Estimation of Relationships between 85th Percentile Speed, Standard Deviation of Speed, Roadway and Roadside Geometry and Traffic Control in Freeway Work Zones

Richard J. Porter
Research Assistant
The Pennsylvania State University
Pennsylvania Transportation Institute
201 Transportation Research Building
University Park, PA 16802
Tel: (814) 865-2814
Fax: (814) 865-3039
rjp167@psu.edu

Kevin M. Mahoney
Senior Research Associate
The Pennsylvania State University
Pennsylvania Transportation Institute
201 Transportation Research Building
University Park, PA 16802
Tel: (814) 865-2815
Fax: (814) 865-3039
kmm28@psu.edu

John M. Mason, Jr.
Professor of Civil Engineering and
Director, Pennsylvania Transportation Institute
The Pennsylvania State University
101 Hammond Building
University Park, PA 16802
Tel: (814) 865-4542
Fax: (814) 863-0497 (fax)
jmason@engr.psu.edu

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ABSTRACT

Current work zone design and traffic control guidance is heavily based on desirable speed-related outcomes, but knowledge related to actual speed-related outcomes of design and traffic control decisions is limited. The objective of this research is to investigate relationships between speed behavior, roadway and roadside geometrics and traffic control in work zones. The objective is accomplished through specification and estimation of a seemingly unrelated regression (SUR) model. The dependent variables modeled were 85th percentile passenger car speed and standard deviation of passenger car speed. Work zone design and traffic control features were investigated as explanatory variables. Speed and infrastructure data used for estimation were collected in Pennsylvania and Texas work zones. The SUR model accounted for contemporaneous correlations of the disturbance terms in the two speed equations. In the equation for 85th percentile speed, regression parameters were statistically significant for variables representing work zone configuration, type of roadway infrastructure, work zone location, distance traveled from the beginning of the work zone, posted speed limit, vertical alignment and total paved cross section width. In the equation for standard deviation of speed, parameters were statistically significant for variables representing distance traveled from the beginning of the work zone, total paved cross section width, reduction in posted speed and roadside conditions. Several recommendations for future work are provided, including expansion of the system of equations to include 85th percentile truck speeds and standard deviation of truck speeds and consideration of possible contemporaneous relationships between speed measures.

INTRODUCTION

The *Manual on Uniform Traffic Control Devices* (*MUTCD*) defines a work zone as an area of highway with construction, maintenance or utility work activities (*1*). Work zones are designed to accommodate these activities in addition to traffic movement. Reduced cross sections, increased curvature and other temporary design and traffic control features may be present, resulting in deviations from pre- or post work zone operations. National guidance related to work zone design and traffic control decisions is currently provided by the *MUTCD*, published by the Federal Highway Administration (FHWA) and *A Policy on Geometric Design of Highways and Streets* (*Green Book*) and *Roadside Design Guide*, both published by the American Association of State Highway and Transportation Officials (AASHTO) (*1-3*). Table 1 provides a summary of the scope of these publications and their application to work zone design.

As indicated by Table 1, limited guidance on roadway geometrics and roadside design for work zones exists. The *MUTCD* addresses this gap with the following philosophy (*1*):

> "The basic safety principles governing the design of permanent roadways and roadsides should also govern the design of [temporary traffic control] TTC zones. The goal should be to route road users through such zones using roadway geometrics, roadside features, and TTC devices as nearly as possible comparable to those for normal highway situations."

Although not explicitly stated, the passage is recommending the use of geometric and roadside design criteria for permanent facilities but is allowing flexibility. The use of permanent roadway and roadside criteria are often impractical given the temporary nature of work zones and physical constraints associated with accommodating work activity in addition to traffic movement. As a result, some state departments of transportation (DOTs) have developed "in-house" work zone design guidance. State practices vary (*4*).

Published research documents also include work zone design recommendations (*5-8*). The most recent were part of a research effort sponsored by the National Cooperative Highway Research Program (NCHRP) to develop design-decision guidance for construction work zones on high-speed highways (*4, 5*). An important commonality between national guidance, state DOT-developed guidance and research recommendations is the prominent role of speed in work zone design and traffic control decisions.

Speed and Work Zone Design

Speed is a primary input into past and current geometric and roadside design processes for permanent facilities. It is an important performance measure used to assess the quality of highway operation. Ideally, the speed that drivers travel on a facility should match the intended purpose of that facility and be harmonious with the surrounding environment. This is not always the case. Most recent research and opinion recognize that driver speed is a "complex issue involving engineering, driving behavior, education and enforcement." (*9*)

Speed is also prominent in current work zone design policies and practice. It is an input to several decisions related to TTC covered by the *MUTCD* (see Table 2). In addition, the *MUTCD* recommends an overall design philosophy of maintaining upstream or pre-work zone speeds if practical and minimizing magnitudes of speed reductions if necessary. The following excerpts illustrate this philosophy (*1*):

"Reduced speed limits should be used only in the specific portion of the TTC zone where conditions or restrictive features are present."

"A TTC plan should be designed so that vehicles can reasonably safely travel through the TTC zone with a speed limit reduction of no more than 10 [miles per hour] mph."

"A reduction of more than 10 mph in the speed limit should be used only when required by restrictive features in the TTC zone. Where restrictive features justify a speed reduction of more than 10 mph, additional driver notification should be provided. The speed limit should be stepped down in advance of the location requiring the lowest speed, and additional TTC warning devices should be used."

Limiting speed reductions to 10 mph is based on desirable speed variance effects:

"Smaller reductions in the speed limit of up to 10 mph cause smaller changes in speed variance and lessen the potential for increased crashes. A reduction in the regulatory speed limit of only up to 10 mph from the normal speed limit has been shown to be more effective."

The work zone speed philosophy endorsed by the *MUTCD* is consistent with state DOT practice and recommended design procedures in published research literature (*5-8*). The idea is to route motorists through a work zone without a posted speed reduction. If restrictive features are present and a posted speed reduction is considered appropriate, it should be limited to 10 mph. The basis is a research study which showed that a 10 mph posted speed reduction resulted in the smallest increase in speed variance (*6*). In addition, work zones with a 10 mph posted speed reduction experienced the smallest increase in crash rate from preconstruction periods on rural freeways when the work activities were on or near the traveled way (*6*). Drawbacks of the referenced study were relatively small sample sizes and lack of statistically significant findings. Rationale for basing a speed limit procedure on these results was provided: "Despite the lack of statistical significance, rational policies for setting work zone speed limits must be developed."(*6*) The guidance is logical, but difficult to apply given the current state of work zone speed-related knowledge. Several observations support this general conclusion:

- Recommendations based on research results related to reductions in posted speed have been applied to other work zone speed measures (e.g. design speed, target speed, anticipated operating speed). These measures may or may not be surrogates for each other or actual operating speeds.
- Although current work zone design guidance is heavily based on desirable speed-related outcomes (e.g. maintaining certain operating speeds, minimizing speed

variance), knowledge related to actual speed-related outcomes of design and traffic control decisions is limited.

- Speed-related work zone design decisions use a variety of speed inputs interchangeably (e.g. speed limit, speed category, 85th percentile speed and design speed). Relationships between these measures are not consistent for permanent roadways or work zones.
- Existing and proposed design and traffic control practices are based on achieving desirable speed magnitudes while minimizing speed variance. These objectives may be complimentary or conflicting depending on the design or traffic control decision.
- Inconsistencies between pre-work zone operating speeds, desired operating speeds, posted speed and actual operating speeds lead to reactive implementation and unanticipated expenditures for work zone speed management strategies (e.g. police presence, intelligent transportation systems) when actual speeds are higher than intended speeds or after the occurrence of one or more severe crashes.

RESEARCH OBJECTIVE

The objective of this research is to investigate relationships between speed behavior, roadway and roadside geometrics and traffic control in work zones. Current and recommended work zone design processes would benefit from an understanding of the speed-related outcomes of design and traffic control decisions. The research need is illustrated by the bulleted observations above.

The objective is accomplished through specification and estimation of a seemingly unrelated regression (SUR) model. Current work zone design and traffic control guidance is based on outcomes related to speed magnitude and speed variance. Eighty-fifth (85th) percentile speed is the most commonly referenced measure of speed magnitude used in design and traffic control decision processes. Standard deviation of speed is directly related to speed variance and has units consistent with 85th percentile speed. Therefore, the dependent variables modeled are 85th percentile speed and standard deviation of speed. Work zone design and traffic control features are investigated as explanatory variables. Passenger cars and trucks have inherently different physical dimensions and performance capabilities; different speed behavior is expected. Passenger car speeds are the focus of this paper.

Although some studies have investigated speed effects of work zone design and traffic control decisions (e.g. *6, 8, 10-15*), a regression model of this type does not exist. This first modeling step is intended to discover possible associations between work zone variables and speeds.

DATA COLLECTION

This research focused on construction work zones, locations of long-term stationary work for the purpose of construction, reconstruction, rehabilitation or preventive maintenance. A number of work zone traffic control strategies exist. The feasibility of specific strategies is dependent on facility type; a large number of facility type-work zone strategy combinations are possible [see (*5*)]. In addition, speed data may be collected under a variety of conditions (e.g., day, night, clear weather, rain, congested, free-flow conditions etc.). For this study, free-flow speeds (defined as speeds of vehicles having time headways greater than 4 seconds from preceding vehicles) were collected for passenger cars in lane closure and median crossover work zones. All data were collected in dry, daylight conditions on four-lane divided freeways in Pennsylvania and Texas. Definitions follow:

Lane closure: a construction work zone type for which one or more travel lanes and any adjacent shoulders are closed to traffic. On four-lane divided highways, the closure occurs either on the outside lane and shoulder or the median lane and shoulder, with traffic using the remaining open lane and shoulder.

Median crossover: a construction work zone type used on freeways and expressways wherein:

- The number of lanes in both directions are reduced;
- At both ends, traffic in one direction is routed across the median to the opposite-direction roadway on a temporary roadway constructed for that purpose;
- Bi-directional traffic is maintained on one roadway while the opposite direction roadway is closed.

Four-lane divided freeway: A divided facility with two-lanes per direction and full control of access (i.e. access provided only through grade separated interchanges).

Example plans for typical lane closures and median crossovers on four-lane divided freeways are illustrated in Figures 1 and 2. All freeways had pre-work zone posted speeds ranging from 55 to 70 mph.

Data were collected in a total of 17 construction work zones; 11 lane closures and 6 median crossovers. For crossovers, data were only collected in the travel direction with the crossover. The work zone set-ups were "standard"; anomalies designed to accommodate uncommon situations were avoided. At each work zone, anywhere from 2 to 19 locations were selected for speed data collection. One location was upstream of the work zone and any associated temporary traffic control devices. Upstream speed characteristics were tested as candidate explanatory variables of work zone speeds. The remaining locations were located in the lane taper and the work area. The lane taper was defined as the area of transition between the normal cross section and the work zone cross section. Tapers were typically created by a series of channelizing devices such as vertical panels or drums. The work area comprised the remainder of the work zone from the end of the lane taper to the termination point.

Data collection locations were selected to provide a range of conditions for roadway cross sections, roadside features and horizontal and vertical alignment. Locations where vehicle speeds appeared to be affected by the presence of entrance or exit ramps were avoided. At each location, approximately 200 free-flow speeds were collected with either Light Detection and Ranging (LIDAR) or Radio Detection and Ranging (RADAR) guns. Data collectors concealed themselves from the view of drivers to avoid influencing vehicle speeds by their presence. RADAR was used when the smaller beam of LIDAR was not practical given the location of the data collector relative to traffic. At these locations, cosine corrections to the observed speeds were made. The RADAR was turned off until the moment of speed measurement to try and minimize the effects on drivers with radar detecting equipment. Independent samples were collected at each work zone location (i.e. the same vehicle was not tracked through the work zone).

Work zone geometry and traffic control data were also collected at each location, including geometry of the permanent infrastructure. Sources of this data were as-built plans/drawings located in Pennsylvania and Texas DOT district offices, temporary traffic control plans located in DOT project offices and observations and measurements made at the construction sites. A typical protocol for work zone and infrastructure data collection involved the following steps:

1. Videotape a drive through of the subject work zone and record (vocally) notes of general geometric and traffic control observations.
2. Using video and notes, select potential data collection locations based on obtaining a representative range of geometry in the work zone.
3. Collect speed data and record geometric and traffic control observations at selected locations.
4. Determine data collection locations in reference to the nearest mile marker.
5. Collect relevant geometric and traffic control information from temporary traffic control plans in state DOT project field office and verify with field observations made in step 3.
6. Determine geometrics of permanent infrastructure at work zone location from as-built plans in state DOT district offices and verify with field observations made in step 3.

The following geometric and traffic control information was collected at all locations: travel lane width, right and left shoulder width, right and left shoulder type, presence of and offset to roadside objects (e.g. temporary or permanent barrier, work zone channelizing devices, other roadside conditions), radius of horizontal curves, vertical grade, rate of vertical curvature, posted speed limit, downstream distance from the lane taper and cross slope. The final data set consists of 18,739 free-flow passenger car observations at 136 locations. Table 3 summarizes descriptive statistics of the dependent variables (85th percentile passenger car speed and standard deviation of passenger car speed) by work zone location. Tables 4 and 5 summarize the descriptive statistics of the categorical and continuous work zone variables collected at the lane taper and work area locations.

MODELING APPROACH

Models for 85th percentile passenger car speed and standard deviation of passenger car speed were estimated. Only exogenous or predetermined variables (i.e. geometric characteristics, traffic control and upstream speed characteristics) were tested as potential right hand side (RHS) variables. The general model structure is illustrated below:

$$y_i = \alpha + \beta X_i + \varepsilon_i \tag{1}$$

$$\sigma_i = \tau + \eta V_i + \nu_i \tag{2}$$

where: y_i = 85th percentile speed of passenger cars at location i

X_i = vector of exogenous variables influencing y_i (i.e. roadway and roadside geometrics, traffic control variables and upstream speed characteristics)

σ_i = standard deviation of passenger car speed at location i

V_i = vector of exogenous variables influencing σ_i (i.e. roadway and roadside geometrics, traffic control variables and upstream speed characteristics)

$\alpha, \beta, \tau, \eta$ = vectors of coefficients to be estimated

ε_i, ν_i = disturbance terms

Estimating speed models similar to equations 1 and 2 using ordinary least squares (OLS) is the predominant method in speed modeling literature for permanent roadways. It has several advantages including computational ease and relatively robust application when only one dependent continuous variable is involved. OLS of the model above would be classified as a single-equation or limited information method: the parameters for each equation are estimated separately, utilizing the knowledge of restrictions only in the particular equation being estimated. Given interpretation of the disturbance terms, other methods may be superior in this empirical setting.

The random disturbance terms (ε_i and ν_i) are present for several reasons, but primarily because one cannot measure every influence on the dependent variable of interest. The omitted influential factors are captured in the disturbance. Other contributors to the disturbance include errors in measurement. Measurement error in the dependent variable is often not considered a large problem because it is captured in the disturbance term. There may be similar factors affecting the disturbances for 85th percentile speed and standard deviation of speed, resulting in contemporaneous correlation between ε_i and ν_i. Estimating the model as a system may result in efficiency gains. Since only exogenous RHS variables are included in the specifications, the equations are linked only through their disturbances. This technique, referred to as seemingly unrelated regression (SUR), was introduced by Zellner (*16*).

SUR estimation is classified as a full-information method and uses a generalized least squares (GLS) estimator. The difference between OLS and SUR models arise from assumptions regarding the contemporaneous correlation of ε_i and ν_i. OLS assumes this correlation is zero, whereas SUR does not impose this constraint. SUR models using the GLS estimator offer efficiency gains when two conditions hold: (1) cov(ε_i, ν_i) ≠ 0, and (2) $X_i \neq V_i$. If either of these does not hold, then OLS and GLS are the same and the SUR model reduces to an equation-by-equation OLS regression model. GLS offers greater efficiency gains with increasing correlation between the disturbances (ε_i, ν_i) and diminishing correlation between the exogenous variable matrices (X_i, V_i).

Consistent with work by Shankar and Mannering (*17*), the logarithms of 85th percentile speeds and standard deviations of speeds were used for model estimation. A log-linear functional form maintains two desirable properties: non-negativity of speed measures and monotonic relationship between left-hand-side (LHS) and RHS variables (i.e. no large "jump" in the LHS variables with a small change in RHS variables). It is important, however, to note the resulting multiplicative structure of the model:

$$\ln(y_i) = \alpha + \beta X_i + \varepsilon_i \tag{3}$$

$$y_i = \exp(\alpha + \beta X_i + \varepsilon_i) = e^{\alpha} e^{\beta X_i} e^{\varepsilon_i} \tag{4}$$

The parameters and other model statistics (e.g., R-squared) are applicable to the logarithms of 85th percentile speed and standard deviation of speed. Transformations to the multiplicative form are needed to interpret relationships between RHS variables and actual speed measures.

A general-to-specific specification strategy was used in a sense that all variables related to traffic control, roadway and roadside infrastructure and other work zone features may possibly be associated with speed magnitudes and deviations. General categories for exogenous RHS variables are summarized in Tables 4 and 5. Variables representing different elements of the work zone environment took several forms as continuous and/or dummy variables. Continuous variable forms usually consisted of actual dimensional values (e.g. traveled way width in units of feet). Dummy variable forms were categorical (e.g. a binary variable indicating whether traveled way width is greater than 12 feet).

Parameter stability during the inclusion or exclusion of new predictors was also observed. In most cases, unstable parameters were the result of too few cases within a dummy variable category. Therefore, a minimum mean of 0.1 (10 percent) for all dummies was used as a rule-of-thumb, but not a requirement. Similarly, a rule-of-thumb for the probability of making a type I error was approximately 0.05 percent.

The estimation results for the SUR models are shown in Tables 6 (85th percentile speed) and 7 (standard deviation of speed).

INTERPRETATION OF RESULTS

Interpretation of the variables and parameters is summarized in Tables 8 and 9. It should be noted that in reading the findings, the phrase "given that values for other variables remain constant" was not included but is implied. Measures of horizontal alignment (e.g. radius of curve, inverse of radius, degree of curve, etc.) have been prevalent in speed models for two-lane rural highways. A variety of horizontal alignment variables were tested for this research. The parameters were not significantly different from zero. The finding is likely attributable to the flat radii (i.e. greater than 2000 feet) observed at most locations.

CONCLUSIONS AND RECOMMENDATIONS

This research investigated relationships between 85th percentile passenger car speed and standard deviation of passenger car speed, roadway and roadside geometrics and traffic control in construction work zones on four-lane divided freeways. The following conclusions were reached:

- SUR estimation should be considered when two or more operational measures are being modeled. SUR models account for correlations between disturbance terms by using a single simultaneous estimation of the parameters in all equations. Efficiency gains result if two conditions hold: 1) correlations between disturbances exist and 2) the set of explanatory variables are different across equations.

- In the reported model for 85th percentile passenger car speed, regression parameters were statistically significant for variables representing work zone configuration, type of roadway infrastructure, work zone location, distance traveled from the beginning of the work zone, posted speed limit, vertical alignment and total paved cross section width.
- In the reported model for standard deviation of passenger car speed, regression parameters were statistically significant for variables representing distance traveled from the beginning of the work zone, total paved cross section width, posted speed reduction, the presence of temporary concrete barrier and the presence of a clear roadside.
- Standard deviation of passenger car speed was lowest in work zones with a posted speed reduction of 10 or 15 mph compared to work zones with no posted speed reduction. This finding appears to contradict guidance in the *MUTCD* that a reduction in posted speed is associated with an increase in speed variance.

Recommendations of the research are:

- Expand the system of equations to include 85th percentile truck speeds and standard deviation of truck speeds. Contemporaneous relationships between speed measures should also be investigated.
- Conduct a large national research effort aimed at developing work zone speed models. Results will aid in the development of consistent design and traffic control guidance for work zones.
- Investigate the use of purely predictive modeling techniques. These include models with lagged endogenous and exogenous variables and Artificial Neural Networks.
- Model results and respective conclusions are applicable to work zone strategies, facility types and dimensional ranges of geometric and traffic control features observed in this study. Work zones on other functional classifications and facility types should also be observed. Differences in design practices, traffic volumes and traffic mix on these facilities are likely to influence speed-related findings.

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REFERENCES

1. *Manual on Uniform Traffic Control Devices*. Federal Highway Administration, Washington, DC, 2003.
2. *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials, Washington DC, 2005.
3. *Roadside Design Guide*. American Association of State Highway and Transportation Officials, Washington, DC, 2002.

4. Mahoney, K.M., Porter, R.J., Taylor, D.R., Kulakowski, B.T. and Ullman, G.L. *Design of Construction Work Zones on High-Speed Highways*. NCHRP Web Only Document 105. National Cooperative Highway Research Program, Transportation Research Board, 2007.
5. Mahoney, K.M., Porter, R.J., Taylor, D.R., Kulakowski, B.T. and Ullman, G.L. *Design of Construction Work Zones on High-Speed Highways*. NCHRP Report 581. National Cooperative Highway Research Program, Transportation Research Board, 2007.
6. Procedure for Determining Work Zone Speed Limits. *National Cooperative Highway Research Program research Results Digest No. 192*, Transportation Research Board, National Research Council, Washington, DC, 1996.
7. Richards, S.H. and Dudek, C.L. Implementation of Work Zone Speed Control Measures. In *Transportation Research Record, Journal of the Transportation Research Board, No. 1086*, TRB, National Research Council, Washington, D.C., 1986, pp. 36-42.
8. Graham, J.L., Paulsen, R.J. and Glennon, J.C. *Accident and Speed Studies in Construction Zones*. Publication FHWA-RD-77-80. Federal Highway Administration, U.S. Department of Transportation, 1977.
9. Federal Highway Administration. *Speed Management*. http://safety.fhwa.dot.gov/speed_manage/index.htm. Accessed July 6, 2006.
10. Graham, J.L., Harwood, D.W. and Sharp, M.C. Effects of Taper Length on Traffic Operations in Construction Zones. In *Transportation Research Record, Journal of the Transportation Research Board, No. 703*, TRB, National Research Council, Washington, D.C.,1979, pp. 19-24.
11. McCoy, P.T. and Peterson, D.J. Safety Effects of Two-Lane Two-Way Segment Length through Work Zones on Normally Four-Lane Divided Highways. In *Transportation Research Record, Journal of the Transportation Research Board, No. 1163*, TRB, National Research Council, Washington, D.C., 1988, pp. 15-21.
12. Jiang, Y. Traffic Capacity, Speed and Queue Discharge Rate of Indiana's Four-Lane Freeway Work Zones. In *Transportation Research Record, Journal of the Transportation Research Board, No. 1657*, TRB, National Research Council, Washington, D.C., 1999, pp. 10-17.
13. Benekohal, R.F., Kaja-Mohideen, A.Z. and Chitturi, M.V. Methodology for Estimating Operating Speed and Capacity in Work Zones. In *Transportation Research Record, Journal of the Transportation Research Board, No. 1883*, TRB, National Research Council, Washington, D.C., 2004, pp. 103-111.
14. Zhu, J. and Saccomanno, F.F. Safety Implications of Freeway Work Zone Lane Closures. In *Transportation Research Record, Journal of the Transportation Research Board, No. 1877*, TRB, National Research Council, Washington, D.C., 2004, pp. 53-61.
15. Chitturi, M.V. and Benekohal, R.F. Effect of Lane Width on Speeds of Cars and Heavy Vehicles in Work Zones. In *Transportation Research Record, Journal of the Transportation Research Board, No. 1920*, TRB, National Research Council, Washington, D.C., 2005, pp. 41-48.

16. Zellner, A. An Efficient Method of Estimating Seemingly Unrelated Regressions and Tests for Aggregation Bias. In *Journal of the American Statistical Association No. 57*, pp. 348-368, 1962.
17. Shankar, V. and Mannering, F. Modeling the Endogeneity of Lane-Mean Speeds and Lane-Mean Speed Deviations: A Structural Equations Approach. In *Transportation Research - Part A, Vol. 32, No. 5*, 1998, 311-322.
18. Breusch, T.S. and A.R. Pagan. The Lagrange Multiplier Test and its Application to Model Specification in Econometrics. *Review of Economic Studies No. 47*, pp. 239-253, 1980.
19. Greene, W.H. *Econometric Analysis: Fifth Edition*. Prentice Hall, New Jersey, 2003.

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TABLE 1 Scope of Work Zone Design Guidance in Existing National Publications

Publication	Scope of Publication	Construction Work Zone Design Coverage
MUTCD	Traffic control devices	Typical applications of temporary traffic control devices for work zones that consider the needs and control for all road users Limited guidance on work zone geometrics and roadside features
AASHTO *Green Book*	Geometric guidance for all types of roads	Very limited (2 pages) coverage regarding work zone geometrics. No dimensional guidance or quantitative methods are included.
AASHTO *Roadside Design Guide*	Roadside design practice and principles	Comprehensive guidance regarding physical characteristics and crashworthiness of work zone traffic control and other roadside devices and barriers. Limited dimensional and quantitative design guidance with respect to clear zones, slopes, horizontal clearance, and temporary barrier use.

TABLE 2 Summary of Speed-Related Temporary Traffic Control Decisions in the *MUTCD*

Traffic control decision	Speed measure used as decision input
Location of first advanced warning sign	Speed limit
Distance between advance warning signs	Speed category of roadway (e.g. low-speed, high-speed)
Stopping sight distance	Posted speed, off-peak 85th percentile speed prior to work or anticipated operating speed
Length of taper	Posted speed, off-peak 85th percentile speed prior to work or anticipated operating speed
Distance between taper devices	Speed limit
Use of temporary traffic barriers	Speed of traffic

TABLE 3 Descriptive Statistics for 85th Percentile Speed and Standard Deviation of Speed by Work Zone Location

	Aggregated 85th Percentile Passenger Car Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	59	79	73.63	4.38
Lane Taper	23	57	76	66.81	5.85
Work Area	96	43	73	61.71	5.24
	Aggregated Standard Deviation of Passenger Car Speed (mph)				
Location Type	**N**	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
Upstream	17	3.14	6.36	5.04	0.833
Lane Taper	23	4.45	6.68	5.46	0.648
Activity Area	96	2.81	8.61	4.83	0.959

TABLE 4 Descriptive Statistics of Candidate Categorical Predictor Variables

		Lane Taper (23 locations)		Activity Area (96 locations)	
Variable	**Categories**	**Frequency**	**Percent**	**Frequency**	**Percent**
Lane closed	Left	7	30.4%	9	9.4%
	Right	16	69.6%	87	90.6%
Posted speed	50	4	17.4%	25	26.0%
	55	2	8.7%	8	8.3%
	60	4	17.4%	31	32.3%
	65	7	30.4%	16	16.7%
	70	6	26.1%	16	16.7%
Police presence	no	21	91.3%	92	95.9%
	yes	2	8.7%	4	4.2%
Roadway type	Permanent	23	100.0%	66	68.8%
	Temporary	0	0.0%	30	31.3%
Horizontal alignment	Tangent	19	82.6%	52	54.2%
	Curve to the left	2	8.7%	27	28.1%
	Curve to the right	2	8.7%	17	17.7%
Vertical alignment	Flat (-1 to 1)	12	52.2%	41	42.7%
	Upgrade	2	8.7%	21	21.9%
	Downgrade	1	4.3%	25	26.0%
	Crest curve	7	30.4%	4	4.2%
	Sag curve	1	4.3%	5	5.2%
Location in vertical curve	Incoming grade	2	8.7%	0	0.0%
	Middle	1	4.3%	5	5.2%
	Outgoing grade	1	4.3%	2	2.1%
	N/A	15	65.2%	87	90.6%
	Missing	4	17.4%	2	2.1%
Traffic control device (TCD) to the left	None	15	65.2%	31	32.3%
	Drum	7	30.4%	7	7.3%
	Panel	0	0.0%	2	2.1%
	Guardrail	0	0.0%	4	4.2%
	Concrete barrier	1	4.3%	50	52.1%
	Opposing traffic	0	0.0%	2	2.1%
Traffic control device (TCD) to the right	None	7	30.4%	36	37.5%
	Drum	8	34.8%	17	17.7%
	Panel	1	4.3%	9	9.4%
	Guardrail	0	0.0%	9	9.4%
	Concrete barrier	4	17.4%	20	20.8%
	Other	3	13.0%	5	5.2%

TABLE 5 Descriptive Statistics of Candidate Continuous Predictor Variables

	Lane Taper (23 locations)					Activity Area (96 locations)				
Variable	**N**	**Minimum**	**Maximum**	**Mean**	**STD**	**N**	**Minimum**	**Maximum**	**Mean**	**STD**
Downstream distance from taper (miles)	23	0	0.2	0.06	0.08	96	0.2	10.6	3.03	3.03
Radius of curve (ft)	4	2292	7640	4018	2448	44	1911	11480	5743	3198
Superelevation (%)	22	2	7.5	2.46	1.48	81	2.0	7.5	2.56	1.43
Incoming grade (%)	22	-3.22	3	0.39	1.35	96	-4.0	3.0	-0.33	1.77
Outgoing grade (%)	5	-3.5	-2	-2.96	0.61	7	-2.7	3.0	-0.18	2.41
Rate of vertical curvature, K (ft/%)	7	247	615	364	127	9	150	500	258	128
Traveled way width (ft)	23	12	24	17	4.6	96	11	16	12.44	1.29
Right shoulder width (ft)	23	0	10	3	4.6	96	0	16	4.17	4.10
Left shoulder width (ft)	23	0	8	3.7	3	96	0	36	3.23	4.40
Total paved width (ft)	23	16	34	23	5.3	96	12	48	19.14	4.89
Left offset to TCD (ft)	8	0	5	1.1	1.8	65	0	48	3.91	9.44
Right offset to TCD (ft)	16	0	4	1.3	1.4	60	0	24	2.78	3.79

TABLE 6 SUR Estimation of 85th Percentile Passenger Car Speed

Variable	Estimated coefficient	S.E.	t-ratio	p-value	$\overline{X}$
Equation 1: logarithm of 85th percentile speed (mph)					
Constant	4.063	0.013	308.31	<0.0001	
Indicator of work zone type (1 if single lane closure; 0 if median crossover)	-0.073	0.016	-4.506	<0.0001	0.429
Indicator of roadway infrastructure type (1 if permanent; 0 if temporary)	0.042	0.014	3.035	0.0024	0.748
Indicator of location in work zone (1 if location is within the lane taper; 0 otherwise)	0.065	0.015	4.212	<0.0001	0.193
Downstream distance from lane taper (mile)	-0.007	0.002	-3.310	0.0009	2.457
Posted speed indicators (1 if 60 mph; 0 otherwise)	0.085	0.017	4.901	<0.0001	0.294
Posted speed indicators (1 if 65 mph; 0 otherwise)	0.094	0.017	5.599	<0.0001	0.193
Posted speed indicators (1 if 70 mph; 0 otherwise)	0.120	0.017	7.077	<0.0001	0.184
Vertical alignment indicator (1 if -1% ≤ grade ≤ 1%; 0 otherwise)	0.044	0.013	3.378	0.0007	0.496
Total paved width indicator (1 if ≤ 15 feet; 0 otherwise)	-0.063	0.019	-3.376	0.0007	0.092
Vertical alignment indicator (1 if crest curve; 0 otherwise)	-0.049	0.020	-2.435	0.0149	0.092
SSE = 0.303 Standard error of e = 0.0529 R^2 = 0.673 Adjusted R^2 = 0.643 F [10,108] = 22.27 ($p < 0.0001$) X^2 [10] = 144.71 ($p < 0.0001$)					

TABLE 7 SUR Estimation of Standard Deviation of Passenger Car Speed

Variable	Estimated coefficient	S.E.	t-ratio	p-value	$\overline{X}$
Equation 2: logarithm of standard deviation of speed (mph)					
Constant	1.738	0.022	77.768	<0.0001	
Downstream distance from lane taper (mile)	-0.022	0.005	-4.143	<0.0001	2.457
Total paved width indicator (1 if ≤ 15 feet; 0 otherwise)	0.140	0.042	3.357	0.0008	0.092
Indicator for difference in work zone and upstream posted speed (1 if 10 or 15 mph; 0 if 0mph)	-0.068	0.026	-2.624	0.0087	0.580
Roadside device and offset indicator (1 if PCB in left or right roadside with less than or equal to 1 foot offset; 0 otherwise)	-0.119	0.028	-4.185	<0.0001	0.479
Roadside device indicator (1 if right roadside clear; 0 otherwise)	-0.052	0.026	-2.036	0.0418	0.361
SSE = 1.8574 Standard error of e = 0.1282 R^2 = 0.543 Adjusted R^2 = 0.523 F [5,113] = 26.83 ($p < 0.0001$) X^2 [5] = 93.30 ($p < 0.0001$)					

TABLE 8 Interpretation of Model Parameters for OLS Estimation of 85th Percentile Speed

Variable	Finding
Constant	The estimated constant can be interpreted as approximately 58 mph ($e^{4.063}$).
Indicator of work zone type	Expected 85th percentile free flow speed is approximately 7 percent slower in lane closures compared to work zones with median crossovers. This may be due, in part, to the closer proximity of work to the traffic in lane closures.
Indicator of roadway infrastructure type	Expected 85th percentile speed is 4 percent faster on infrastructure that is permanent compared to speeds on temporary infrastructure. In this dataset, temporary infrastructure consisted of reverse horizontal curves on a median crossover.
Indicator of location in work zone	Expected 85th percentile speed is approximately 7 percent higher in the lane taper than in the remainder of the work zone.
Downstream distance from lane taper (miles)	Expected 85th percentile speed decreases by approximately 1 percent for every mile traveled in the work zone.
Posted speed indicator (60 mph)	Expected 85th percentile speed is approximately 9 percent higher in work zones with posted speeds of 60 mph than in work zones with posted speeds of 50 or 55 mph.
Posted speed indicator (65 mph)	Expected 85th percentile speed is approximately 10 percent higher in work zones with posted speeds of 65 mph than in work zones with posted speeds of 50 or 55 mph.
Posted speed indicators (70 mph)	Expected 85th percentile speed is approximately 13 percent higher in work zones with posted speeds of 70 mph than in work zones with posted speeds of 50 or 55 mph.
Vertical alignment indicator ($-1\% \leq$ grade $\leq 1\%$)	Expected 85th percentile speed is faster on flat grades than on steeper (than 1 percent) downgrades or upgrades.
Total paved width indicator (15 feet)	Expected 85th percentile speed is approximately 6 percent slower when the total paved width is less than 15 feet compared to larger total paved widths.
Vertical alignment indicator (crest)	Expected 85th percentile speed is approximately 5 percent slower on crest vertical curves than on sag curves or vertical tangents.

TABLE 9 Interpretation of Model Parameters for Standard Deviation of Speed

Variable	**Finding**
Constant	The estimated constant can be interpreted as approximately 5.7 mph ($e^{1.738}$).
Downstream distance from lane taper (miles)	Expected standard deviation of free flow speed decreases by approximately 2 percent for every mile traveled in the work zone.
Total paved width indicator (15 feet)	Expected standard deviation of free flow speed is approximately 15 percent higher when the total paved width is less than 15 feet compared to greater total paved widths.
Indicator for difference in work zone and upstream posted speed (10 or 15 mph)	Expected standard deviation of free flow speed is approximately 7 percent lower when there is a posted speed reduction in the work zone (compared to upstream or pre-project posted speed) of 10 or 15 mph then when there is no posted speed reduction.
Roadside device and offset indicator (TCB in left or right roadside with less than or equal to 1 foot offset)	Expected standard deviation of free flow speed is approximately 11 percent lower at locations where there is a temporary concrete barrier less than or equal to 1 foot from the traveled way (compared to all other roadside conditions).
Roadside device indicator (right roadside clear)	Expected standard deviation of free flow speed is approximately 5 percent lower at locations where the right roadside is clear (compared to all other roadside conditions).

FIGURE 1 Example plan for lane closure.

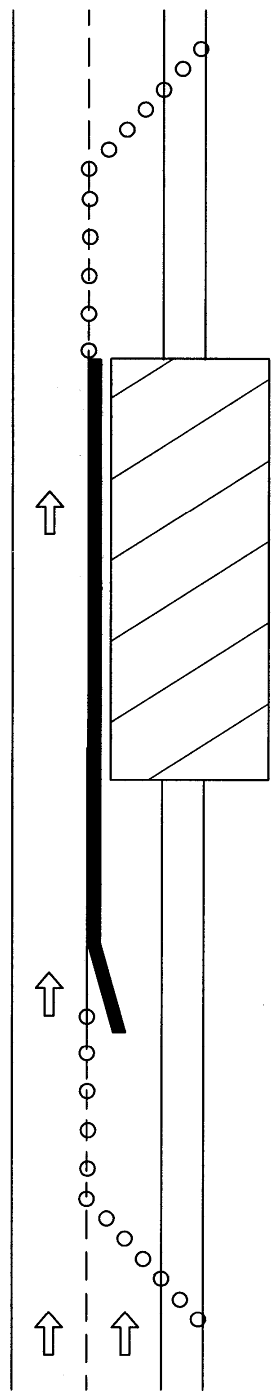

FIGURE 2 Example plan for median crossover.