time slice associated with any rainfall was marked for removal.

Incidents

Because traffic incidents are a major source of nonrecurring congestion (*18*), TMC incidents were compiled from the TxDOT database for the same months as the speed data. This information was used to remove potentially 'abnormal' speeds that could have been influenced by these nonrecurring events. Most of the incidents for the time periods considered in this study were collisions (63 percent) and construction (25 percent). All amber and news alerts, public service announcements, and public emergency incidents were not included because they are more areawide in nature rather than being associated with a specific detector or freeway section.

The research team merged the incident data with the speed data using the latitude and longitude coordinates for the incident and the detector and the date and time variables. The speed record was flagged as being associated with an incident and were removed if the following conditions were met:

- The incident occurred on the same roadway as the speed record.
- The incident started within 10 minutes prior to the 5-minute time slice for the speed record or ended within 20 minutes of the 5-minute time slice.
- The distance between the incident and the detector was less than or equal to 3 miles.
- The incident was not an abandonment. An abandonment is when an unattended vehicle is located and tagged by law enforcement on one of the shoulders. Abandonments were not flagged because they are assumed to cause minimal disruption to traffic flow in the travel lanes.

Light

The research team identified the sunrise for each day represented in the data using archived almanac records (timeanddate.com). Dawn was defined as within 30 minutes before or after sunrise. Dusk was defined as within 30 minutes before or after sunset. The research team combined light condition data with the speed records and designated each record as dawn, day, dusk, or night. Data for only the daytime light condition were used in the analysis.

Citations

The researchers acquired available enforcement speeding citation data from the Department of Public Safety (DPS) and city and county police departments, as the level of enforcement might have an impact on operating speed. Based on local knowledge, the thoughts are that drivers are becoming more familiar with higher operating speeds with the recent opening of several tollways in the area. In addition, drivers may be noticing lower enforcement levels due to a reduction in workforce, caused by higher turnover and lower academy enrollment, or changing enforcement patterns due to recent social issues. Figure 1 shows there was an 11-percent decrease in speeding citations by municipalities and a 25-percent decrease by DPS between 2016 and 2019.

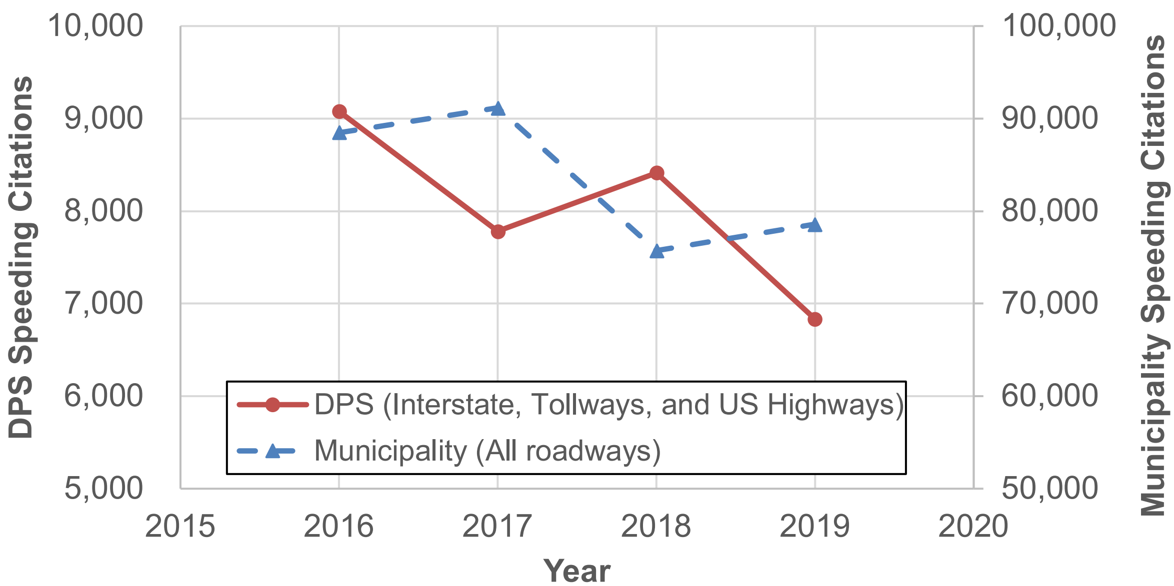


Figure 1. Tarrant County Speeding Citations.

Freeway Database

The research team imported and processed the speed data for the months of May 2015, May 2016, May 2017, May 2018, May 2019, and April 2020. Each record in the speed data represented vehicles at one detector going in the same direction for one 5-minute time slice. The data records included overall time-mean speeds and lane-weighted time-mean speeds per direction. Records were removed for the following reasons:

- Record contained no vehicles or no speed observation.
- Construction was present on the link during the given month and year.
- Precipitation was recorded during the hour that included the 5-minute time slice.

- Record was associated with an incident.
- Speeds (average or lane-weighted) was less than 53 mph (assumed value that indicates that congestion may be beginning) or greater than 90 mph (assumed value for potential sensor error).
- The vehicle count suggested a flow of greater than 3000 veh/hr/lane.
- The light condition was dusk, night, or dawn.

Initial attempts to use the screened sample database with approximately 3 million records resulted in multiple computer failures because of the size of the database. The research team decided to address the database size issue by creating 15-min speed readings based on merging data from three consecutive 5-minute time slices. This approach allowed the research team to use the entire database rather than starting from a sample of the data and then confirming the preliminary findings using the complete database.

The overall average speed per year and PSL is shown in Figure 2. Figure 3 provides the average operating speed by year for each of the control and treated (where PSL changed) groups. Overall, the speeds are fairly similar for 70-mph freeways between 2016 and 2019. The potential impacts of the pandemic stay-at-home restrictions (both businesses and schools), including lower volumes and less enforcement, can be seen in the 2020 data where overage operating speeds are notably higher for each PSL. A recent study conducted by Das et al. (*19*) showed that higher operating speed during COVID-19 is associated with higher fatal and injury crashes on urban freeways. When focusing on 2015 to 2019, the curves for 60 and 65 mph speed limits show an upward trend of higher operating speeds for later years while the data for 70 mph roads show similar average driving speeds for each year.

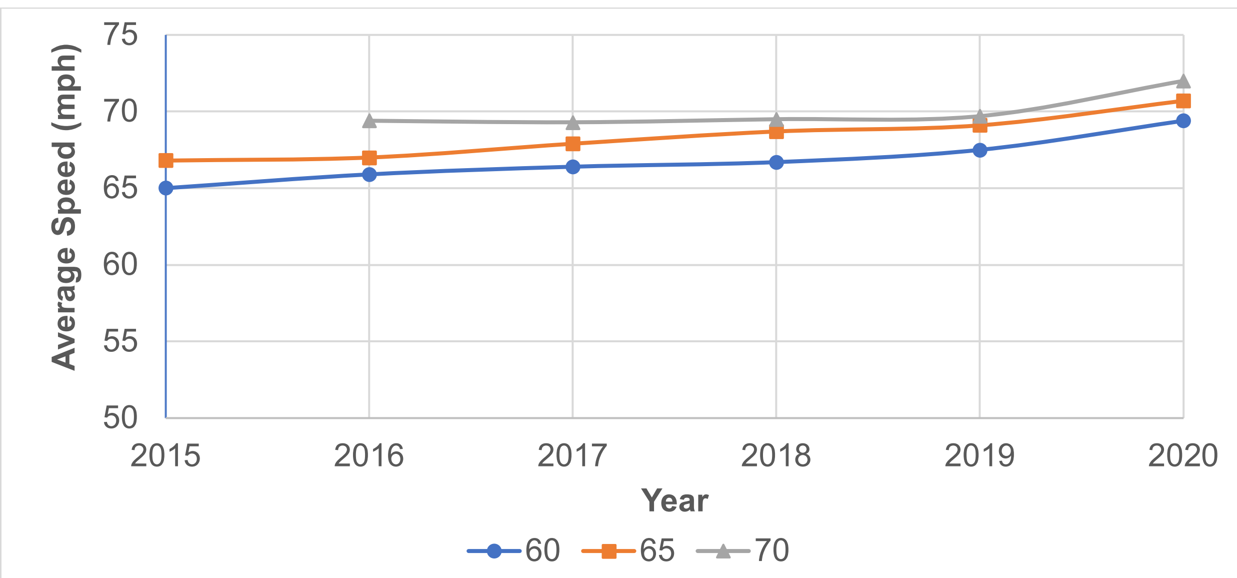
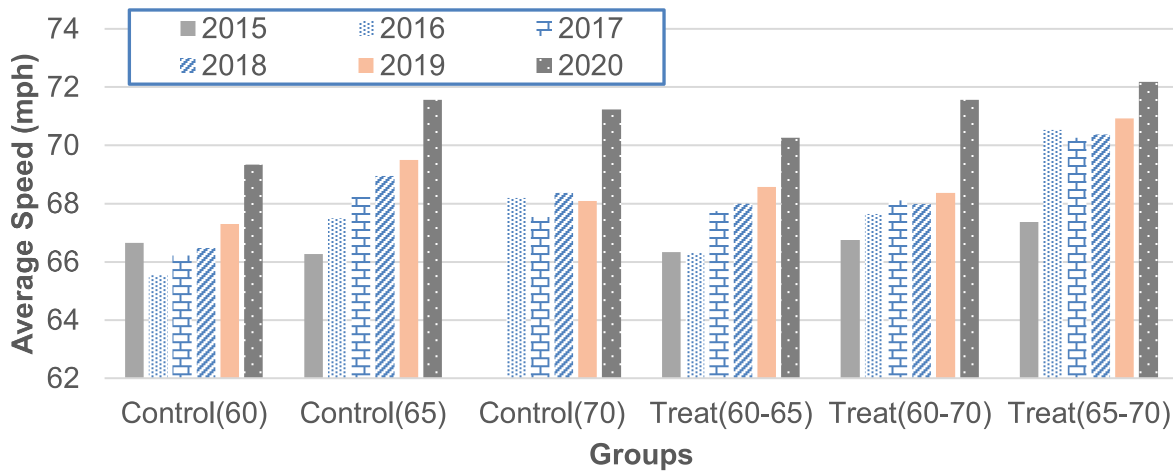


Figure 2. Average Operating Speed by Year and PSL.



Where the groups included the following:

- Control(60) = the detector location had a 60-mph PSL for all years.
- Control(65) = the detector location had a 65-mph PSL for all years.
- Control(70) = the detector location had a 70-mph PSL for 2016 to 2020 (none of the sites in this database had a 70-mph speed limit during 2015).
- Treat(60-65) = the detector location had 60-mph PSL in 2015 and a 65-mph PSL in other years.
- Treat(60-70) = the detector location had 60-mph PSL in 2015 and a 70-mph PSL in other years.
- Treat(65-70) = the detector location had 65-mph PSL in 2015 and a 70-mph PSL in other years.

Figure 3. Average Freeway Operating Speeds by Year for Control or Treated Groups.

Because of the apparent difference in operating speeds for the time period where COVID pandemic stay-at-home restrictions were in place, the research evaluations did not include the 2020 speed data. Descriptive statistics for the site variables are provided in Table 1.

Table 1. Descriptive Statistics for Site Variables for 2015 to 2019 Speed Data

Variable	Measure	60-mph Sites	65-mph Sites	70-mph Sites	All Speed Limit Sites
Number of Sites	Count	147	111	108	366
Number of 15-minute Speed Observations	Count	238,461	220,750	434,922	894,133
Lane Width (ft)	Mean	12	12	11.9	12
	Std. Dev.	0.3	0.3	0.3	0.3
	Range	11.0 to 12.5	11.3 to 12.5	11.2 to 12.5	11.0 to 12.5
Left Shoulder Width (ft)	Mean	9.8	9.4	8.9	9.2
	Std. Dev.	3.6	2.3	2.3	2.7
	Range	4 to 25	4 to 18	4 to 14	4 to 25
Right Shoulder Width (ft)	Mean	10.6	10.2	10.9	10.7
	Std. Dev.	2.4	2.5	2.1	2.3
	Range	4 to 19	4 to 20	6 to 21	4 to 21
Downstream Ramp Distance (ft)	Mean	1241	1115	1902	1530
	Std. Dev.	967	1004	1592	1364
	Range	80 to 6460	80 to 9120	115 to 9120	80 to 9120
Upstream Ramp Distance (ft)	Mean	1333	1313	1989	1646
	Std. Dev.	913	1056	1676	1404
	Range	45 to 6110	55 to 8670	45 to 8670	45 to 8670
Speed (mph)	Mean	67	68.7	70.1	68.9
	Std. Dev.	3.6	3.7	3.8	4.0
	Range	53 to 82	53 to 83	53 to 90	53 to 90
Volume (veh/hr/lane)	Mean	622	647	692	662
	Std. Dev.	426	422	444	435
	Range	2 to 2971	3 to 2976	3 to 2944	3 to 2976

Evaluation – Research Question 1

The change in environmental speed limits can be used to address Research Question 1, "do freeway operating speeds change following an increase in PSLs?." Speed data for May 2015 and May 2016 were compared to identify the amount of operating speed change after the speed limit increase.

Because of construction or data availability for a detector, there could be sites considered in one year but not the other. Table 2 shows the count (sample size) and mean operating speed for each group. For treatment sites with 5-mph PSL increase, all groups experienced higher average operating speed in the after year. For control site groups, while the mean speed is higher the differences are negligible in values (only 0.02 mph for 60-mph control group and 0.04 for the 65-mph control group).

Table 2 provides the statistical comparison between the before and after mean operating speeds. Within the sections with PSL increases (treatment group), the average operating speed increased between 2.4 to 4.0 mph as compared to the 5-mph increase in PSL or 2.9 mph for the 10-mph increase in PSL. These operating speed increases were statistically significant. The control groups – either Group = Control(60-60) or Control(65-65) – saw negligible (in value) increase in average operating speed; and these increases were not statistically significant. The change in average operating speed was only 0.02 to 0.04 mph for those roadway segments with no change in the PSL.

Table 2. Comparison of Mean Speeds by Treatment and Control Groups for Before-After Periods.

Group	**Control (60-60)**	**Control (65-65)**	**Treat (60-65)**	**Treat (60-70)**	**Treat (65-70)**
N 2015	2,782	1,670	4,922	2,531	6,840
N 2016	39,501	6,015	22,853	35,773	39,618
Mean Speed (mph) 2015	65.47	66.2	64.38	64.7	66.83
Mean Speed (mph) 2016	65.49	66.24	66.79	67.62	70.85
Change (mph)	0.02	0.04	2.41	2.92	4.02
Effect Size	0.01	0.01	0.45	0.63	0.91
t-score	0.25	0.41	26.67	27.44	62.95
95% CI	[−0.04, 0.05]	[−0.04, 0.07]	[0.42, 0.48]	[0.58, 0.68]	[0.88, 0.94]
P-value	0.81	0.68	<0.001	<0.001	<0.001

Evaluation – Research Question 2 and Question 3

Panel Model using Binned Freeway Database

The format of the available data fit a panel database structure; therefore, the research team decided to use a mixed effect statistical model with nested random effects. This model specification makes an explicit distinction between variables considered either a fixed feature of the facility (for example, cross-sectional elements) and variables with a more transient nature (for example, hourly fluctuations). Given this distinction, there are variables that fall in a gray area; for example, AADT was treated as a fixed effect even though it is not exactly a fixed feature of the facility, but because it represents a measurable objective systematically defined the same way for each facility under study.

Therefore, in the model specification the research team assigned an initial definition of fixed and random effects for the variables that would clearly fall under each category. A highway corridor variable was initially included in the specification of the random effects to account for spatial proximity, but it was found to correlate with other fixed effects predictors and was thus removed from the model.

Additionally, the research team tested (based on the Akaike Information Criterion or AIC, a measure of model entropy) if additional key variables would be more suitable to be modeled as either a fixed or a random effect. Equation 1 shows the general form of the model specification.

$$Average.Speed_{ijkl} = \boldsymbol{X}' \cdot \boldsymbol{\beta} + Z_i + Z_{ij} + Z_{ijk} + \varepsilon_{ijk} \qquad \text{Equation 1}$$

Where:

$Average.Speed_{ijkl}$	=	Average 15-min binned speed for the ith Link_Name, jth Year, and kth level for GroupDays.
$\boldsymbol{X}$	=	Vector of fixed-effects.
$\boldsymbol{\beta}$	=	Vector of fixed-effects coefficients.
Z_i, Z_{ij}, and Z_{ijk}	=	Random effects (or random parameters), at a given level of aggregation.
ε_{ijk}	=	Residual error.

When handling time series data, it is important to consider explicitly the likely codependence between observations close in time. The mixed-effects framework used in this research allows the implementation of error correlation structures as needed, see Pinheiro and Bates for additional information on the framework (*20*) and the TxDOT project report (*2*) for additional details. After several rounds of model selection within the model structure in Equation 1, the research team arrived at the specification shown in Equation 2. The coefficients were estimated using R, open statistical software and packages. (*21*, *22*)

$$Average.Speed_{ijkl} = \beta_0 + \beta_1 \cdot \ln(AggTotalVol + 0.5) + \beta_2 \cdot SL_{Rf60} + \beta_3 \cdot L_{shld_{wid_{Rf4}}} + \beta_4 \cdot R_{shld_{wid_{Rf10}}} + \beta_4 \cdot \ln(Mun.Citations/78586) + \beta_5 \cdot \ln(DPS.Citations/6833) - \beta_{ramp\_type} \cdot \ln(Ramp\_dist + 0.5) + Z_{0_i} + Z_{0_{ij}} + Z_{0_{ijk}} + \varepsilon_{ijk}$$

Equation 2

Where:

$Average.Speed_{ijkl}$	=	Average 15-min binned speed for the ith Link_Name, jth Year, and kth level for GroupDays.
AggTotalVol	=	15-min volume.
β_n	=	N-th fixed effect coefficient.
β_0	=	Global model intercept (at the fixed-effects level).
β_{ramp_type}	=	One of four coefficients for the different ramp types in the dataset (Upstream Entry, Upstream Exit, Downstream Entry, and Downstream Exit).
$Ramp\_dist$	=	One of four variables in the dataset indicating the distance to one of the four ramp types in the dataset (Upstream Entrance, Upstream Exit, Downstream Entrance, and Downstream Exit).
$R_{shld_{wid_{Rf10}}}$	=	Right shoulder width (ft) with respect to a 10-ft shoulder. A 10-ft shoulder would have a value of 0, while a 11-ft shoulder would have a value of 1, etc. for this variable.
$L_{shld_{wid_{Rf4}}}$	=	Left should width (ft) with respect to a 4-ft shoulder. A 4-ft shoulder would have a value of 0, while a 5-ft shoulder would have a value of 1, etc. for this variable.
SL_{Rf60}	=	Speed limit (mph) with respect to 60 mph (i.e., a 65-mph speed would have a value of 5 mph in this database).
Mun.Citations	=	Total number of yearly citations issued by municipalities within the county on all types of roads
DPS.Citations	=	Total number of yearly citations issued by DPS within the county freeways
Z_{0_i}	=	Local model intercept for i-th Link_Name (level of spatial aggregation).

$Z_{0_{ij}}$	=	Local model intercept for j-th Year for i-th Link_Name (first level of temporal aggregation).
$Z_{0_{ijk}}$	=	Local model intercept for k-th GroupDays for j-th Year for i-th Link_Name (second level of temporal aggregation).

It should be noted that the number of citations is passed to the model divided by the number in 2019, considered a reference year for the analysis.

Table 3 shows the estimates for the fixed effects part of the model that used the binned database (i.e., 15-min period data where all three consecutive 5-min periods were available). The results have direct implications in understanding the relationships between operational speed and other key variables found relevant in the final model. The following sections describe those implications in more detail.

Table 3. Model Parameter Estimates

Fixed Effects						
Parameter	**Variable**	**Estimate**	**Std. Err**	**DF**	**t-value**	**p-value**
β_0	Base Speed (intercept)	65.3979	1.9216	694010	34.0330	<1e-04
β_1	15-min Volume	-1.0132	0.0079	694010	-127.733	<1e-04
β_2	Speed Limit relative to 60 mph	0.1898	0.0409	587	4.6362	<1e-04
β_3	Left Shoulder relative to 4 ft	0.1232	0.0620	239	1.9885	0.0479
β_4	Right Shoulder relative to 10 ft	0.1146	0.0698	239	1.6417	0.1020
β_5	Number of municipal citations in a year	-4.4433	0.6854	587	-6.4825	<1e-04
β_6	Number of DPS citations in a year	-5.8184	0.5160	587	-11.2758	<1e-04
$\beta_{Down\_Ramp\_typeEN}$	Distance to closest downstream ramp, entrance	-0.6325	0.2001	239	-3.1615	0.0018
$\beta_{Down\_Ramp\_typeEX}$	Distance to closest downstream ramp, exit	-0.5526	0.2139	239	-2.5835	0.0104
$\beta_{Up\_Ramp\_typeEN}$	Distance to closest upstream ramp, entrance	-0.5315	0.1795	239	-2.9610	0.0034
$\beta_{Up\_Ramp\_typeEX}$	Distance to closest upstream ramp, exit	-0.6085	0.1695	239	-3.5893	0.0004
Random Effects and Residuals						
Parameters	Variable	Standard Deviation				
Z_{0_i}	Link_Name	2.478064				
$Z_{0_{ij}}$	Year	1.354728				
$Z_{0_{ijk}}$	GroupDays	1.070744				
$\varepsilon_{0_{ijk}}$	Independent Residual	2.023818				
ρ	Autocorrelation parameter	+0.6412				

Fixed Effects Coefficients

From the fixed-effects coefficient estimates (see Table 3) the model indicates the following:

- Operating speed decreases with increasing 15-min volume in non-congested conditions. A 50 percent increase in volume is associated with a reduction of 0.41 mph (-1.013*ln(1.5)=-0.4108) in average operating speed, or a reduction of 0.70 mph if the volume doubles (-1.013*ln(2)=-0.7023).
- Operating speed increases with increasing speed limit. For each 5 mph increase in the PSL, the average operating speed increases by 0.95 mph (0.1898*5=0.949), or an increase of 1.90 mph for a 10-mph increase in posted speed, say going from a 60-mph freeway to a 70-mph freeway, all other characteristics staying the same (0.1898*10=1.898).
- Operating speed increases with wider left shoulder. For an additional foot of left shoulder, the average operating speed increases by 0.12 mph (0.1232*1.0=0.01232).
- Operating speed increases with wider right shoulder. For an additional foot of right shoulder, the average operating speed increases by 0.11 mph (0.1146*1.0=0.1146).
- Number of yearly citations was found to have an impact on operating speeds. For example, a 20 percent increase in DPS citations is expected to result in a 1.06 mph decrease in operating speed (calculated as -5.818*ln(1.2)=-1.061).

As expected, operating speeds are higher when the distances to upstream and downstream right-side ramps are longer (statistically significant). It should be noted that this finding does not apply to left-side ramps, as this database did not contain locations where the closest upstream or downstream ramp was on the left side. They were removed due to the small number of sites with that geometric feature. Speeds are increasing with greater distances even though the coefficient has a negative sign because the model format as shown in Equation 2 includes a negative sign prior to the coefficient. For example, if the closest downstream ramp is an entrance ramp and the distance is 100 ft, the operating speed is estimated to be higher by 2.92 mph (2.9159 = 0.6325*ln(100+0.5)), compared to a point just at the ramp. If the closest downstream entrance ramp is 1000 ft, the operating speed is estimated to be higher by 4.27 mph (4.3695 = 0.6325*ln(1000+0.5)), compared to a point just at the ramp.

The fixed effects are the part of the model that can be interpreted more directly. The following sections describe the results from other model components and their implications.

Random Effects Coefficients

In the model estimation, the random-effects coefficients are estimated for each unit of nested aggregation as described when defining the model. However, interpreting the individual values of those estimates is generally not relevant as the estimate is specific to a given location or given period at a given location. It is of interest; however, to provide some descriptive statistics on the random-effect estimates as they describe general trends in the data not explicitly captured in the fixed-effects part of the model. The model in this research has nested random effects with one tier of spatial aggregation and two tiers of temporal aggregation as described next.

Spatial Random Effects

The first level of aggregation is spatial by specific detector location within a freeway corridor. Figure 4 shows the histogram of the adjustments per detector location, which the model applies in addition to the fixed effects. It can be seen from Figure 4 that the amount of variation captured by the detector location-specific random effect is significant: the approximate range of these adjustments is [-6 mph, 4 mph].

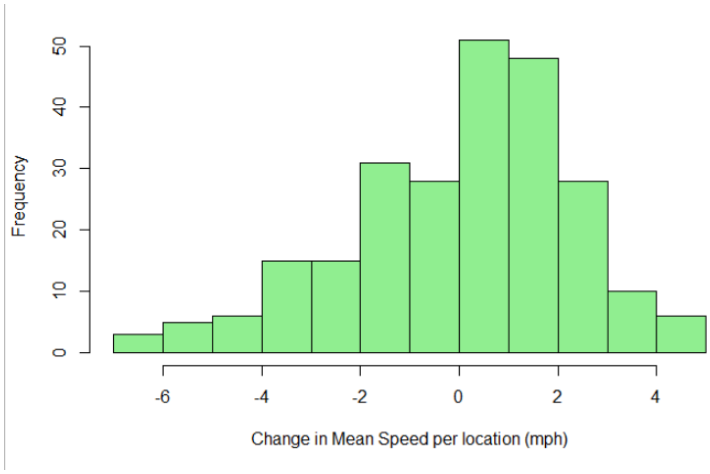
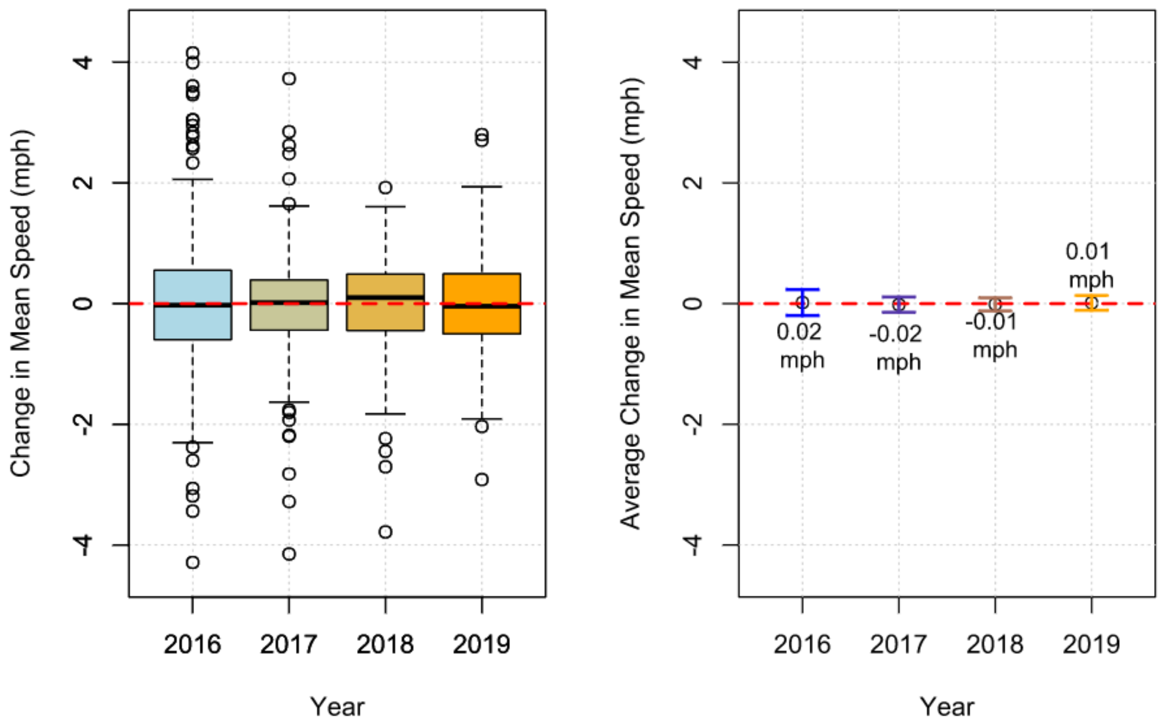


Figure 4. Histogram of Adjustment Per Detector Location.

Temporal Random Effects

In order to capture yearly trends at specific locations, the model provides an adjustment per each year with data at each detector location under study. These yearly adjustments are applied in addition to the spatial adjustment discussed in the prior section. Figure 5 shows boxplots of all yearly adjustments versus year which do not suggest a trend that mean speed varies with increasing year, other things equal. Additionally, when calculating 95 percent confidence intervals around the means of these adjustments, all the intervals contain zero, confirming the absence of a trend by year (see Figure 5).



(a) Yearly Random Effects **(b) Mean of Yearly Effects (with 95% CI)**

Figure 5. Random Effects by Year.

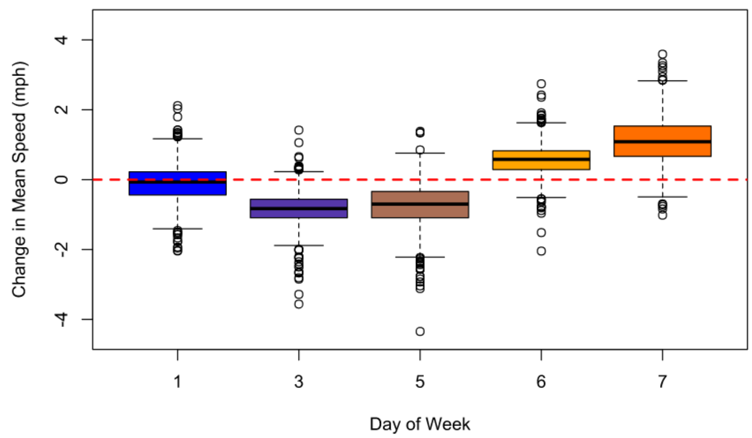
Finally, in the last level of aggregation, the model applies an adjustment per day of the week at each detector location per year of data in the analysis. It can be seen that the speed adjustments drop from the initial baseline on Monday and remain relatively flat for Tuesday through Friday (i.e., comparable baseline speeds) and then it consistently increases from Saturday to Sunday. When plotting all week-day random effects (see Figure 6), a pattern of being relatively similar speeds during weekdays and higher speeds on weekend. Monday tends to have faster speeds compared to Tuesday through Friday. Saturday and Sunday remain the days with fastest speeds, after adjusting for other variables.

The Relative Contribution of Different Factors to the Variability of Operating Speed

To gain perspective of the factors that explain the variability observed in the key variables this section quantifies the contribution of said factors to the operating speed variability, as estimated by the model described in the previous section. This model provides an explicit account of how the factors of interest relate with the operational speed and therefore, it is possible to quantify their systematic variation. The total variability by all explanatory factors in the model, combined with the residual variability that remains unexplained by the model, should amount to the total variability in the response variable.

Table 4 summarizes the breakdown of the variation in the response variable by level of aggregation according to the model. The fourth column of

Table 4 (percent of incremental explained variance) shows the percent of variation in operational speed associated with each explanatory factor in the model. Only 4.4 percent (0.6920 mph^2) of the total variability in the response variable (15.3867 mph^2) can be explained by the variation in 15-min volumes. Although this percentage appears somewhat small, as a reminder, the dataset was based on uncongested traffic conditions as previously described. The finding demonstrates that even in uncongested conditions, speeds are affected by traffic density and proximity to other vehicles.



Note: 1=Monday, 3=either Tuesday, Wednesday, or Thursday, 5=Friday, 6=Saturday, and 7=Sunday (different colors are present; however, they are provided to help the reader to see the differences between the boxplots).

Figure 6. Weekday Random Effects.

Table 4. Variation in Response Variables by Level of Aggregation.

Explanatory Factor (i.e., variables)	**Cumulative Variance (mph^2)**	**Incremental Explained Variance (mph^2)**	**Percent of Incremental Explained Variance (percent)**	**Standard Deviation of Speed (cumulative) (mph)**	**Expected range of variation (95% coverage Interval) (mph)**
15-min Volume	0.6920	0.6920	4.4%	0.8319	+/- 1.63
Speed Limit	1.3322	0.6402	4.1%	1.1542	+/- 2.26
Geometrics	2.5132	1.1810	7.5%	1.5853	+/- 3.11
Citations	3.0845	0.5713	3.6%	1.7563	+/- 3.44
Link_Name	8.4188	5.3343	33.8%	2.9015	+/- 5.69
Year	10.0881	1.6693	10.6%	3.1762	+/- 6.23
GroupDays	11.2243	1.1362	7.2%	3.3503	+/- 6.57
Residuals	15.3867	4.1624	26.4%	3.9226	+/- 7.69

For PSLs, 4.1 percent (1.3322 mph^2) of the total variation in operational speed can be attributed to the operational differences at different speed limits according to the analysis. In other words, the range of variability that can be attributed to PSL and not to other factors is expectedly small. Other variables describing freeway geometric configuration (i.e., shoulder widths and relative location of ramps) are associated with 7.5 percent of the operational speed variation (1.1810 mph^2).

Although Table 3 indicates that the impact of citations on operational speeds is clear, intuitive, and statistically significant, the corresponding share of explained speed variability is smaller than the amount explained by PSL: 3.6 percent or 0.5713 mph^2. This finding, given the relatively robust effects implied by the coefficient estimates, suggests that the amount of variation in the number of citations year by year at the site level is relatively small so that larger changes in future years have large potential to affect operational speeds.

Jointly, the factors in the fixed effects (i.e., 15-min volume, speed limit, geometrics, and citations) explain 20.05 percent of the total variation in operational speed in the dataset (3.0845 mph^2). In contrast, the model attributes a larger amount of variation (5.3343 mph^2 or 33.8 percent) to other unaccounted factors at the detector location (i.e., Link_Name variable) level. This amount of variance is captured as the variation of the Link_Name specific random effects. Because these random effects are gross adjustments of the model to the data per detector location, it follows that a significant amount of variation (33.8 percent) exists from detector location to detector location, such that it is not explained by any of the other variables in the model.

10.6 percent (or 1.6693 mph^2) of variation in operational speed is associated with the differences by year at the Link_Name level. In comparison, 7.2 percent or 1.1362 mph^2 can be attributed to differences in speeds by day of the week.

Finally, 26.4 percent of the variation in the operational speed was captured in the model residuals (4.1624 mph^2) , which means that the remaining 73.6 percent of speed variation is explained by the fixed and random effects combined. Because the residual variation represents variation not explicitly accounted for by any of the model parameters nor the aggregation structure, the interpretation of this result is that operating speed varies by 26.4 percent at each site due to other factors not explicitly considered in this study (e.g., differences in driver speed preference, lane changing behavior, etc.).

Conclusions and Recommendations

An evaluation of speeds on Texas freeways used data from 243 sensors located in Fort Worth representing operating speeds during daytime and clear weather conditions from 2015 to 2019. The initial evaluation explored how much average operating speeds increased when the posted speed limit was raised from 60 to 65 mph, 60 to 70 mph, or 65 to 70 mph. The average operating speed increased between 2.4 to 4.0 mph for 5-mph increase in PSL or 2.9 mph for the 10-mph increase in PSL.

The next evaluation identified the variables associated with variations in average freeway operating speeds during daytime without rain or incidents, and in uncongested periods. The range of posted speed limits represented in the database was 60, 65, or 70 mph. Following are the key conclusions and recommendations from the evaluation:

1. The most significant amount of operating speed variation was found to be unidentified localized factors representing 33.8 percent of variability due to differences from detector location to detector location. The researchers theorize that possible sources could be local attractors, traffic generators including those associated with heavy truck traffic, facility types connecting to and from the nearby ramps, or driver’s familiarity or trip purpose.
2. The next most important source of speed variation was found at the speed location (26.4 percent of total variation represented in the residuals). Differences between driver speed preferences, vehicle types, and number and characteristics of lane changing maneuvers are examples of transient events that were not identified nor explicitly accounted for in the model that should affect the speed measured from period of analysis to period of analysis and thus captured in this source of variation.
3. Yearly shifts in speeds at a given location was found the third most relevant source of speed variation (10.6 percent). These yearly shifts could be explained by economic fluctuations and other factors that might change from year to year, including, perhaps, the local population being more willing to operate at higher speeds or drivers becoming more familiar with the area.
4. Geometry was found as the fourth most influential factor affecting operating speed, as it was estimated that it explains about 7.5 percent of the speed variation in this dataset.

5. Weekly patterns at specific sites were found as the fifth most influential factor on operating speed, accounting for 7.2 percent of the total speed variation.
6. Differences in volume between 15-min periods only accounted for 4.4 percent of total speed variation. The research team expected this variable to have minimal impact as periods with high volume were removed from the dataset.
7. Second to last, varying posted speed limit values was found to affect the operating speed only by 4.1 percent. The range of posted speed limits included in the dataset was 60, 65, and 70 mph.
8. Finally, the level of enforcement was found to impact operating speeds significantly with more citations being associated with lower expected speeds. However, the size of that effect and the range of citation levels represented in the data only account for 3.6 percent of the total variation in operational speed.

Citations together with PSL and geometry represent the range of influence that engineering, law enforcement, and traffic management can influence operating speed. This study estimates that a strategy that entails modifying geometry, changing the PSL, and varying the level of law enforcement presence within the ranges included in this study may impact freeway operational speeds up to 6.2 mph (depending upon existing conditions along with the changes in the geometry, PSL, and enforcement).

Comparing the amount of influence between points 1 and 7, a recommendation would be that design and area-wide traffic management are important, but that a significant amount of effort needs to be devoted to looking at localized factors at specific sites, which can be more influential than design and operations management.

Another recommendation would be to examine what other factors by location and by year within location might be systematic and could be explicitly measured with additional variables in the analysis. Factors associated with location or years at a given location amount to 40.4 percent of speed variation in the dataset, but the researchers were unable to identify these specific factors with the resources available in the project.

Regarding point 8 above, it should be noted that the account for law enforcement presence in the current analysis was as yearly levels of citations for the overall study area, both in all municipal roads and in all freeways by DPS. Future work should consider additional efforts to account for law enforcement with more sensitivity to the locations and periods of time with law enforcement presence. Expectedly, an analysis with such an account of this important factor could help explain some of the variability currently found as uncharacterized operational differences from location to location and from year to year (points 1 and 3, which combined currently account for 47.2 percent of the total variability in the speed data).

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: this research was sponsored by Texas Department of Transportation (TxDOT) as part of TxDOT research project 0-7049 (Improving and Communicating Speed Management Practices).

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