SAE International™	**SURFACE VEHICLE RECOMMENDED PRACTICE**	**SAE J2944** **Proposed Draft** **February 12, 2013**
		Issued Revised Superseding

OPERATIONAL DEFINITIONS OF DRIVING PERFORMANCE MEASURES AND STATISTICS

RATIONALE

A common and consistently defined vocabulary is a basic requirement for comparing studies and test procedures and their results for driving contexts, vehicles, and vehicle components, and is the reason for foundational documents such as SAE J1100 Motor Vehicle Dimensions (2009) and related mobility documents (Steinfeld, Fong, Kaber, Lewis, Scholtz, and Goodrich, 2006). (See also National Research Council, 2011.) As shown by Savino (2009) and Green (2012), many terms used to describe driving performance are not consistently named, defined (if they are defined at all), or used, in the automotive research and engineering literature. This inconsistency makes comparing studies and test procedures and their results difficult, compromising safety and usability, a major problem. To overcome the inconsistency problem, this document provides standard names and definitions of driving performance measures and statistics, as well as supporting information to encourage their use.

1. SCOPE

The purpose of this Recommended Practice is to operationally define driving performance measures and statistics concerned with on-road driving so that the measurements and statistics are calculated and reported in a consistent manner in various studies and test procedures, so the results can be compared. Only measures and statistics pertaining to driver/vehicle responses that affect the lateral and longitudinal positioning of a road vehicle are provided in this document for now. Measures and statistics covering other aspects of driving performance may be included in future editions

1.1 Applicable Vehicles

This Recommended Practice applies for both left- and right-hand-drive wheeled vehicles having a steering control, accelerator pedal, and a brake pedal. The vehicles shall have at least four wheels, one at each corner of the vehicle. Thus, this Recommended Practice applies primarily to passenger vehicles, heavy trucks, and buses, but may be useful in part for other types of vehicles. For agricultural, construction, industrial equipment, and military vehicles, this Recommended Practice only applies when those vehicles are driven on-road, not off-road. Motorcycles and mopeds, as well as three-wheel and tracked vehicles are excluded from the scope to avoid complicating the specification of lane-related measures. Road vehicles operated only by hand controls are also excluded.

In addition, Section 7, concerning reaction, movement, and response measures for foot pedals assumes that the vehicle is equipped with an automatic transmission, which is commonly the case for test vehicles and passenger-car driving simulators. In contrast, manual transmissions with clutches are quite common in the vehicle fleet, especially outside of the North America. For vehicles with manual transmissions, especially motorcycles, drivers may decelerate or accelerate by downshifting or upshifting, though that is not common in emergencies. Foot-pedal related measures and statistics for vehicles with clutches have not been considered in this edition of J2944 so that the document could be developed more speedily. However, all other measures are applicable to vehicles with clutches.

1.2 Applicable Contexts

This Recommended Practice is applicable to studies and tests of vehicles and drivers conducted on public traveled ways, on private traveled ways, on test tracks, or in driving simulators. All functional classes of highways and streets, as defined by the AASHTO Green Book, chapter 1 (AASHSTO, 2011) are included so as to support naturalistic driving studies.

1.3 Purpose

The measures and statistics defined in this document are intended to be used to describe the lateral and longitudinal control of road vehicles as part of safety/distraction and/or usability evaluations of (1) telematics systems (e.g., navigation systems, in-vehicle cell phones), (2) driver awareness and assistance systems (e.g., adaptive cruise control, lane keeping assistance, collision warning, crash avoidance braking), (3) fitness to drive/licensing, (4) drug and medication use by drivers, (5) autonomous driving, and (6) for other purposes. These measures and statistics appear in SAE and ISO standards, journal articles, proceedings papers, technical reports, and presentations.

2 REFERENCES

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Phone: +1 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J1100 Motor Vehicle Dimensions

SAE J2399 Adaptive Cruise Control (ACC) Operating Characteristics and User Interface

SAE J2400 Human Factors in Forward Collision Warning Systems: Operating Characteristics and User Interface Requirements

SAE J2808 Road/Lane Departure Warning Systems: Information for the Human Interface

SAE J2802 Blind Spot Monitoring System (BSMS): Operating Characteristics and User Interface

NAKAYAMA, O., FUTAMI, T., NAKAMURA, T., AND BOER, E.R. (1999). Development of a Steering Entropy Method for Evaluating Driver Workload (SAE paper 1999-01-0892), Warrendale, PA.

2.1.2 Other Publications

Several definitions included in this Recommended Practice have been taken verbatim or nearly verbatim from published articles listed in this section. The complete mathematical derivations of them, copied from the original articles, appear in the appendices. Minor changes were made to improve clarity or to be consistent with SAE practice.

BOER, E.R., RAKAUSKAS, M.E., WARD, N.J., AND GOODRICH, M.A. (2005). Steering Entropy Revisited, *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design,* 25-32, (http://drivingassessment.uiowa.edu/DA2005/PDF/05_Boerformat.pdf, Retrieved June 7, 2011).

BROWN, T. (2005). Adjusted Minimum Time-To-Collision (TTC): A Robust Approach to Evaluating Crash Scenarios, *Proceedings of the Driving Simulation Conference North America, 40-48*, (http://www.nads-sc.uiowa.edu/dscna07/DSCNA05CD/papers/Adjusted_Minimum_TimeToCollision.pdf).

KERSLOOT, T., FLINT, A., AND PARKES, A. (2003). Steering Entropy as a Measure of Impairment, Presented during the Young Researchers Seminar 2003 (http://www.ectri.org/YRS03/Session-6/Flint.pdf, Retrieved June 7, 2011).

MINDERHOUD, M.M., AND BOVY, P. H.L. (2000). Extended Time-to-Collision Measures for Road Traffic Safety Assessment, *Accident Analysis and Prevention, 33(1), 89-97.*

OSTLUND, J., PETERS, B., THORSLUND, B., ENGSTROM, J., MARKKLA, G., KEINATH, A., HORST, D., JUCH, S., MATTES, S., AND FOEHL, U. (2005). *Driving Performance Assessment – Methods and Metrics* (AIDE deliverable D2.2.5), Brussels, Belguim: European Commission (www.aide-eu.org/pdf/sp2_deliv_new/aide_d2_2_5.pdf).

VAN DER HORST, A.R.A. (1990). *A Time-based Analysis of Road User Behaviour in Normal and Critical Encounters* (Ph.D. thesis), Delft, Netherlands: Delft University of Technology, (http://repository.tudelft.nl/assets/uuid:8fb40be7-fae1-4481-bc37-12a7411b85c7/emc_horst_19900424.PDF).

VAN WINSUM, W., BROOKHUIS, K.A., AND DEWAARD, D. (2000). A Comparison of Different Ways to Approximate Time-to-Line Crossing (TLC) during Car Driving, *Accident Analysis and Prevention, 32*(1), 47-56.

VAN WINSUM, W. AND GODTHELP, H. (1996). Speed Choice and Steering Behavior in Curve Driving, *Human Factors*, *38*(3), 434-441.

3 INTRODUCTION

3.1 Background and Current Practice

Historically, there have been few comprehensive attempts to define terms used to describe driver performance, and only Savino (2009) examines common practice. As part of his master's thesis, Savino established a set of criteria for defining and naming standard terms. Savino's thesis was the motivating document for this Recommended Practice. To determine names and terms that were used in the literature, Savino examined the driving performance literature from 2000-2005 including every article in *Human Factors, Ergonomics*, the *Driving Assessment and Human Factors and Ergonomics Society Conference Proceedings*, as well as Gawron's 2000 *Human Performance Measurements Handbook* and DOT technical reports. Some 498 publications were examined, of which 111 were relevant. Based on this research, Savino identified the relative frequency with which various driving performance terms were used and the definitions for them. In brief, there were essentially no terms for which there was a single common name, and definitions for terms were rarely provided. In a more recent review, Green (2012) reached similar conclusions.

A few of the terms have also been defined in SAE and ISO ACC standards (SAE J2399, ISO 15622, ISO 22179), and the SAE and ISO lane departure warning (LDW) standards (SAE J2808, ISO 17631). In addition, there is relevant information in the three most influential documents related to highway design:

(1) AASHTO Green book (AASHTO, 2011), and
(2) FHWA Highway Capacity Manual (U.S. Department of Transportation, 2010),
(3) MUTCD (U.S. Department of Transportation, 2010).

Derived from these documents, and often cited as a source for terms related to highway design is the Federal Highway MIRE manual (U.S. Department of Transportation, 2010).

A second perspective is the crash literature. The key source is:

ANSI D16.1-2007, ANSI accident classification manual (American National Standards Institute, 2007)

Derived from these documents, and often cited as a source for terms related to crash investigation and analysis are (1) Model Minimum Uniform Crash Criteria (MMUCC) Guideline (U.S. Department of Transportation, 2013) and (2) Fatality Analysis Reporting System (FARS) 2011 User's Manual (U.S. Department of Transportation, 2012).

For a single concise review that contains data relevant to many of the measures and statistics in this document, readers should see Yekhshatyan, L. (2008).

Although definitions relevant to driving performance measures and statistics appear in many documents, they are generally not cited (Savino, 2009; Green, 2012). In some cases definitions are not explicitly provided but can be inferred from other definitions, figures, or usage of the terms in a document (e.g., roadway was not defined, but roadway departure was). Even when cited or provided, some of the definitions conflict and others are not specific enough. Furthermore, definitions have not been created in a manner that produces a family of consistent names and allows for future expansion of that family of definitions as new relevant terms are needed (for example, time and distance measures of a characteristic).

3.2 Approach

In some cases multiple definition options are provided for a term to (1) be consistent with current standards and guidelines, (2) support the variety of methods used in current real world practice or to be used in future practice, and (3) accelerate the process of reaching agreement on how to define measures and statistics related to driving performance. Being inclusive will encourage use of this document.

Furthermore, typical values and frequency distributions for many of these measures and statistics from naturalistic and other driving studies have been provided to aid in understanding these definitions and to help users assess the reasonableness of their measurements when applying these definitions. Important references are provided to further understanding and encourage use of these definitions and this document. Again, the intent is to provide definitions for measures and statistics used in driving studies, encourage their use, and as a consequence, improve the quality of human factors evaluations of driving.

3.3 Typical Driving Performance and Representative Measurements and Statistics

When driving, drivers maintain a speed that considers the speed limit, keeping up with moving traffic (which may not be traveling at the speed limit), environmental and road conditions, and other factors. In addition, drivers attempt to maintain a distance between themselves that considers the distance needed to stop should a lead vehicle stop suddenly, providing sufficient distance to discourage excessive cut-ins, and the need to make maneuvers such as passing, turning, or stopping for signs and signals. This leads to continual adjustment of the accelerator, producing a signal such as that shown in Figure 1.

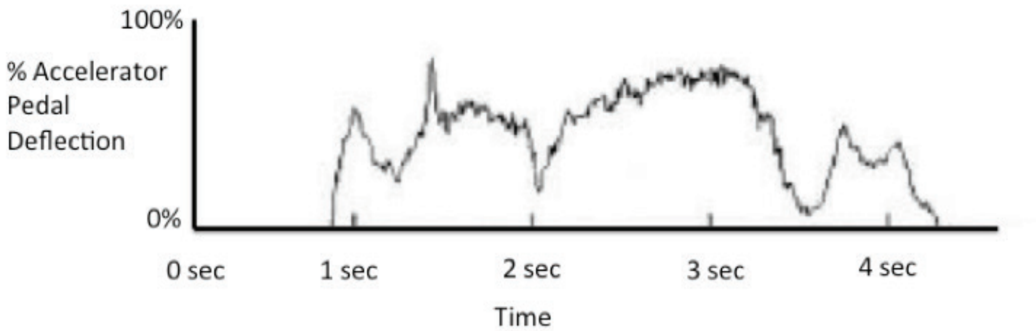


FIGURE 1 -- EXAMPLE THROTTLE SIGNAL
Source: McGehee (2012), personal communication

In addition, the drivers steer the vehicle, attempting to stay in their lane, adjust for traffic, and at times, change lanes or turn. Figure 2 shows a typical steering signal, which in many ways resembles the previous figure. Maintaining a path is a dual criterion process in that the driver controls lateral position to center themselves in the lane and they control heading to ensure they stay in the lane in the future (McLean and Hoffman, 1973; Land and Lee, 1994; Land and Horwood, 1995, 1996). When corrections are needed, the driver smoothly turns the steering wheel in the direction desired to change the heading angle, and then after some period of time, countersteers, so that the heading is parallel to the desired path. In a lane change, as shown in Figure 2, countersteering (resembling a single period of a sine wave after t(0)) is prominent. For a comparison of steering wheel statistics, see Boyraz, Sathyanarayana, and Hansen (2010).

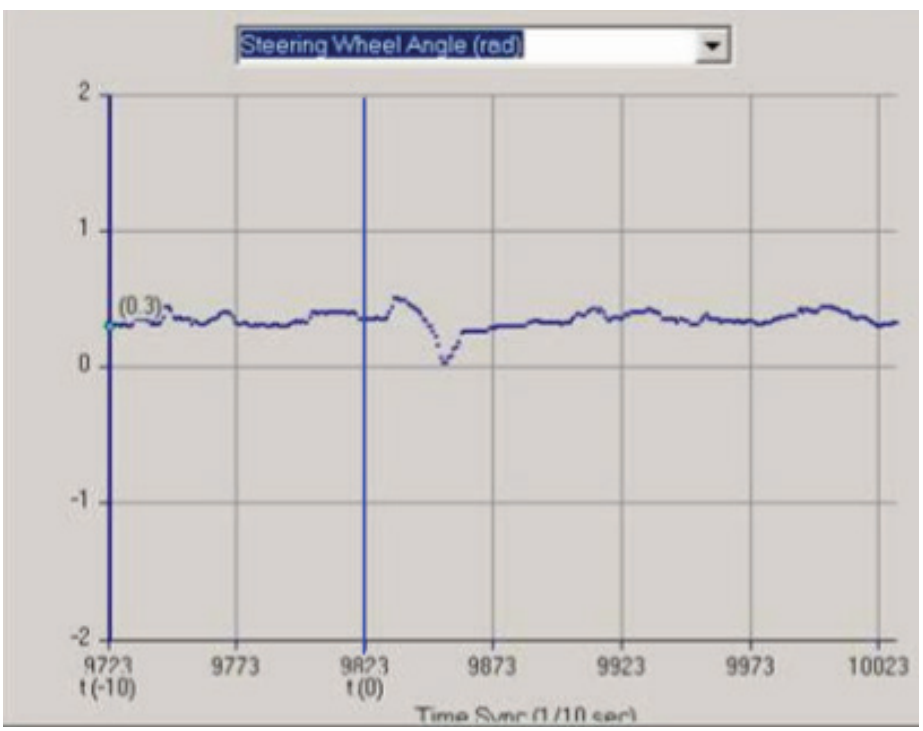


FIGURE 2 -- STEERING, COUNTERSTEERING PROCESS
Source: Lee, Olsen, and Wierwille (2004), p. 80

For both the steering and throttle data, the challenge is to separate the signal from the driver from the noise in the recorded output, and to identify changes in the signal due to factors such as driver fatigue, lack of alertness, distractions, etc.

Particularly important is determining when drivers respond to some disruption to driving and how long it takes to do so. As the primary response usually is a change in speed, characteristics of interest are acceleration, deceleration, braking, and in manual transmission vehicles, upshifting and downshifting. Deceleration can involve the release of the accelerator pedal only or both release of the accelerator pedal and applications of the brake pedal, and in vehicles with manual transmission, downshifting. The driver's actions involve (1) detecting a threat(s) (or stimulus onset in experimental terms) in the external event, (2) moving the foot[1] from its initial position on a pedal (accelerator or brake) or on the floor, and (3) possibly, moving another pedal (often the service brake) to achieve the desired change of speed. Step 2 can involve (1) release of the pedal currently actuated and (2) movement to contact the other foot pedal. Historically, this has been referred to as brake response time.

Figure 3 shows a conceptual accelerator pedal release and brake pedal application. In this figure, the accelerator pedal deflection decreases to 0% (the pedal is released) shortly after stimulus onset (i.e., threat). The 0 state between the accelerator release and the brake press is the transition time—where the accelerator and brake pedal both have 0 deflections. Once the brake is applied—sharply in this case, brake pressure increases quickly.

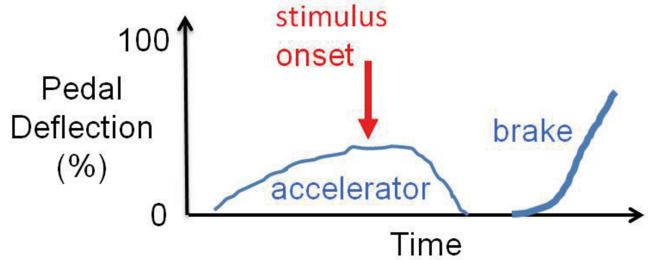


FIGURE 3 -- CONCEPTUAL EXAMPLE OF ACCELERATOR PEDAL RELEASE AND BRAKE PEDAL APPLICATION

During any conditions that involve uncertainty, drivers may not immediately press the brake. Instead they may release the currently depressed pedal and hold a foot above the accelerator or brake pedal, or rest their foot on the brake without applying it. This detail becomes important when assessing the overall driver response to normal changing conditions or a threat.

Thus, measuring the driver response to a stimulus is no simple matter. Depending on the situation, different endpoints may be appropriate. For example, if the driver is slowing down, then either when the accelerator pedal is rotated (the first sign of a response), when the pedal is released (more easily detected) or when some brake action occurs (pedal contact, brake lamp on, 25% of maximum brake pressure, brake jerk) may be appropriate. If the action involves acceleration, the brake pedal release or accelerator pedal contact may be appropriate end points.

Being able to reliably and repeatedly capture driver actions and separate signals from noise requires a rigorous measurement process. Replicability also requires reporting of key details. Key aspects of a high quality measurement process are described in the next section.

4. GENERAL MEASUREMENT GUIDANCE AND REQUIREMENTS

4.1 Specify a Well-Defined Start Point

The start point may be an event or a movement such as when: (1) the illumination of a vehicle's brake lamps reaches some value, (2) the illumination of a traffic signal reaches some value, (3) when the first word of a spoken warning is completed, (4) lead vehicle deceleration above some threshold, (5) a turn signal lamp has gone off, on and then started to turn on again, indicating a vehicle was going to change lanes, (6) when the front bumper of a vehicle on an intersecting path crossed a particular marking for a pedestrian crossing, or (7) when a pedestrian

[1] Foot includes the shoe or any other material covering the foot. Foot movements to a pedal are delineated as the point when the foot sole covering contacts the actuating surface (pad) of the pedal.

begins to move a leg to move in a particular direction. The start point shall be clearly defined, measurable, and reported when the definition is first used in a document.

In field experiments, video-based detection of events in the traffic environment is currently the usual way to determine the start point (the initiating event onset). Determination of start point is more challenging in the field than in a simulator, in part because there is less control over the initiating event.

4.2 Specify a Well-Defined End Point

The most significant problem in interpreting and comparing response time data is that what constitutes a response is not clearly defined. Is it some movement of the accelerator, complete release of the accelerator, touching the brake pedal, activating the stop lamp, full activation of the brake, or something else? Differences in the end point lead to substantial, practical differences in the values obtained.

The end point is a distinct, well-defined point of the movement in response to the external event, not random variation in the accelerator movement that is directionally correct. The amount of movement, such as the angular rotation of the steering wheel (usually in degrees) or the movement of the accelerator (often in percentage displacement), and the time window over which the movement is detected shall be reported. Example end points could be: (1) when the foot is no longer in contact with the accelerator or (2) when the brake lamps illuminate in response to depressing the brake pedal. The end point shall be clearly defined, measurable, and reported when the definition is first used in a document.

4.3 Measure Driver Control Movements

Steering wheel and pedal movements are generally determined in one of three ways: (1) directly from the Controller Area Network (CAN) bus (becoming the most common method), (2) using displacement sensors on the accelerator and/or brake pedal to detect the onset of a driver pedal application or release (e.g., percentage pedal displacement); and (3) manually coding the pedal response using frame-by-frame video analysis.

Placing marks on the steering-wheel rim to make its angle more readily apparent facilitates video analysis. However, most steering measures require considerable accuracy (<0.5 deg), a level that may be difficult to achieve visually (Johansson, Engstrom, Cherri, Nodari, Tofetti, Schindhelm, and Gleau, 2004). Displacement sensors may also be paired with a load cell on the pedal itself to provide a better indication of the initial pedal contact time, as well as to measure the pedal forces applied by the driver. As described in section 7.2, contemporary automation systems may independently apply the brakes, so the brake pressure may not always reflect driver actions. Obtaining CAN codes can be difficult for evaluators who do not work for manufacturers or suppliers. CAN codes are proprietary and often closely guarded by their developers. They are more widely available then in the past.

Another more binary method to determine when a brake is initially pressed as part of an emergency response is to place a microphone on or near the brake. The sound report can provide an accurate initial touch to the brake pedal. This method is not commonly used and will eventually be replaced by an electronic signal from brake-by-wire systems.

4.4 Eliminate Random Movements

When looking at hand- and foot-movement data, the analyst should filter out any electronic noise from the sensor and random movements of the driver. The focus is on a driver’s intentional steering and pedal input in response to the event. Random hand and foot movements not associated with a response should be discarded from analyses.

4.5 Eliminate Sensor and Sensor Integration Lags

There are inherent lags in on-board sensors, sensors added by experimenters, and systems associated with processing multiple sensors and integrating their output. In aggregate, lags can be quite large. For example, systems to determine foot movement may have mechanical and/or electronic sensor lags that can be as large as 300 ms (Lee, McGehee, Dingus, and Wilson, 1996).

More specifically, the delay that a driver experiences from the time of an input until the system responds is known as mechanical system lag time (Bullenger, Kern, & Braun, 1997). This lag is generally imperceptible to a driver, but in frame-by-frame analysis of video data, this lag becomes noticeable. However, detecting these lags may be difficult, depending on how the data is collected. In the U.S. video data is commonly recorded at 30 Hz, so a video record could lag an event by up to 33 ms. Furthermore, if multiple video streams are processed, multiplexing systems may wait until the last source is complete (another 33 ms). There may be other delays associated with processing and storing frames. Krishnan, Gibb, Steinfeld, and Shladover (2001) estimate sensor delays are 0.1 s.

For radar and LIDAR sensors, there may also be delays due to their scan times and reporting criteria. For example, the sensor may not report a target if it is detected on a single scan, but may require two successive scans or use some other rule such as two out of three successive scans.

REQUIREMENT: Because delays associated with lags can be a substantial fraction of response time, adjustments for lags shall be identified and reported.

4.6 Separate Vehicle Automation Actions from Driver Actions

Automation includes conventional and adaptive cruise control, lane keeping assistance systems, crash avoidance braking systems, and other systems that control some or all of driving task.

Conventional cruise control and adaptive cruise control do not require the driver's foot to be on the accelerator pedal to provide throttle input. Lane-keeping and stability-control systems may apply the brakes to some or all of the wheels, and/or provide mild steering actions, partially overriding driver actions. Pre-crash/forward collision-avoidance braking systems intervene to help the driver avoid or reduce the severity of a collision. These systems may supplement or override driver actions, may pre-charge the brake, and cutoff or reduce the throttle (Marshek, Cuderman, and Johnson, 2002; Forkenbrock, Snyder, and Jones, 2010). Pre-charging the brakes reduces the pedal displacement required for some responses to occur. Regenerative braking systems may slow the vehicle without any change in brake pressure. Furthermore, at some times, the vehicle may be automatically driven without any driver input.

Thus, automation-controlled actions must be separated from those of the driver. This may require the foot responses (and possibly steering responses) to be coded manually using frame-by-frame video analysis. (Though not reliable now, future image processing systems may be able to track the foot and hands.) The initial position of the foot (usually the right foot) should be taken from its position just before movement is initiated.

4.7 Identify When Drivers Have Both Hands Off of the Steering Device

Sometimes drivers will remove both hands from the wheel, because they are distracted and performing another task (e.g., eating a sandwich with two hands), gesturing in conversation, or for some other reason. During those situations drivers may (1) steer using some means other than their hands (e.g., driving with a knee), (2) only damp steering movement (by resting their wrist on top of the steering device), or (3) provide no steering input at all. There may also be situations where a passenger steers. Situations where both hands are off the steering device shall be reported.

4.8 Exclude Preparatory Movements from Accelerator or Brake Response Times

Sometimes drivers will move a foot to be near or on a pedal anticipating a potential or developing threat. Such preparatory moves can be recorded but the primary response of interest is the driver response after the threat is perceived. This can be problematic for sensors as the pressure of the left foot on the brake pedal can cause a brake sensor to indicate some displacement prior to a response event. When the left foot rests on the brake pedal, it can activate a brake lamp. If this is the case, the brake position should be plotted in a time series to identify the point at which willful displacement of the brake pedal occurs. When timing driver foot movements, use the first pedal movement (brake or accelerator) to determine when response time begins. If the foot rests lightly on the brake before the brake pedal is pressed in response to a threat, the movement of primary interest starts when the downward brake pedal motion is detected.

The brake pressure or other sensed indicator of brake position will depend on the system. Normally, 0% of maximum brake pressure (above nominal) indicates the foot is off the brake and 100% is maximum pressure (and full pedal application), but that is not always the case. If a foot is resting on the brake pedal, the initial percentage of maximum brake pressure may not to be 0%. Hence, the indication of when braking has occurred may not be when brake pressure changes from 0% of maximum brake pressure. To fully understand when meaningful braking has occurred and when a driver has responded by braking, the function relating brake pressure (or brake pedal position) to braking force is needed. Further, the analyst should work backward from the maximum braking pressure to ensure that the initial braking response is accurately captured. A foot camera view of the accelerator and brake pedal is useful to validate initial accelerator pedal and brake pedal movements.

4.9 Identify When Drivers Use Both Feet to Drive

Some drivers, primarily older drivers in right-hand drive vehicles, rest their left foot on the brake while they use their right foot to operate the accelerator (two-footed drivers/brakers). See Figures 4 and 5. In a manner similar to that in section 4.8, the left foot resting on the brake may lead to a non-zero brake pedal pressure, suggest braking has begun, and likely activate the brake lamps. As before, brake application begins when the brake pedal moves downward and brake pressure increases beyond the resting value.

FIGURE 4 -- USING BOTH FEET TO DRIVE
Source: Pettinato and Best (2012), personal communication

FIGURE 5 -- TWO-FOOT BRAKING
Source: Pettinato and Best (2012), personal communication

In addition, for two-footed brakers the release of the accelerator pedal may partially overlap with application of the brake pedal. In that case, the actions of the brake pedal should be considered the dominating activity.

If automated sensor data are used, the brake pedal position should be carefully examined to ensure that the appropriate braking start time is recorded. There are four cases to consider, (1) only the driver responded, (2) only the automation responded, (3) the driver responded first but then the automation took control, (4) the automation responded first but then the driver took control. Analysts have the option of (a) pooling trials in which either the driver or automation responded, (b) reporting all response types separately, or (c) ignoring the trials in which the automation responded. To adequately assess the benefits of automation, reporting the various types of trials separately is recommended, along with summary statistics of for all cases to assess overall benefit.

4.10 Select the Response Measure Appropriate for the Question(s) Posed

Historically, brake response time has been the most common measure cited in the literature. However, with the decrease in sensor and communication cost and increase in sensor fidelity, detailed access to the accelerator and brake pedal movement is much more widely available. Therefore, distinctions among different aspects of brake response time are much easier to determine.

Prior to data collection, the analyst should determine and clearly define the specific questions to be investigated. From these questions, the analyst can determine the most suitable response measures. For brake applications the measures should track the driver's pedal response from the onset of a stimulus, to the initial pedal release, the transition time to the brake, the initial brake application; and through to the full brake application (maximum). Drivers frequently modulate their pedal inputs as traffic and road circumstances dictate, complicating the analysis. Although a choice response paradigm can be simple, determining what a driver is responding to in the naturalistic domain can be more of a challenge.

For additional information about measuring real-world driver responses to various events, see (Green, 2000).

4.11 Report More than Means and Counts

As data from driving studies is now being used to build simulation models in addition to determining statistically significant differences, authors are encouraged to not only report counts and means, but also to report standard deviations, best fitting distributions, and distribution parameters for the measures and statistics in this document.

4.12 General Measurement Requirements

The following items shall be reported for all measures and statistics:

1. The (a) start and (b) end points of the triggering event, if any,
2. The (a) salience of the triggering event, (b) if it is expected, and (c) how often it has been seen before,
3. The (a) alertness/fatigue of the driver, and (b) where they are looking,
4. The (a) start and (b) end points of the sampling period or response,
5. How the data were collected,
6. (a) Lags and (b) noise in the data collection devices, and
7. How drivers are using their (a) hands and (b) feet to drive, and (c) if there were any extraneous motions.

5. CITING J2944 DEFINITIONS

REQUIREMENT: The first time any terms defined in this Recommend Practice are used in a document, SAE J2944 shall be identified. For definitions with multiple options, the option used shall be identified. For definitions for which there are parameters, for example a value greater than which data are excluded in a calculation, those parameter values shall be identified. More specific requirements for each definition are given with that definition.

EXAMPLE 1: "The dependent statistic of interest was mean response time until accelerator pedal release, per SAE J2944."

EXAMPLE 2: "The dependent statistic of interest was mean value of time-to-line crossing, option B per SAE J2944. All momentary TLC values in excess of 10 s were excluded."

6. GENERAL DEFINITIONS

Many of the definitions in this section are used in definitions in the operational definition section. For example, *leading and trailing surfaces*, defined in this section, are used in the operational definition for *gap* provided later.

Other terms generally defined in this section, for example response time, are given more application-specific definitions in the operational definitions section. For example, *response time until brake light on* has an operational definition.

6.1 Vehicle Reference Surfaces

6.1.1 Leading Surface

Part of the vehicle or anything mounted to or carried in/on a vehicle that is the most forward part of the vehicle, including accessories such as a snowplow or winch.

6.1.2 Trailing Surface

Part of the vehicle or anything mounted to or carried in/on a vehicle that is the rearmost part of the vehicle, such as a trailer hitch, salt spreader, ladder, or lumber (Figure 6).

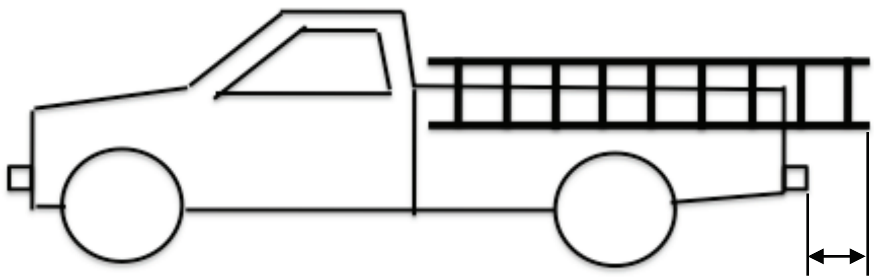


FIGURE 6 -- TRUCK WITH A LADDER THAT ADDS A TRAILING SURFACE TO ITS LENGTH

NOTE: In some situations, a vehicle may be sliding or in general may not be traveling approximately parallel to a lane boundary. In this case the most forward part may not be on the "front" of the vehicle, and the most rearward part may not be on the "rear" of the vehicle.

6.1.3 Surfaces Beyond Vehicle Bumpers

If in the evaluated conditions a vehicle is fitted with accessories or cargo that add to the length of the vehicle, the added length of those accessories or cargo beyond the side view bumper prominence shall be reported as part of the evaluation vehicle description (Figure 6).

6.2 Trafficway Elements

The major problem in the literature is there are many terms related to roads - highway, roadway, trafficway, traveled way, lane, and the term road itself, that can have conflicting and/or multiple meanings, some of which sound alike, and many of which are confused with each other. This problem results from conflicting definitions in the literature and lack of knowledge by users regarding what these terms truly mean. The two core documents for the definitions in section 6.2 are (1) AASHTO's A Policy on Geometric Design of Highways and Street (the Green Book, AASHTO, 2011 and Errata, 2012) and (2) ANSI D16.1-2007 (7^{th} edition), a core standard for traffic safety. Definitions from these documents are in turn used in (1) the Manual on Uniform Traffic Control Devices (MUTCD, U. S. Department of Transportation, 2009), (2) the Highway Capacity Manual (HCM, Transportation Research Board, 2010), (3) Fatality Analysis Reporting Systems (FARS), www-fars.nhtsa.dot.gov/, (4) the Crashworthiness Data System (CDS), http://www.nhtsa.gov/Data/National+Automotive+Sampling+System+(NASS)/NASS+Crashworthiness+Data+System, and (5) the General Estimates System (GES), http://www.nhtsa.gov/Data/National+Automotive+Sampling+System+(NASS)/NASS+General+Estimates+System.

6.2.1 Trafficway

Any right-of-way open to the public as a matter of right or custom for moving persons or property from one place to another, including the entire width between property lines or other boundaries (Figure 7).

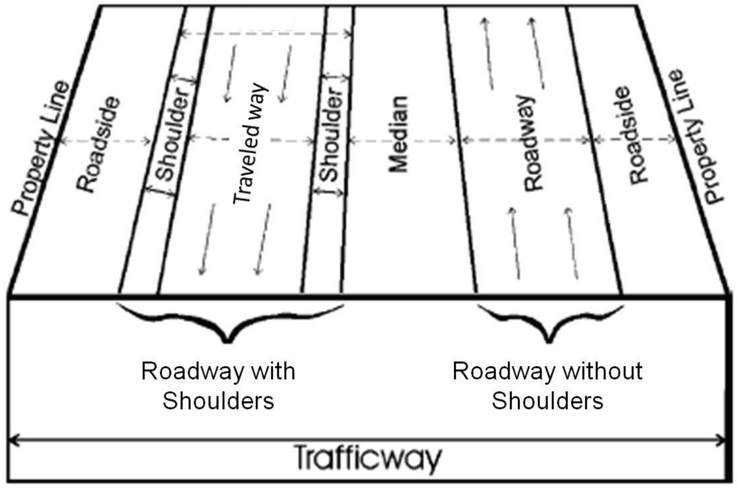


FIGURE 7 – TRAFFICWAY, TRAVELED WAY, AND ROADWAY
Source: Modified from American National Standards Institute (2007), p. 3.
Also in U.S. Department of Transportation (2012), page 515

NOTE 1: The trafficway includes not just the surface on which vehicles normally travel but also the shoulders, median, and roadsides.

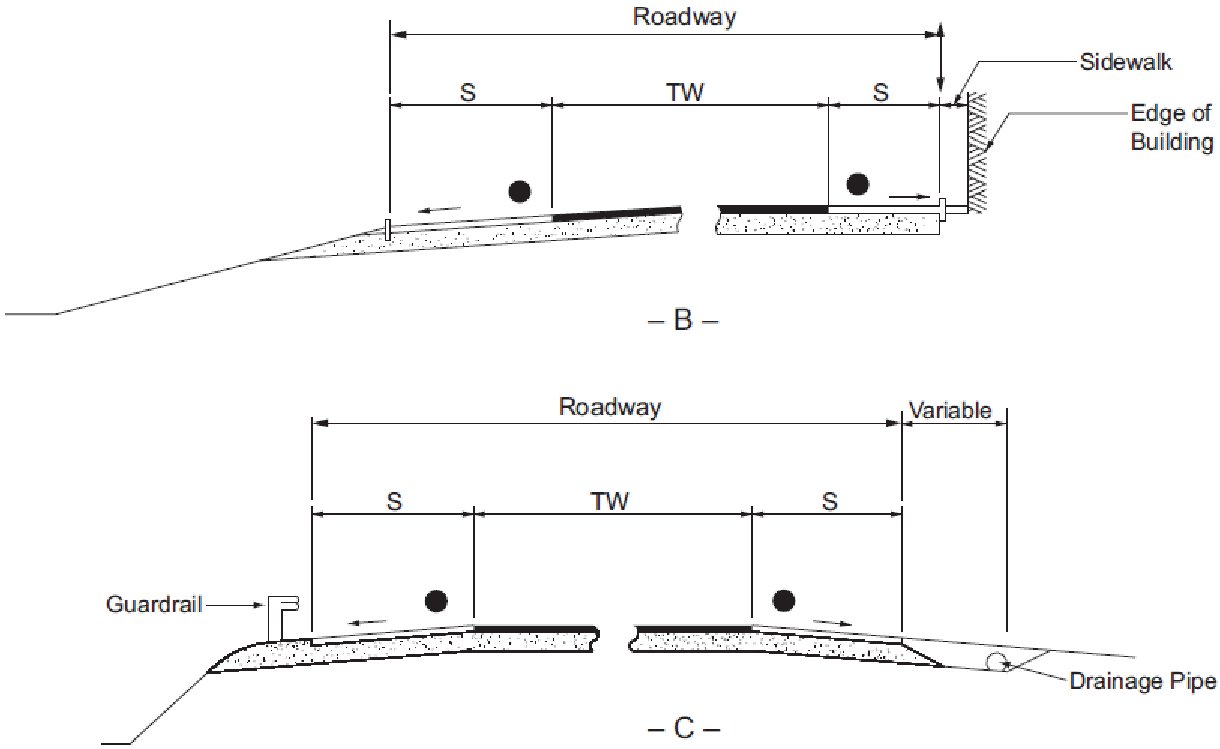
NOTE 2: This definition is taken verbatim from the Glossary (Appendix B, page 364) of *National Transportation Statistics* published by the Bureau of Transportation Statistics (U. S. Department of Transportation, 2013). (http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/appendix_b.html). The Bureau of Transportation Statistics definition lists highway as a synonym. The Bureau of Transportation Statistics definition is essentially the same as the ANSI D16.1-2007 definition 2.2.1 (American National Standards Institute, 2007).

NOTE 3: The MUTCD (U.S. Department of Transportation, 2009, page 14) calls this the highway (definition 84). The AASHTO Green book, though never formally defining the terms, uses highway or street instead of trafficway. The Highway Capacity Manual (U.S. Department of Transportation, 2009) does not define trafficway or right-of-way. However, on page 9-9, highway is defined as “A general term for denoting a public way for purposes of vehicular travel, including the entire area within the right-of-way.” This definition is equivalent to that for trafficway given here. Similarly, the Federal Highway Administration Planning Glossary (http://www.fhwa.dot.gov/planning/glossary/glossary_listing.cfm?TitleStart=H) states a highway “Is any road, street, parkway, or freeway/expressway that includes rights-of-way, bridges, railroad-highway crossings, tunnels, drainage structures, signs, guardrail, and protective structures in connection with highways. The highway further includes that portion of any interstate or international bridge or tunnel and the approaches thereto (Title 23-United States Code, § 101a).

Guidance for Trafficway: Use of the term trafficway is recommended. This term is consistently defined wherever it is used. The terms highway, street, and even road or roadway are sometimes used to mean the same as trafficway, but these terms are inconsistently defined across various publications, and the general public’s impression is that these other terms refer to just pavement. The term *right-of-way* is sometimes used, but this term not as precisely defined as trafficway.

6.2.2 Traveled Way

Portion of the trafficway for the movement of vehicles, exclusive of shoulders, parking lanes, and bicycle lanes (Figures 7, 8).



Note: TW = Traveled Way
S = Usable Shoulder
● = Rate of Slope 2 to 6%

FIGURE 8 – TRAVELED WAY, ROADWAY, AND USABLE SHOULDER
Source: AASHTO (2012 ERRATA)

NOTE 1: This definition is taken from the AASHTO Green Book (2011 and errata 2012) and the MUTCD. Figure 8 shows the traveled way using the corrected figure found in the 2012 Green Book errata. This term is not defined in ANSI D16.1-2007 or in the Highway Capacity Manual.

NOTE 2: A traveled way includes the visually contiguous road surface beyond the lane edge line. In Figure 9, the concrete surface from the edge line to the paved asphalt shoulder is considered part of the traveled way. In Figure 10, the traveled way is paved with asphalt and the usable shoulder is paved with concrete. The concrete curb and gutter are part of the roadside.

FIGURE 9 – EXAMPLE OF VISUALLY CONTIGUOUS PAVED TRAVELED WAY AND A PAVED SHOULDER
Source:
http://www.deldot.gov/information/community_programs_and_services/DSHSP/roadway_departure_crashes.shtml

FIGURE 10 -- EXAMPLE OF A U.S. URBAN TRAVELED WAY WITH A GUTTER AND CURB
Source: http://collegetri.files.wordpress.com/2012/06/curb-of-a-road.jpg

NOTE 3: The outside edge of the traveled way may be identified by a change in the color of the paving material, a seam, a control joint for expansion, a change in cross slope drainage, or a vertical drop off of more than one inch in the pavement edge (Figure 11).

When the pavement edge drop off exceeds one inch vertically, loss of control is more likely to occur because of a change in the aligning moment (Gillespie, 1992) and the probability of a safe return to the traveled way declines (Hallmark, Veneziano, MacDonald, Graham, Bauer, Patel, and Council, 2006; Transportation Research Board, 2009). The U.S. Federal Highway Administration (FHWA) suggests the angle of the pavement edge drop off should be 30 degrees to allow a safe return to the traveled way (Graham, J.L., et.al, 2011; see also http://www.youtube.com/watch?v=asy33BGQwUw). See also Stoughton, Parks, Stoker and Nordin (1979), Gross, Jovanis, Eccles, and Chen, (2009), Ivey, Johnson, Nordlin, and Zimmer (1984), Spainhour and Abhishek (2008), and Lord, Brewer, FItzpatrick, Geedipally, and Peng (2011) for additional information on shoulder design, shoulder drop offs, loss of control, and crashes.

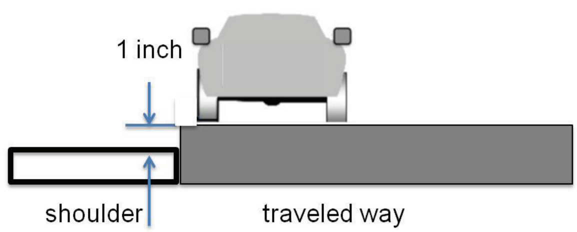


FIGURE 11 – ILLUSTRATION OF VERTICAL DROP OFF

NOTE 4: A traveled way consists of one or more vehicle lanes and may include part of the paved surface outside of the vehicle lane marking. For two-lane roads with no edge lines, the traveled way and vehicle lanes are the same.

6.2.3 Roadway

Portion of a trafficway improved, designed, or ordinarily used for vehicular travel and parking lanes.

NOTE 1: A divided trafficway has two or more roadways.

NOTE 2: There are three commonly used, well-entrenched, and conflicting definitions of the term *roadway* – (A) AASHTO, (B) ANSI/MUTCD/FARS/HCM, and (C) FHWA. The AASHTO definition (option A, 6.2.3.1) includes the usable shoulders. The ANSI/MUTCD/FARS/Highway Capacity Manual definition (option B, 6.2.3.2) excludes shoulders.

NOTE 3: FHWA has varying definitions for roadway depending on their application. The Model Inventory of Roadway Elements (MIRE) report (U.S. Department of Transportation, 2010d) never defines what a roadway is. However, included among the roadway elements are the number of through lanes, right and left shoulder types, and left and right side slopes, which implies roadway is synonymous with their definition of highway and the definition of trafficway given here. The FHWA Highway Performance Monitoring System Field Manual (U.S. Department of Transportation, 2012b, page B-3) defines roadway rather imprecisely as "the portion of a highway intended for vehicular use." (See also http://www.fhwa.dot.gov/ohim/hpmsmanl/chapt2.cfm.) That definition is consistent with options A and B given here. For roadway departures FHWA explicitly excludes shoulders but includes opposing lane(s) of vehicles, so crossing a lane centerline is viewed as a roadway departure (option C, 6.2.3.3).

6.2.3.1. Including Usable Shoulders (Option A)

Portion of a trafficway improved, designed, or ordinarily used for vehicular travel and parking lanes, <u>including</u> the usable shoulders.

NOTE 1: This definition appears in the AASHTO Green book (AASHTO, 2011, page 4-1).

NOTE 2: This yields the widest roadway of the three roadway definition options.

6.2.3.2. Excluding Shoulders (Option B)

Portion of a trafficway improved, designed, or ordinarily used for vehicular travel and parking lanes, <u>excluding</u> the shoulders.

NOTE 1: This definition appears in ANSI D16.1-2007 as definition 2.2.28. (American National Standards Institute, 2007, page 12).

NOTE 2: The MUTCD Manual of Uniform Traffic Control Devices (MUTCD, 2009, page 19), defines the roadway as, "that portion of a highway improved, designed, or ordinarily used for vehicular travel and parking lanes, but exclusive of the sidewalk, berm, or shoulder**…"** The Highway Capacity Manual (2010, p. 9-16) uses verbatim the definition that appears in MUTCD.

NOTE 3: In the NHTSA Model Minimum Uniform Crash Criteria (MMUCC, U.S. Department of Transportation, 2008), page 6, roadway is defined by implication to exclude shoulders. Variable C8 (Location of First Harmful Event Relative to the Trafficway) has 10 attributes include "on roadway" and "shoulder." FARS, in its users' manual, which is based on the MMUCC, similarly defines variable C22 (Relation to Trafficway) as having nine attributes, including "on roadway" and "shoulder." Though it is never stated in these crash databases, roadway is assumed to include parking lanes.

6.2.3.3. Excluding Shoulders and Opposing Traffic (Option C)

Portion of a traveled way bounded by edge lines or a centerline/median, excluding opposing traffic.

NOTE 1: This definition is derived by implication from the FHWA definition of a roadway departure. They define roadway departure as, "A non-intersection crash in which a vehicle crosses an edge line, a centerline, or leaves the traveled way" (http://usroadwaysafety.org/sites/default/files/listserv-archives/2009/5b8417eaa18ba2a7a1c883c0ff58804f-0-RD%20Criteria%20&%20Definition%20_final_.pdf).

NOTE 2: This FHWA definition is a derivative of the ANSI definition modified to suit FHWA needs for evaluating their trafficway safety improvement programs. In essence, it is the lane in which the driver is traveling as defined in 6.2.6, plus other lanes in the same direction of travel. FHWA decided to define roadway departure as they did to be consistent with FARS, to facilitate the evaluation of countermeasures (in particular shoulder and center rumble strips), and to be consistent with their prior practice and organizational structure. FHWA is continuing to review this and other terms related to roadway and lane departure but is unlikely to revise their definition of roadway departure unless it contributes to improving road safety (Sutherfield, 2012, personal communication). For information on a different FHWA definition of roadway, see the FHWA MIRE manual (Lefler, Council, Harkey, Carter, McGee, and Daul, 2010).

REQUIREMENT: The first instance the term *roadway* is used in a document, the definition used (option A, B, or C) shall be reported.

Guidance on Roadway: Because the alternative definitions of roadway are so different, phrasing to reinforce the definition used (including shoulders, excluding shoulders, etc.) is recommended. Of these definitions, option A (traveled way plus shoulders) is recommended because option B is nearly synonymous with traveled way, and use of the term traveled way is preferred. For FHWA projects involving roadway departures, use of their definition (option C) is likely to be required. However, an alternative name is desired for that option.

6.2.4 Shoulder

Paved or unpaved part of a roadway contiguous with the traveled way for emergency use, for accommodation of stopped road vehicles, and for lateral support of the traveled way structure (Figures 7 - 10).

NOTE 1: This definition is a slight modification of the definition for shoulder in the AASHTO Green book (2011), page 4-8, the Highway Capacity Manual (2010) page 9-17, and ANSI D16-2007, page 13 (definition 2.2.32).

NOTE 2: The shoulder usually varies in width from only 0.6 m (2 ft) on minor rural roadways to approximately 3.6 m (12 ft) on major roadways. For modern high speed, high volume roadways, the shoulder width is typically 3.0 m (10 ft) to enable a stopped vehicle to clear the edge of the traveled way by at least 0.3 m (1 ft), and preferably by 0.6 m (2 ft).

NOTE 3: On low-volume roadways, roadside barriers may be placed at the outer edge of the shoulder; in this case AASHTO (2011) recommends a minimum clearance of 1.2 m [4 ft] should be provided from the traveled way to the barrier.

NOTE 4: In the U.S., some traveled ways may have no shoulder at all. Also, sometimes there may be no visible indication of a shoulder if the entire shoulder is paved the same as the traveled way.

6.2.5 Usable shoulder

Actual width of the shoulder, usually measured in feet or meters, available for the driver to make an emergency stop or for parking.

NOTE 1: This definition is taken from AASHTO (2011).

NOTE 2: The width is measured from the edge of traveled way to the point of intersection of the shoulder slope and mild slope (for example, 1:4 or flatter) or to beginning of rounding to slopes steeper than 1:4.

NOTE 3: FHWA recommends but does not require that usable shoulders be paved (U.S. Department of Transportation, 2007).

6.2.6 Roadway Pavement

Portion of a roadway, <u>including</u> usable shoulders and parking lanes, that is paved with asphalt or concrete for vehicular use.

NOTE 1: When a vehicle departs the traveled way, it may encounter (1) no usable shoulder, (2) gravel, shell, crushed rock, or bituminous shoulder surfaces, (3) shoulders that are partially paved, and (4) shoulders that are completely paved. As maneuvering is much easier on a paved surface, knowing when a departure from a paved surface has occurred is important.

NOTE 2: The FHWA Model Inventory of Road Elements (MIRE) manual (Lefler, Council, Harkey, Carter, McGee, and Daul, 2010), page 26 refers to the “total paved surface width.”

6.2.7 Vehicle Lane

Part of the traveled way intended for use by a single line of moving vehicles and usually delineated by pavement markings to guide drivers and reduce potential traffic conflicts.

6.3 Trafficway Element Boundaries

Depending on the trafficway element and its design, a boundary could be defined by a painted line, objects abutting the road surface (a drainage ditch, a curb, a gutter, a gutter cover), objects extending above the road surface (a bridge abutment, a tunnel or retaining wall, a guardrail, a fence, a Jersey barrier), decrease in pavement elevation (a drop off), change in cross slope, a change in the traveled way surface material, or by other means.

The terms in section 6.3 serve as the basis for determining when a departure from the lane, roadway, or roadway pavement has occurred.

6.3.1 Roadway Boundary

Outermost edges of the roadway.

NOTE: Boundaries may be defined by edges of pavement markings, edge drop offs, changes in paving materials, or barriers such as curbs, gutters, guard rails, bridge abutments, or other roadside appurtenances.

REQUIREMENT: The first instance the term *roadway boundary* is used in a document, the option used to identify the *roadway* (A, B, or C) and the roadway boundary(s) shall be clearly defined.

6.3.2 Lane Boundary

Physical or implied indicators on the traveled way that define the lateral edges within which a vehicle moving single file in the same direction is expected to drive, except when passing, changing lanes, or exiting the traveled way.

NOTE 1: On paved traveled ways the lane boundaries are usually defined by pavement markings (single or double line, solid or dashed), Botts dots or other raised pavement markers, or barriers (guard rails, Jersey barriers, bridge abutments, tunnel walls, etc.). Unpaved traveled ways usually do not have an outside edge line marking or a centerline marking.

NOTE 2: For traveled ways intended to support two lanes of travel in opposing directions without a centerline marking, the boundary between the two lanes is the imaginary centerline between the pavement edges. If no outer edge markings are provided, the outer lane edge is the edge of the traveled way surface.

NOTE 3: For U.S. practice on pavement markings, see Chapter 3 (Markings) in the MUTCD (U.S. Department of Transportation, 2009).

REQUIREMENT: The first instance the term *lane boundary* is used in a document, that boundary shall be clearly defined.

6.4 General Terms for Driver Reactions to Events and Movements

NOTE: The terms reaction time, response time, and movement time, as defined in this section, refer to reactions, responses, and movements of the driver.

6.4.1 Event

Stimulus primarily leading to a driver response involving steering, braking or acceleration of the vehicle being driven.

EXAMPLES - Events could be the movement of other vehicles (e.g., braking, accelerating, or merging) or pedestrians, the change in state of a traffic sign or traffic signal, or the onset of a warning sound.

NOTE: Sometimes a driver may fail to respond to an event.

GUIDANCE for Event: Report how often drivers do not respond to events. Some consider no response to indicate an infinite response time, a value not compatible with computing a mean time. For trials with no response, consider computing statistics based on inverse time (in which case an infinite response is treated as zero).

6.4.2 Reaction Time, RT

Time interval, usually measured in seconds or milliseconds, from onset of an initiating event to the first movement of the driver's hand (on the steering wheel) or foot (on a pedal or from the floor)

NOTE 1: If desired, separate reaction times can be defined for foot movements that result in positive or negative accelerations, e.g.

RT_{+} = reaction time to accelerate in response to external event; foot on accelerator or floor
RT_{-} = reaction time to decelerate in response to external event; foot on either pedal or on floor

NOTE 2: *Steering reaction time* (defined later) is an analogous term.

REQUIREMENT: The first instance the term *reaction time* is used in a document, the start and end points of the reaction shall be reported.

6.4.3 Movement Time, $MT_{X—Y}$

Time interval, usually measured in seconds or milliseconds, from the starting foot or hand position (X) to a predefined end of the foot or hand movement (Y)

NOTE 1: The foot movement can start with the foot on either pedal or on the floor and end with the foot on the same or other pedal.

NOTE 2: The amount of brake pedal movement will be different for vehicles that pre-charge the brake pressure and/or preposition the brake disc pads when crash conditions are detected.

NOTE 3: When moving the foot, a driver may unintentionally make contact with the accelerator pedal prior to moving to and applying the brake. If a pedal misapplication occurs, this movement time is added into the total movement time.

NOTE 4: *Steering movement time* (defined later) is an analogous term.

GUIDANCE for Reaction Time: Warshawsky-Livne and Shinar (2002) report movement times from the first movement of foot on the accelerator to contact with the brake pedal of 0.15 to 0.20 s for alerted subjects responding to brake lights in a simulator across repeated trials. In contrast, Engstrom, Aust, and Vistrom (2010) report mean movement times of 0.65 to 0.77 s, where that time was defined beginning when 2% of full accelerator depression was reached during accelerator release and ending when the brake reached 2% of maximum brake pressure. Their data was also collected in a driving simulator, but the scenario was the cut-in of a vehicle from an adjacent lane on a 4-lane road.

REQUIREMENT: The first instance the term *movement time* is used in a document, the start and end points (the x and y values) shall be reported.

6.4.4 Response Time, $RspT_{X—Y}$

Sum of reaction time and movement time, usually in seconds or milliseconds, from the movement start point X to the end point Y.

NOTE 1: A foot movement can start with the foot on either pedal or on the floor and end with the foot on the same or other pedal.

NOTE 2: *Steering response time* (defined later) is an analogous term.

REQUIREMENT: The first instance the term *response time* is used in a document, the initiating event, and the start and end points (the X and Y values) of the movement shall be reported, unless these items were already reported.

GUIDANCE for Response Time: When response time is reported and it is undefined, the measure is usually some sort of brake response time, not accelerator response time, primarily because brake response time is easier to measure. For that reason, reporting the end point is essential.

7. LONGITUDINAL CONTROL: OPERATIONAL DEFINITIONS FOR DRIVER'S PEDAL RESPONSES

7.1 Accelerator Response Time

Time interval, usually measured in seconds or milliseconds, from an initiating event until the accelerator pedal is first contacted or moved a specified amount in response to that event (Figure 12).

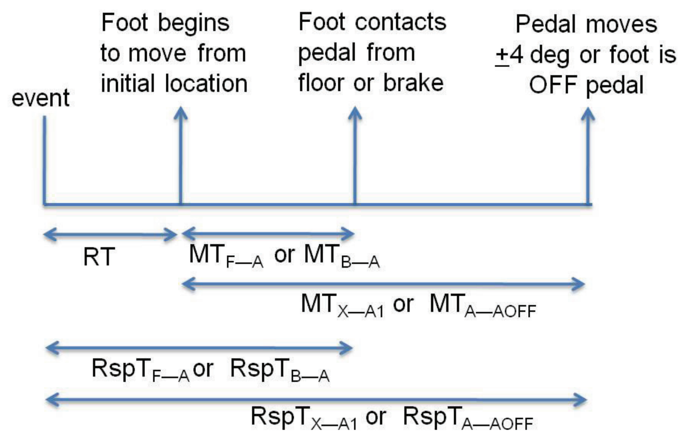


FIGURE 12 -- ACCELERATOR RESPONSE AND MOVEMENT TIMES
X represents the initial foot location (B=brake pedal, F=floor, A=accelerator pedal).

NOTE: Three accelerator response times are defined based on different foot movement end points.

GUIDANCE for Accelerator Response Time: Differences in what constitutes the movement end point can affect accelerator response time by about 100 ms.

7.1.1 Response Time until Accelerator Pedal Contact, $RspT_{F\text{-}A}$ or $RspT_{B\text{-}A}$

Time interval, usually in seconds or milliseconds, from onset of initiating event to first foot contact with the accelerator pedal.

NOTE: This end point only applies when the foot is not initially on the accelerator pedal. It could be on the floor, on the brake pedal, or hovering near the accelerator pedal. For data on floor location see McLaughlin and Serafin (1999).

7.1.2 Response Time until Accelerator Pedal Movement, $RspT_{X—A1}$

Time interval, usually in seconds or milliseconds, from onset of initiating event until accelerator is moved ± 4 degrees from its initial pedal position.

NOTE: Subscript X indicates the foot can be on the brake, floor, or accelerator at event onset. In most cases, the movement of interest will be a release of the accelerator pedal to slow down, but there may be instances where the response is accelerator pedal depression to speed up.

GUIDANCE for Accelerator Pedal Movement, $Rspt_{x—A1}$: Reported mean times for response time until accelerator pedal rotation vary from 0.9 to 2.2 s (Brown, Lee, and McGehee, 2001; Perez, Doerzaph, and Neale, 2004, Wiese and Lee, 2004; Li and Milgram, 2005; McGehee and Carsten, 2011).

7.1.3 Response Time until Full Accelerator Pedal Release, $RspT_{A—AOFF}$

Time interval, usually in seconds or milliseconds, from onset of initiating event until the foot is no longer in contact with the accelerator pedal or when the accelerator position signal reaches zero, within the noise limits of sensor measurement.

NOTE 1: The foot is on the accelerator pedal at event onset.

NOTE 2: The zero position is the easiest end point to measure.

NOTE 3: Position measurements should not be used to determine response time if the accelerator does not return to an undepressed condition when released. In this case, use video recording to determine foot release point. Data analysts may have to work backward to determine when the final release occurred.

GUIDANCE for Response Time until Accelerator Pedal Release: Initial accelerator pedal release is described in McGehee, Mazzae, and Baldwin, 2000 and McGehee, Brown, Lee, and Wilson, 2002. Initial accelerator pedal release times ranged from 0.96 to 1.26 s for data collected in a driving simulator and on a test track. See also McGehee and Carsten, (2010) and Curry, Greenberg, and Kiefer (2005).

7.2 Brake Response Time

Time interval, usually in seconds or milliseconds, from an initiating event until the brake pedal is first contacted or moved a specified amount in response to that event (Figure 13).

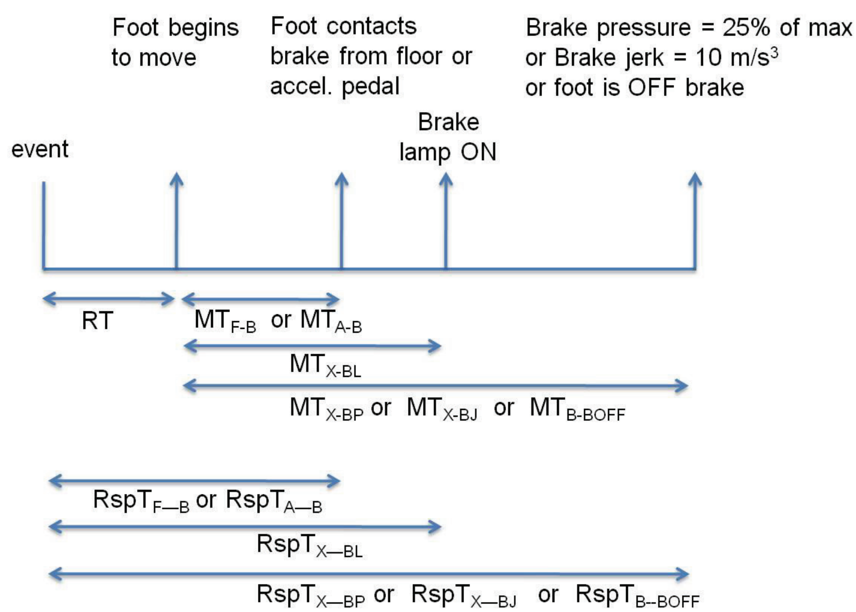


FIGURE 13 -- BRAKE RESPONSE AND MOVEMENT TIMES

NOTE 1: The subscripts indicate the starting and ending foot location.

NOTE 2: Four brake response times are defined based on four different methods to determine the end point of the foot movement response.

REQUIREMENT: The first instance the term *brake response time* is used in a document, the start and end points shall be reported.

GUIDANCE for Brake Response Time: *Brake response time* is the most common term used in the literature, though sometimes the term perception-response time is used, especially in crash reconstruction (Olson, 1986; 2002; Triggs and Harris, 1982). For crash reconstruction, perception response time is assumed to be about 1.5 s.

One of the major problems with the literature is the term is often undefined, and when it is, it is not defined consistently.

Response times are generally reported in seconds (usually to nearest 100^{th}) or milliseconds, often reflecting the accuracy to which response time is measured. Keep in mind that when response time is obtained using video data (often recorded 60 Hz (interlaced) in the US and Japan, 50 Hz in Europe (noninterlaced)), times cannot be any more accurate than the inverse frame rate, 33 or 20 ms. To reflect such, mixed units (s, ms) appear in the paragraph that follows.

The most extensive summary of brake response times is Young and Stanton (2007), who show mean brake response times ranging from 350 to 6300 ms and mean movement times of 170 to 180 ms. As examples, for responding to a center high-mounted stop lamp (CHIMSL) in a driving simulator, Warshawsky-Livne and Shinar (2002) report brake response times of a 0.39 s on average, with a movement time of about 0.17 s. For brake response times to a warning sound, Cheng, Hashimoto, and Suetomi (2002) report times ranging from 0.52 to 2.4 s with a mean of 1.08 s and a median of 0.96 s. The figure they provide suggests the distribution is log normal. See also Smith, Najm and Lam (2003) and Markkula, Benderius, Wolff, and Wahde (2012). For additional information see Kiefer, LeBlanc, Palmer, Salinger, Deering, and Shulman (1999), Krishnan, Gibb, Steinfeld, and Shladover (2001), and Berndt, Wender, and Dietmayer (2007).

For data on the braking performance of vehicles, a topic of interest to those predicting crash risk, see Marshek, Cuderman, and Johnson (2002a,b,c).

7.2.1 Response Time until Brake Pedal Contact, $RspT_{F\text{-}B}$ or $RspT_{A\text{-}B}$

Time interval, usually in seconds or milliseconds, from onset of initiating event to first foot contact with the brake pedal.

NOTE 1: Pedal contact point may be determined from video recordings, contact switches, brake force sensor, brake line pressure changes, or other means.

NOTE 2: This time is the most accurate end point.

7.2.2 Response Time until Brake Lamp On, $RspT_{X\text{-}BL}$

Time interval from onset of initiating event until the brake lamp illuminates in response to the initiating event.

NOTE: Subscript X indicates the foot can be on the brake, floor, or accelerator at event onset.

7.2.3 Response Time Until 25% of Brake Pressure Maximum, $RspT_{X\text{-}BP}$

Time interval from onset of initiating event until the brake line pressure reaches a pre-determined value, typically 25% of the maximum pressure, in response to the initiating event.

GUIDANCE for Response Time until Brake Lamp On, $RspT_{X\text{-}BP}$: Assuming that the driver is engaged, the time between the initial brake press and 25% of max brake pressure should be swift (about 250 ms) in an imminent collision situation. Drivers may modulate their brake press if there is uncertainty in the collision threat (e.g., a car is spinning out of control and the driver does not know whether to brake, steer, or both) or to compensate for a slow initial response (Lee, McGehee, Brown, and Reyes, 2002).

Readers should be aware that the time for a brake lamp to illuminate depends on the type of lamp. For incandescent brake lamps, no measurable light appears until about 50 ms after the voltage is applied, and it typically takes a quarter of a second for the lamp to reach 90% of maximum output. The rise times to 90% output are much less than 1 ms for LED lamps, a value too small to affect response time measurements (Sivak, Flannagan, Sato, Traube, and Aoki, 1993).

REQUIREMENT: Report the type of brake lamp and the rise time to 90% lamp output.

7.2.4 Response Time until Brake Jerk, $RspT_{X\text{-}BJ}$

Time interval, usually in seconds or milliseconds, from onset of initiating event until the brake jerk (the derivative of acceleration) reaches a pre-determined value, typically 10 m/s^3, in response to the initiating event.

NOTE 1: Previously, this measure and other measures related to jerk have not been commonly collected. However, as comfort issues related to adaptive cruise control, lane keeping assistance, and other systems supporting longitudinal and lateral control become increasingly common, so too will the use of jerk-related measures.

NOTE 2: For additional information, see Nygard (1999), and Bagdadi and Varhelyi (2011, 2012).

GUIDANCE: Brake jerk is most likely to be determined from either vehicle speed or acceleration data available on the CAN bus.

7.2.5 Response Time until Brake Pedal Release, $RspT_{B—BOFF}$

Time interval, usually in seconds or milliseconds, from onset of initiating event until the foot is no longer in contact with the brake pedal or until the brake position signal reaches zero, within the noise limits of sensor measurement.

Figure 14 shows an example time history.

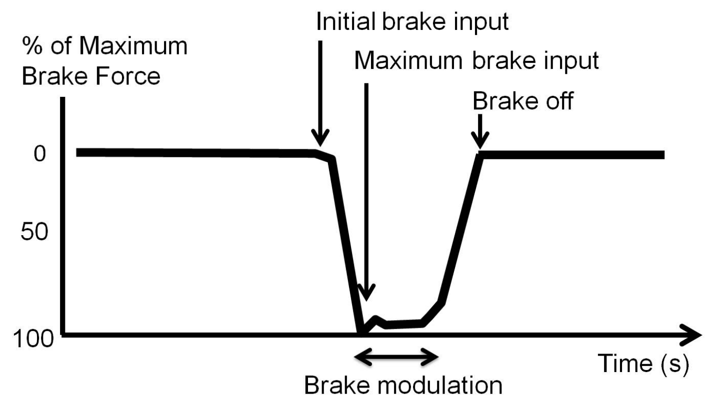


FIGURE 14 – EXAMPLE OF BRAKE APPLICATION AND RELEASE

NOTE: This measure is only applicable if the foot is on the brake pedal when the initiating event occurs.

GUIDANCE: Most commonly, *response time until brake pedal release* is determined from the brake pressure signal.

7.3 Guidance Concerning Use of Accelerator Pedal and Brake Pedal Measures

The most commonly used definitions are likely to be *accelerator response time*, either until accelerator pedal movement or accelerator release and *brake response time until pedal contact*. Accelerator response time is the first indication of a driver reaction to some event.

Brake response time indicates a more substantial response, with *response time until pedal contact or brake lamp on* being preferred because it communicates information to other drivers and is easy to measure in a real vehicle. Simulators and advanced instrumented vehicles may have more sophisticated methods to measure pedal deflection.

Olson (1986) or Olson (2002), as well as Green (2000) and Johansson and Rumar (1971) provide additional information on brake response time. For a more recent study, see Makishita. and Matsunaga (2008). For a study examining multiple pedal measures at the same time, see Lerner, Jenness, Robinson, Brown, Baldwin and Llaneras (2011).

8. LONGITUDINAL CONTROL: OPERATIONAL DEFINITIONS OF VEHICLE-BASED MEASURES

8.1 Vehicle Longitudinal State Measures

For the state measures (e.g., distance gap) in 8.1.1, the most commonly reported statistical measure is the mean. To keep the document compact, the means for the six measures in this section are not specifically defined, and the guidance for those means is reported with the state measures.

For applications of these measures, see NCAP Forward Crash and Lane Departure Warning System 2010 Test Procedures (U.S. Department of Transportation, 2010a, b) and AAM Driver Focus Guidelines (Alliance of Automobile Manufacturers, 2006).

8.1.1 Distance Gap

Longitudinal distance along a traveled way, usually measured in feet or meters, between one vehicle's leading surface and another vehicle's trailing surface.

NOTE 1: This definition was expanded from the Highway Capacity Manual (2011, page 9-8).

NOTE 2: Most commonly, the two vehicles are the subject vehicle, and the vehicle ahead and they are in the same vehicle lane on the same traveled way (Figure 15).

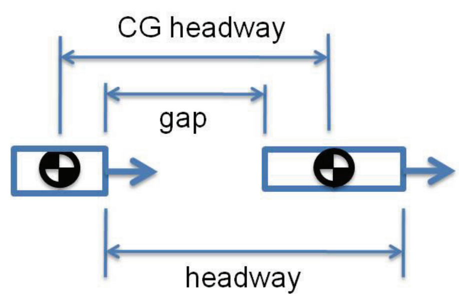


FIGURE 15 -- LONGITUDINAL DISTANCE MEASURES

NOTE 3: For multi-lane traveled ways, gap can refer to (1) the distance between the subject vehicle and a leading or trailing vehicle in the same lane, (2) the distance between the subject vehicle and a leading or trailing vehicle in another lane, or (3) the distance between two vehicles in a lane adjacent to the subject vehicle (Figure 16). The gap between the two vehicles in the adjacent lane would be important if the subject vehicle was to change lanes.

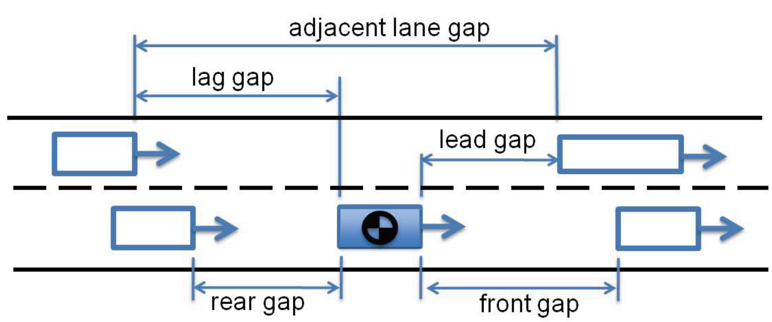


FIGURE 16 – DISTANCE GAP ALTERNATIVES IN A MULTI-LANE TRAVELED WAY

NOTE 4: When the gaps refer to vehicles immediately ahead of and behind the subject vehicle, the terms front and rear gap are used, though the term following gap has also been used in the literature. The gaps in adjacent lanes to vehicles ahead of and behind the subject vehicle are called the lead and lag gaps, respectively. See HIda (2005).

NOTE 5: Figure 17 shows the subject vehicle merging onto a multi-lane traveled way, where the driver has to judge the gap between other vehicles and their relative position in order to merge safely.

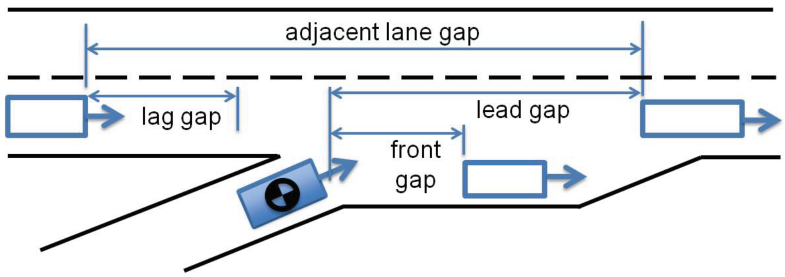


FIGURE 17 – MERGING ONTO A MULTI-LANE TRAVELED WAY

NOTE 6: Figure 18 shows the gaps a driver would need to consider when passing a lead vehicle on a two-lane traveled way.

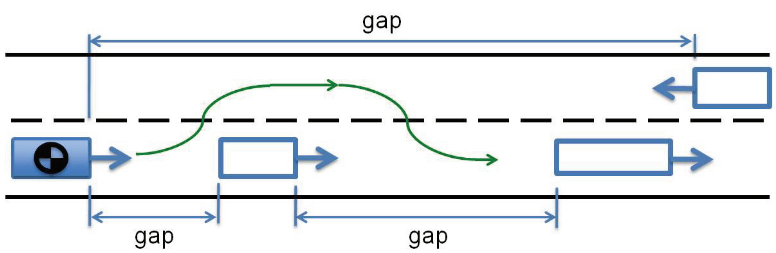


FIGURE 18 – PASSING MANEUVER ON A MULTI-LANE TRAVELED WAY

NOTE 7: The term gap can also refer to the distance between on-coming vehicles in intersecting lanes of traffic (Figures 19 and 20). In this scenario, the gap is measured between the lead surface of the through vehicle and nearest side the crossing vehicle. When deciding to cross intersecting lanes of traffic, drivers have to consider the gaps in the crossing traffic relative to the subject vehicle and the speed(s) of the approaching vehicle(s). The scenarios shown in Figures 19 and 20 can also be applied for the case of a pedestrian at a crosswalk.

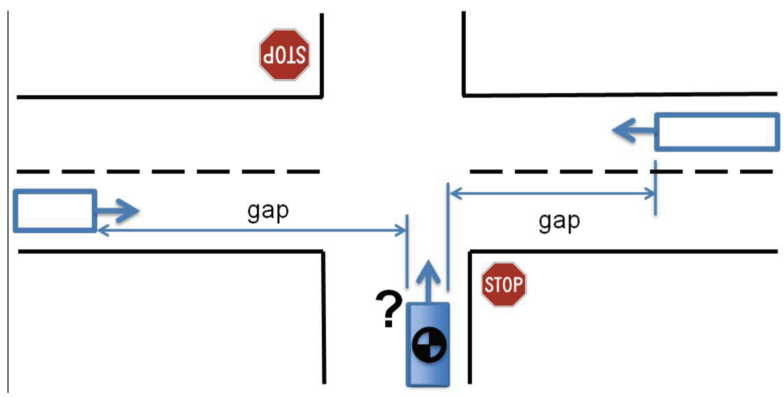


FIGURE 19 – GAPS WHEN PROCEEDING FROM STOP TO CROSS A T-INTERSECTION

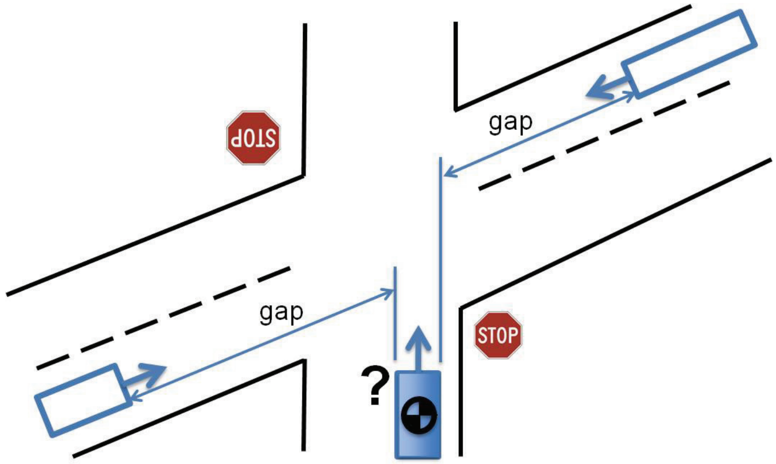


FIGURE 20 – GAPS WHEN PROCEEDING FROM STOP TO CROSS AN ANGLED INTERSECTION

REQUIREMENT: The first instance the term *distance gap* is used in a document, the two vehicles in the gap measurement and the value above which distance gap is ignored, if any, shall be reported. Separate analyses and records of distance gaps shall be kept for each lane location of the leading and trailing vehicles.

GUIDANCE for Distance Gap: Most commonly distance gap represents the clearance between two vehicles in the same lane and is used in safety assessments to indicate safe following distance. This includes making decisions about passing a lead vehicle (and the space between the lead vehicle and the vehicle ahead of it), and at intersections when merging into or crossing a stream of vehicles perpendicular to the subject's direction of travel (gap acceptance studies) (Farber and Silver, 1967; McLean, chapter 8, 1989; Cooper and Zheng, 2002; U.S. Department of Transportation, 2010a). For additional information on gaps in lane changes, see 10.5.1.

Wikipedia notes that the "Average spacing" (presumably gap) between vehicles for "highways" is 550 ft for Level of Service (LOS) A, 330 ft for LOS B, 220 ft for LOS C, 160 ft for LOS D, and 130 ft for LOS E (http://en.wikipedia.org/wiki/Level_of_service, retrieved May 22, 2012). The original source for these data is the 2000 Highway Capacity Manual. Level of Service is an indicator of traffic flow widely used by traffic engineers, with Level A corresponding to free flow, level F corresponding to a lack of free flow, and levels B-E corresponding to intermediate amounts of traffic flow. For further information on Level of Service, see the Highway Capacity Manual (Transportation Research Board, 2010) and the AASHTO Green Book (AASHTO, 2011). For information on the factors that influence the distance and time gaps drivers select when following a vehicle, see Wada, Doi, Imai, Tsuru, and Kaneko (2007).

8.1.2 Time Gap

Time interval, usually measured in seconds, for one vehicle's leading surface to reach the trailing surface of a vehicle ahead.

NOTE 1: This definition was expanded from the Highway Capacity Manual (2010, page 9-8) and modified to be consistent with the wording for gap.

NOTE 2: To determine the time gap, speed is assumed fixed at the current value, so acceleration is not a factor. If one of the vehicles is braking, then time to collision is a more appropriate measure.

NOTE 3: *Distance gap* is equal to *time gap* multiplied by speed of the following vehicle.

NOTE 4: Time gap can also be measured between a lead vehicle and following vehicle in the same lane, between two vehicles in an adjacent lane, or between a vehicle ahead of or behind the subject vehicle (Figures 15 and 16). It can also be measured between crossing vehicles (Figures 19 and 20).

REQUIREMENT: The first instance the term *time gap* is used in a document, the two vehicles in the measurement and the value above which time gap is ignored, if any, shall be reported. Separate analyses and records of time gaps shall be kept for each lane location of the leading and trailing vehicles.

GUIDANCE for Time Gap: There is a considerable body of literature that refers to time headway, though there are some exceptions (Mitra and Utsav, 2011). However, because of the way it is measured, using radar or LIDAR mounted on the subject vehicle and presumably reflected by the rear of the lead vehicle, that data is believed to be time gap (actually range). Some of the most extensive data on time gap, taken from Ervin, Sayer, LeBlanc, Bogard, Mefford, Hagan, Bareket, and Winkler, (2005), appears in Figure 21. Across all of the on-road conditions they examined (speeds greater than 25 mph), they reported time gaps ranging from about 0.3 to 3.0 s with a median of 1.4 s and a mode of about 1.0 s. The distribution appears log normal. They also provide data that shows the effect of driver age and other factors. For urban driving, Michael, Leeming, and Dwyer (2000) show urban time gaps to be between 1.4 and 2.2 s and Mitra and Utsav (2011) show the effects of fog on time gap. For the effect of lane driven, see Ayres, Li, Schleuning and Young (2001). For data on work zones, see Wang, Benekohal Ramezani, Nassiri, Medina, and Hajbabaie (2011).

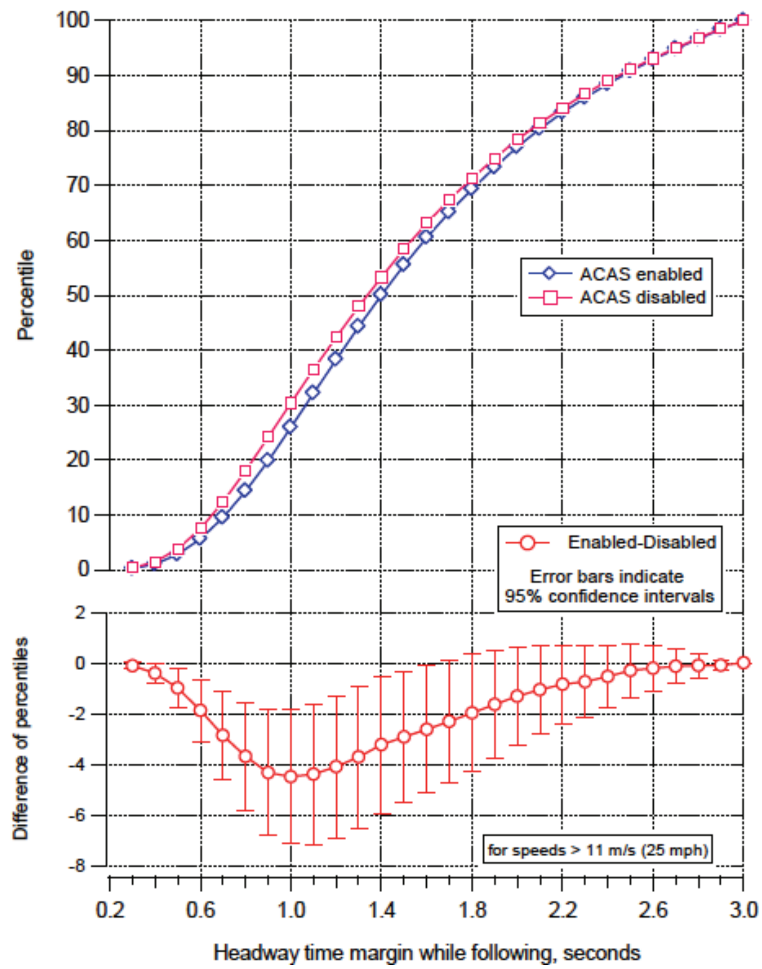


FIGURE 21 -- TIME GAP DISTRIBUTION (WHICH THEY REFER TO AS HEADWAY)
Source: Ervin, Sayer, LeBlanc, Bogard, Mefford, Hagan, Bareket, and Winkler (2005), p. 7-6

Of key importance is the description of the distribution of time gaps. Hoogendoorn and Bovy (1998) state that the distribution of "headway" (what they refer to as "empty zone", but which appears to be mean time gap) is replicated by a Pearson-III-based mixed-vehicle-type Generalized Queueing Model (GQM). For that distribution, they provide distribution parameters (alpha, beta, d, gamma, theta) as a function of vehicle type (car, truck, articulated truck) and as a function of time period (morning, noon, evening). See also Yang and Peng (2010) and Zhang, Shladover, and Zhang, (2007).

The most common statistic based on time gap is mean time gap. Mitra and Utsav (2011) suggest only considering time gaps of 6.0 s or less. Another option is to focus on the median time gap to deal with the problem posed by very large time gaps. Either option is acceptable.

For background information, see Brackstone and McDonald (1999), Brackstone, Sultan, and McDonald (2002), Lee and Peng (2004), Brackstone and McDonald (2007), Brackstone, Waterson, and McDonald (2009), and Fancher, Bareket, and Ervin (2001).

8.1.3 Distance Headway

Longitudinal distance along a traveled way, usually measured in feet or meters, between two vehicles measured from the same common feature of both vehicles (for example, the front axle or front tire contact patch, the front bumper, the leading surface of both vehicles, or the trailing surface, Figure 15).

NOTE 1: This definition was expanded from the Highway Capacity Manual (2010, page 9-9) and modified to be consistent with the wording for gap.

NOTE 2: Most commonly, the two vehicles are a subject vehicle and a vehicle ahead in the same lane (Figure 14).

NOTE 3: Distance headway, when determined at the roadside may use traffic counting devices such as pneumatic road tubes, piezoelectric sensors or inductive loops embedded or cut into the traveled way pavement, or less intrusive methods such as radar or infrared beams to detect vehicles passing a point on the traveled way.

NOTE 4: The *distance gap* and *distance headway* differ by one "vehicle" length, which depending on the location of the reference point, can be the length of the lead vehicle (if the leading surface is used), the length of the following vehicle (if the following surface is used), or some combination of them (for example, if the front axle is used).

REQUIREMENT: The first instance the term *distance headway* is used in a document, the two vehicles in the distance headway measurement and the value above which distance headway is ignored, if any, shall be reported.

8.1.4 Time Headway

Time interval, usually measured in seconds, between two vehicles measured from the same common feature of both vehicles (for example, the front axle or front tire contact patch, the front bumper, the leading surface of both vehicles, or the trailing surface, Figure 11).

NOTE 1: This definition was expanded from the Highway Capacity Manual (2010, page 9-9) and modified to be consistent with the wording for gap.

NOTE 2: *Distance headway* is equal to *time headway* multiplied by the speed of the following vehicle.

NOTE 3: This term is commonly used in the civil engineering literature on traffic flow. In that context, time headway is sometimes measured by waiting for the first vehicle to pass, starting a clock, and stopping it when the second vehicle passes. Using that procedure, acceleration can be a factor. However, this measure is generally determined when speeds are constant, so acceleration is not an issue.

REQUIREMENT: The first instance the term *time headway* is used in a document, the two vehicles in the measurement and the value above which *time headway* is ignored, if any, shall be reported.

GUIDANCE for Time Headway: Time headway is often determined traffic counting devices that determine the inter-arrival times of vehicles. Al-Ghamdi (2001) reports that for arterial roadways the time headway distribution is Gamma and for freeways it is Ehrlang, with the distribution depending upon the flow rate. Furthermore, he notes that the standard deviations of time headway distributions are proportional to the mean headway. See also: Luttinen (1992, 1996); Hoogendoorn, and Bovy (1998); Neubert, Santen, Schadschneider and Schreckenberg (1999); Cowan (2002); and Hoogendoorn (2005).

8.1.5 CG Distance Headway

Longitudinal distance along a traveled way, usually measured in feet or meters, from one vehicle's center of gravity to another vehicle's center of gravity (Figure 15).

NOTE 1: This definition is based upon the definition for *distance gap* in the Highway Capacity Manual (2010, page 9-9).

NOTE 2: Most commonly, the two vehicles are the subject vehicle and a vehicle ahead in the same lane.

NOTE 3: *CG distance headway* equals *headway distance* if the two vehicles are of the same length and have centers of gravity in the same relative longitudinal location.

NOTE 4: Many driving simulators, such as the DriveSafety and RealTime simulators, report distances between vehicles relative to their center of gravity (CG). This is because simulators compute future vehicle positions based on their dynamics, and the local coordinate system for those computations is usually the vehicle center of gravity.

REQUIREMENT: The first instance the term *CG distance headway* is used in a document, the two vehicles in the CG headway distance measurement and the value above which *CG distance headway* is ignored, if any, shall be reported.

8.1.6 CG Time Headway

Time interval, in seconds, for one vehicle's center of gravity to reach the center of gravity of a vehicle ahead (Figure 15).

NOTE 1: This definition is based upon the definition for *time headway* in the Highway Capacity Manual (2010, page 9-9).

NOTE 2: Most commonly, the two vehicles are the subject vehicle and a vehicle ahead in the same lane.

REQUIREMENT: The first instance the term *CG time headway* is used in a document, the two vehicles in the measurement and the value above which *CG time headway* is ignored, if any, shall be reported.

8.1.7 Range

Straight-line (vector) distance between two vehicles, commonly determined by radar or LIDAR (Figure 22).

NOTE 1: *Distance gap is* measured along the traveled way and is not identical to range on a curved travel path.

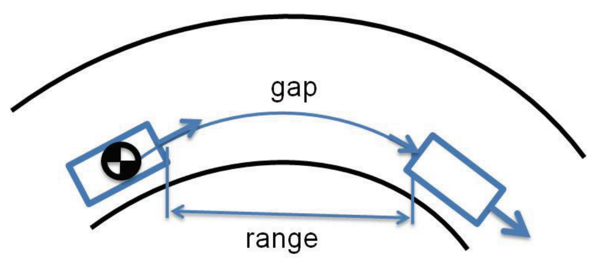


FIGURE 22 – GAP VERSUS RANGE

NOTE 2: The sensor for range is often located in the center of the subject vehicle's grill and the reflector is a license plate on the lead vehicle.

8.1.8 Guidance Concerning Longitudinal State Measures

Time gap and distance gap, time headway and distance headway, and CG time headway and CG time gap are used in human factors studies of rear-end crashes. These terms are important to the design of forward crash warning and braking systems, as well as adaptive-cruise-control (ACC) systems.

A major problem in the literature is that the term *headway* is commonly used to refer to both gap and headway as defined here, and one cannot tell which was intended when the term is undefined. If the lead vehicle is a tractor-trailer, the difference between *distance gap* and *distance headway* is about 55 feet, a significant difference. In general, if the topic is drivers responding to lead vehicles, especially stopping, then gap (time or distance) are the preferred measures. If the topic is traffic flow, then headway measures (time or distance) are preferred.

Furthermore, there is a common misperception that simulators measure gap, when in fact they measure CG gap (Stoner, 2012, personal communication).

For all of the longitudinal state measures in this section, what matters most is when the measured values are small, i.e. the lead vehicle is close to the subject vehicle. Changes that occur when these measures are large are generally not important. For example, there is little difference in how someone drives if a lead vehicle has *time gap* (defined below) of 10 or 20 s. However, the effect of a difference between a 0.5 versus 1.0 s time gap is substantial. What is "small" depends upon what measurement is of interest—crash risk, comfortable following distance or time, or something else, as well as the traffic volume, weather, road geometry, driver age, and many other factors.

On the past, authors have sometimes reported mean values (of time or distance) to vehicles ahead as indicator of following performance. However, measures of central tendency can be misleading because one instance of a large following distance or time can outweigh numerous decreases in short following distances or times. A recommended alternative approach is to compute statistics for censured distributions—to ignore the times and distances above some value that has no major impact on the risk of a forward crash or vehicle following behavior. There is often no agreement as to what these cutoff values should be, but some authors have suggested cutoff values for specific measures described below.

REQUIREMENT: For human factors studies related to crash avoidance, *time gap* and *distance gap* shall be reported. For traffic and highway engineering, *time headway, distance headway, time gap*, and *distance gap* should be reported. For site-based studies all four measures shall be reported. When any of these measures are reported, if any data were censored, the cutoff value(s) and number of values removed from the data shall be reported.

8.2 Vehicle Longitudinal Exposure Statistics

8.2.1 Time to Collision (TTC)

Time interval, usually measured in seconds, required for one vehicle to strike another object.

NOTE 1: The object is often a lead vehicle, but it could be a crossing vehicle or fixed object (e.g., lamppost, tree, parked car). When TTC refers to other than the lead vehicle, that vehicle or object should be identified.

NOTE 2: The computation of TTC for all cases appears in Appendix A and is described in van der Horst (1990). For the original work on TTC, see Hayward (1972).

NOTE 3: TTC is the time period over which the driver shall act to avoid a collision.

NOTE 4: In the psychological literature, sometimes the term time to contact is used (Tresilian, 1991; Cutting, Vishton, and Braren, 1995; Yilmaz and Warren, 1995).

REQUIREMENT: The first instance the term *TTC* is used in a document, the value greater than which *TTC* is ignored shall be reported.

GUIDANCE for Time to Collision: TTC is a commonly used measure, with larger values indicating a greater degree of safety. Although seemingly straightforward, the computation of TTC values requires some thought. If the relative acceleration and velocity are zero or the lead vehicle is accelerating away from the subject, then TTC is infinite, in which case computing a statistic such as a mean becomes difficult. Large TTC values are common when traffic is moving steadily or traffic volume is light. Therefore, standard procedure is to ignore large TTC values where the potential threat is so far in the future that it is given minimal consideration. There is no agreement as to what that value should be. Ostlund, Nilsson, Tornros and Forsman (2005) ignore TTCs in excess of 15 s. In all cases when TTC statistics are reported, the cutoff value shall be reported.

As an example of typical TTC data, in a study of rural driving in a driving simulator, Ostlund, Nilsson, Tornros and Forsman (2006) reported mean TTC values of about 11 s, but about 3.75 s for a more heavily traveled motorway.

In the 100-car naturalistic on-road driving study, McLaughlin, Hankey, and Dingus (2009) provide an example of the distribution of time spent at various TTCs for younger and older drivers (Figure 23).

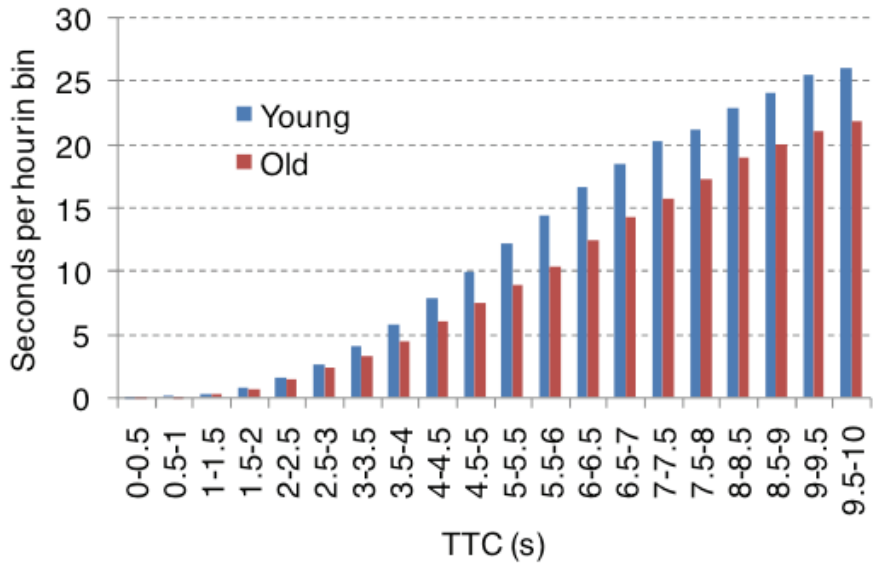


FIGURE 23 -- DISTRIBUTION OF TTC FROM 0 TO 10 SECONDS
Source: McLaughlin, Hankey, and Dingus (2009), p. 410.

Large TTC values do not necessarily mean driving conditions are safe. If the lead vehicle is close and could slow down at any moment, the driver would have little time to react.

TTC can be calculated at anytime during the response – from the initial throttle release, brake application, steering etc. McGehee. Brown, Lee, and Wilson (2002) found that initial throttle release in a lead vehicle stationary rear-end crash condition was at 2.56 s TTC.

For additional information, see van der Horst and Hogema (1993), Gettman and Head (2003), Vogel (2003), Archer (2005), Balas and Balas (2006), Lundgren and Tapani (2006), Ostlund, Nilsson, Tomros, and Forsman (2006), Dijkstra, Drolenga, and van Maarseveen (2007), Ozbay, Yang, Bartin, and Mudigonda (2008), Kusano and Gabler (2011), and Bachmann, Roorda, and Abdulhai (2011).

8.2.1.1 Acceleration Based, TTC (Option A)

Time interval, usually measured in seconds, required for one vehicle to strike another vehicle (or object) if both continue along the same path with constant accelerations.

8.2.1.2 Velocity Based TTC (Option B)

Time interval, usually measured in seconds, required for one vehicle to strike another vehicle (or object) if both continue along the same path at constant velocities.

NOTE: Option B is the original definition of TTC (Hayward, 1972) and is referenced in several publications (Godthelp and Koning, 1981; Godthelp, Milgram, and Blaauw, 1984; van der Horst and Hogema, 1994; van der Horst, 1990).

8.2.2 Minimum Time To Collision (Minimum TTC, TTC_{min})

Minimum time interval, usually measured in seconds, required for one vehicle to strike another vehicle or object over some time period on the order of seconds.

NOTE 1: There are 2 options, acceleration based (Option A) and velocity based (Option B).

NOTE 2: The computation of minimum TTC for all cases appears in Appendix B and is described in van der Horst (1990).

NOTE 3: Figure 24 shows the local minima for TTC.

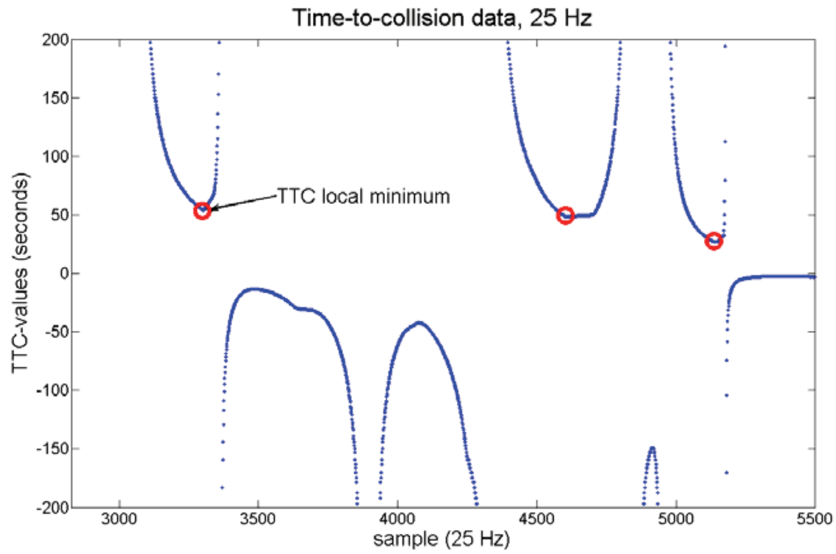


FIGURE 24 -- MINIMUM TIME TO COLLISION
Source: Ostlund, Nilsson, Tomros, and Forsman (2006), p. 15

REQUIREMENT: The first instance the term *minimum TTC* is used in a document, the value greater than which TTC is ignored shall be reported.

GUIDANCE for Minimum Time To Collision: Hogema and Janssen (1996) reported a minimum TTC value of 3.5 s for on-road, baseline driving, and 2.6 s for driving with an ACC system. See also Van der Horst (1993).

8.2.3 Adjusted Time to Collision (Adjusted TTC)

Predicted or actual time interval, usually measured in seconds, for one vehicle to strike another object.

NOTE 1: This term was originally defined by Brown (2007), p 42 as "the amount of spare time the driver had based on the avoidance response chosen by the driver." The wording chosen here assures consistency with other definitions in this document.

NOTE 2: The full mathematical description of adjusted time to collision is given in Appendix C.

NOTE 3: If a collision occurs, adjusted TTC is calculated based on the relative velocity at collision and the deceleration of the driver's vehicle prior to the collision.

NOTE 4: There are 2 options, acceleration based (Option A) and velocity based (Option B).

REQUIREMENT: The first instance the term *adjusted TTC* is used in a document, the value greater than which TTC is ignored and the option shall be reported.

GUIDANCE for Adjusted Time to Collision: This statistic is particularly useful where the outcomes of a series of events (1) that are a mixture of crashes and non-crashes, and (2) the sample size may be small. This statistic incorporates the data from both crash and non-crash outcomes into one measure.

8.2.4 Time Exposed Time to Collision (TETTC, TET)

Time interval, usually measured in seconds, over which the time to collision is less than some undesired threshold.

NOTE 1: This term was originally defined by Minderhoud and Bovy (2001)

NOTE 2: The full mathematical description of time exposed time to collision is in Appendix C.

NOTE 3: As with the other TTC related measures, there are two options, acceleration based (Option A) and velocity based (Option B).

REQUIREMENT: The first time the term *time exposed TTC* is used in a document, the value greater than which TTC is ignored and the option shall be reported.

GUIDANCE for Time Exposed Time to Collision: Van der Horst (1991) and Farber (1991) suggest a TTC of 4 s to distinguish between safe and uncomfortable situations on roads. Hogema and Janssen (1996) suggest a minimum TTC of 3.5 s for drivers without ACC and 2.6 s for drivers with ACC. Kassner (2008) used 4 s as the TTC time threshold as "Traffic situations less than 4 s are considered to be dangerous." (Kassner (2008), p. 330. Van Driel, Hoedemaeker, and Van Arem (2007) considered TTC values below 4 s and 20 s. Ostlund, et al (2004) used 4 s as the threshold.

Although there is some difference of opinion as to what the threshold TTC should be for time exposed TTC, 4 s is a reasonable initial recommendation for a threshold.

For data on the relationship between TET and road geometry, see Bella and D'Agnostini (2010). For additional information on TET see Jamson, Batley, Portouli, Papakostopoulos, Tapani, Lundgren, Huang, Hollnagel and Janssen (2004).

8.2.5 Time Integrated Time to Collision (TITTC, TIT)

Time interval, usually measured in seconds, over which the time to collision is less than some undesired threshold weighted by how far below that threshold the time to collision is at each moment.

NOTE 1: This term was originally defined by Minderhoud and Bovy (2001)

NOTE 2: The full mathematical description of adjusted time to collision is in Appendix D.

NOTE 3: There are two options, acceleration based (Option A) and velocity based (Option B).

REQUIREMENT: The first instance the term *TIT* is used in a document, the value greater than which TTC is ignored shall be reported.

8.2.6 Guidance Concerning Vehicle Exposure Statistics

Generally the values of TIT are highly correlated with TTC, but there are times when TIT tends to "highlight more consistently unsafe conditions than TTC." (Guido, Sacconanno, Vitale, Astarita, and Festa, 2011, p. 490). The conditions they examined were approaching, merging, and driving around a traffic circle in Italy, across which driving safety varied. These measures are used in the collision-warning context and can help the designer pick warning thresholds.

These measures are used to determine driver attention and inattention to maintaining stability. For additional information on TIT see Jamson, Batley, Portouli, Papakostopoulos, Tapani, Lundgren, Huang, Hollnagel and Janssen (2007).

9. LATERAL CONTROL: OPERATIONAL DEFINITIONS FOR DRIVER STEERING RESPONSES TO EVENTS

9.1 Steering Performance Measures

9.1.1 Steering Reaction Time

Time interval, usually measured in seconds or milliseconds, from onset of an initiating event to the first movement of the steering wheel in response (Figure 25).

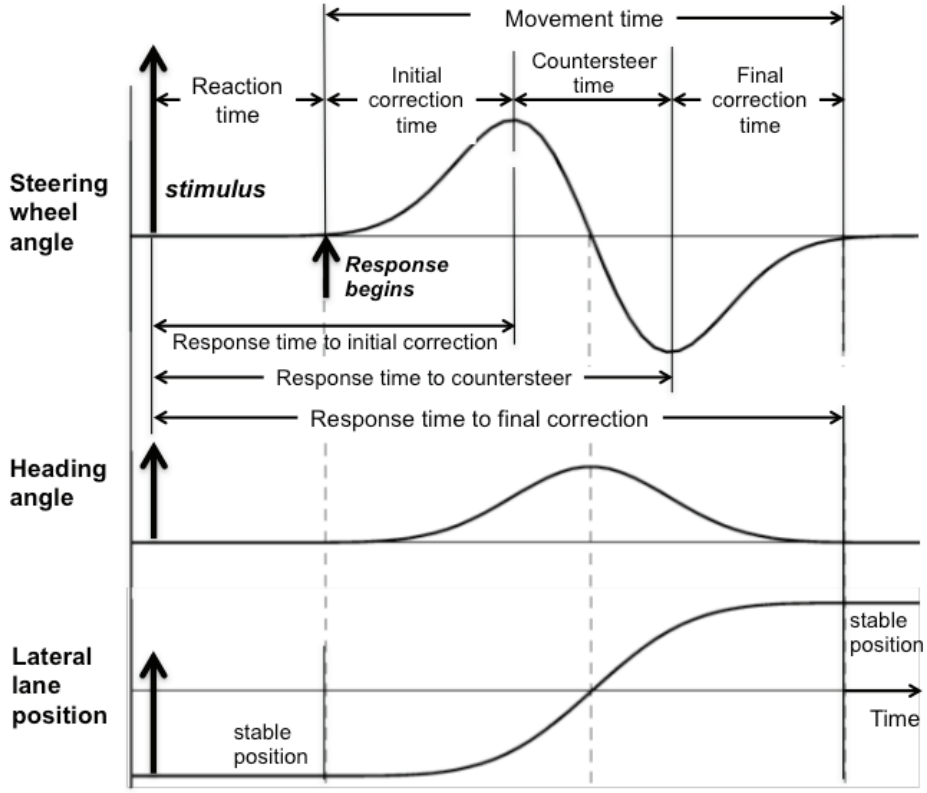


FIGURE 25 – STEERING REACTION, MOVEMENT, AND RESPONSE TIMES

GUIDANCE for Steering Reaction Time: As an example of typical responses, Deroo, Hoc, and Mars (2012) reported mean steering reaction times of 473 ms (straight roads) and 492 ms (curves) in response to haptic warning signals (steering wheel oscillations). For fundamental research on driver steering control see McRuer, Allen, Weir, and Klein (1977) and Jagacinski and Flach (2011).

REQUIREMENT: The first instance the term *steering reaction time* is used in a document, the steering wheel angular change required to identify the movement beginning and the time window in which that angular change must occur shall be reported.

9.1.2 Steering Movement Time

Time interval, usually measured in seconds or milliseconds, from the first movement in response to an initiating event until completion of all steering wheel movements made to bring the vehicle to the desired path of travel (Figure 25).

NOTE 1: See Figure 2 for an example time history.

NOTE 2: When avoiding an object in the current path of travel, steering movements typically involve: (1) an initial movement to avoid the object and (2) a second compensatory correction (countersteer) to return the vehicle to the original path, and (3) one or more final corrective movements to align the vehicle to the desired travel path.

GUIDANCE for Steering Movement Time: In general, as shown in Figures 26 and 27, steering movement times are generally several seconds long, depending upon the maneuver being attempted. Reported steering movement times can vary considerably depending upon whether the time reported is for the entire movement, as defined here, or parts of it, as shown in Figure 18. See McGehee, Lee, Dawson, and Batemen (2004) for data on changes in steering movements during the initial phases of learning to drive a simulator.

REQUIREMENT: The first instance the term *steering movement time* is used in a document, the steering wheel angular change required to identify the movement beginning and end points, and the associated time windows for each shall be reported.

9.1.3 Steering Response Time

Time interval, usually measured in seconds or milliseconds, from the onset of an initiating event until completion of all steering wheel movements to bring the vehicle to the desired path of travel.

NOTE 1: Steering response time is the sum of the steering reaction and movement times.

NOTE 2: If desired, steering response times can be computed for various segments of the movement, as illustrated in Figure 17.

NOTE 3: If response times are computed for various segments of the movement, the term steering response time represents the time from the initial movement response to final correction. Appropriate terms should be added to denote steering response times for the individual movement segments.

REQUIREMENT: The first instance the term *steering response time* is used in a document, (1) the time of stimulus onset (2) the angular change required to identify movement start and end points, and (3) the associated time window within which the movement shall occur shall be reported.

9.1.4 Guidance for Steering Performance Measures

Measures of steering reaction or response time are not frequently reported because the most common driver response to an unexpected event is to brake (Green, Cullinane, Zylstra, and Smith, 2003; Green, Kang, Lin, Lo, Best, and Mize, 2012). However, steering response measures and statistics are becoming more commonly reported as research on lane departure warning and lane keeping assistance systems advance

GUIDANCE for Steering Response Time: Figures 25 (for a driving simulator) and 26 (for a real road) show the mean distance of the vehicle from the lane center in response to a lane departure or a lane change merge warning. Notice that, on average, evidence of the consequence of a steering response begin to appear around 0.5 s after the alert, and that lateral position changes in response to the steering movements for sometimes as long as an additional 2.5 s, with the vehicle response being almost complete after 3.0 s (on average), and fully complete in 5.0 s. Responses could be characterized in other ways, for example, considering only the initial correction to the lane. No matter how the initial response is determined, the method needs to be described so it can be replicated.

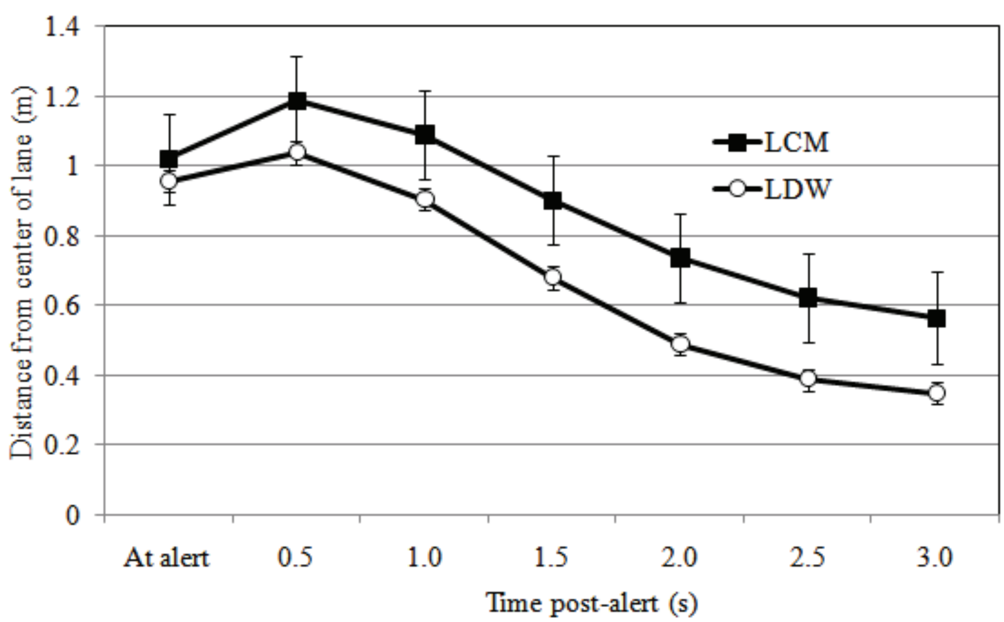


FIGURE 26 -- DRIVER RESPONSE TO LANE DEPARTURE (LDW)
AND LANE CHANGE MERGE (LCM) WARNINGS
Source: Green, Sullivan, Tsimhoni, Oberholtzer, Buonarosa, Devonshire, Schweitzer, Baragar, and Sayer (2008), p. 61

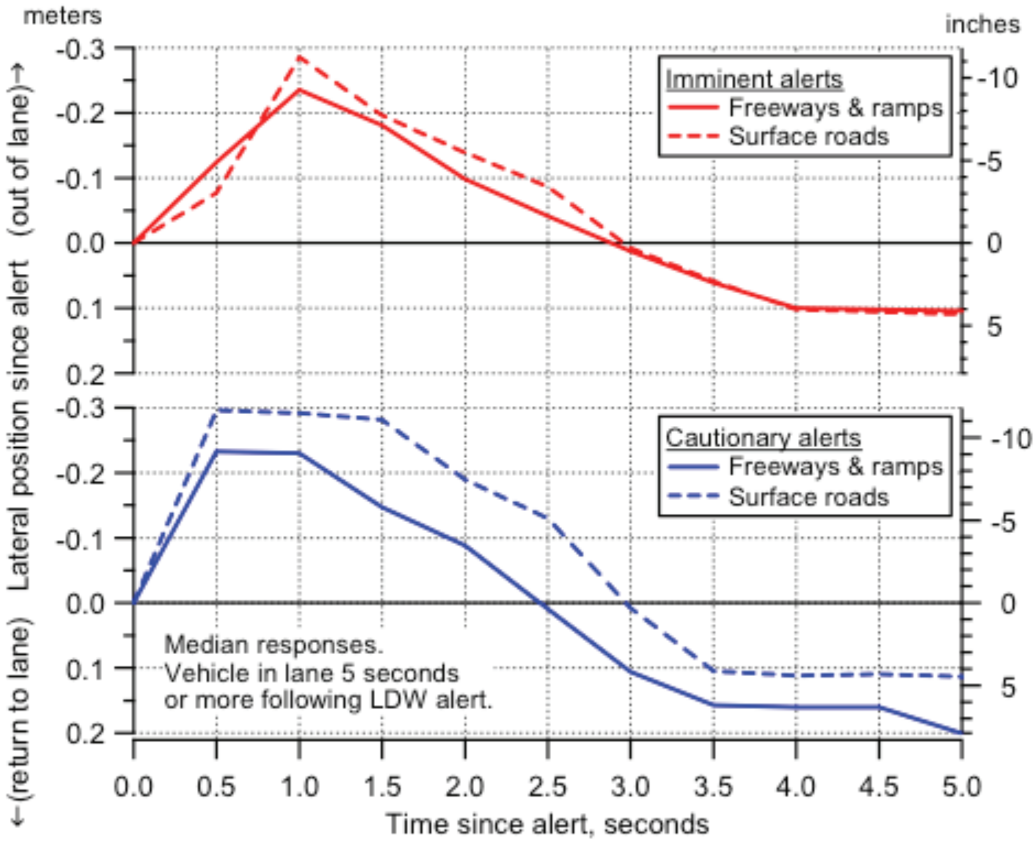


FIGURE 27 – MEDIAN LATERAL POSTION FOLLOWING LDW ALERTS FROM THE RDCW FIELD TEST
Source: LeBlanc, Sayer, Winkler, Ervin, Bogard, Devonshire, Mefford, Hagan, Bareket, Goodsell, and Gordon, (2006), p. 8-4.

9.2 Steering Performance Statistics

9.2.1 Steering Reversal (SR (a,t))

Rotation of a steering wheel of at least Δa deg in one direction followed by a rotation of at least Δa deg in the opposite direction within a moving time window Δt (Figure 28).

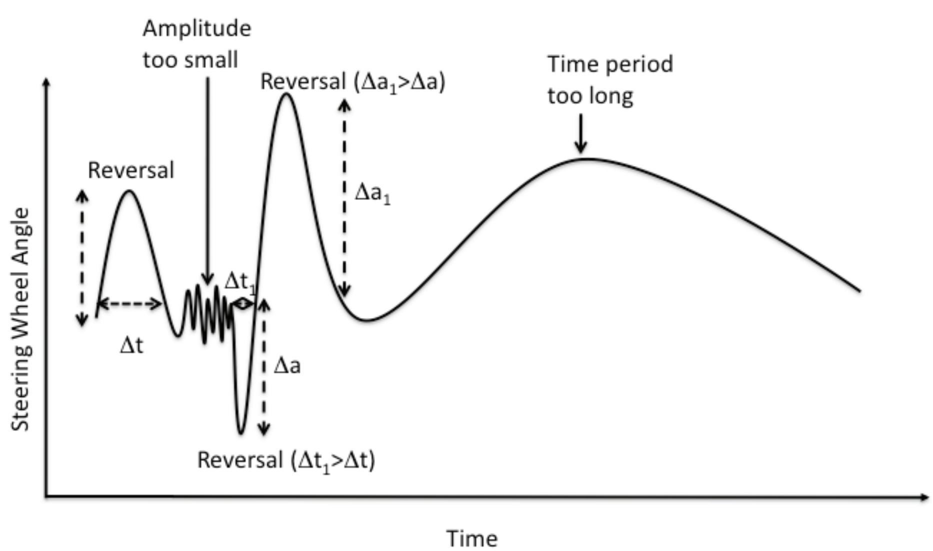


FIGURE 28 -- STEERING REVERSAL

There are at least two different ways to count steering reversals, described below and more fully in Appendix F. Either method is acceptable.

9.2.1.1 Steering Reversal - Direct Method (Option A)

This method looks ahead in time from the current SW angle until a change in steering wheel amplitude equal to or greater than the threshold angle Δa occurs. Then the current SW angle is updated and the time index is incremented. The same procedure is used to look ahead until the amplitude changes beyond the threshold, but in the opposite direction, thus identifying a SW reversal.

9.2.1.2 Steering Reversal - Minimum Curvature Changes in Steering Rate - AIDE Method (Option B)

This method involves applying a low-pass, second-order Butterworth filter to the data, finding the stationary points, and then counting reversals. Details are in Appendix F.

REQUIREMENT: The first time the term *steering reversal* is used in a document, the angular change required, the time window, and the calculation method (option A or B) shall be reported.

GUIDANCE for Steering Reversal: Over the years, many studies have examined steering wheel reversals (Greenshields and Platt, 1967; MacDonald and Hoffman, 1980; McLean and Hoffman, 1973, 1975; Drury, 1985; McGehee, Lee, Rizzo, Dawson, and Bateman, 2004; Skipper and Wierwille, 1986; and Sherman, Elling, and Brekke, 1996). (See also McRuer, Allen, Weir, and Klein, 1977; Karjewski, Sommer, Trutschel, Edwards, and Golz, 2009.) A recent and thorough examination appears in the AIDE methods and measures report (Ostlund, Peters, Thorslund, Engstrom, Markkla, Keinath, Horst, Juch, Mattes, and Foehl, 2005). Previous studies have shown that drivers' attention is increasingly diverted from the primary task of driving, drivers tend to make fewer, but larger, steering corrections (Antin, Dingus, Hulse, and Wierwille, 1990; Dingus, Antin, Hulse, & Wierwille, 1986; Dingus, McGehee, Hulse, Jahns, Manakkal, Mollenhauer, and Fleischman, 1994; McGehee, Brown, Lee, and Wilson, 2002; McGehee, Lee, Dawson, and Rizzo, 2004; and Wierwille and Gutmann, 1978). Of these sources, McLean and Hoffman (1975) is one of the most widely cited.

For small steering wheel angular changes, detecting true steering reversals is difficult because of noise or driver dither in the steering angle signal. Theeuwes. Alferdinck, and Perel (2002) identified steering wheel reversal whenever there was both a change in steering wheel rotational direction and the steering wheel rotational velocity exceeded 3.0 deg/s. McGehee, Lee, Dawson, and Rizzo (2004) defined a change of 6 degrees as being a reversal whereas Wierwille & Gutmann (1978) used 2-degree changes with the steering wheel angle passing through 0. (See also McGehee, Lee, Rizzo, Dawson and Batemen, 2004.) King and Plummer (1973) divided the steering wheel reversal into two groups -- 8.5 degree (macro) and 2.5 degree (micro) -- but also did not specify a time window. The HASTE project considered changes of 1, 3, 5, and 7 degrees. In fact, none of the documents listed provided a time window over which a reversal shall occur.

Reversal thresholds: As a rough rule of thumb, for most passenger cars a 5-degree steering wheel angular change is reasonably free of noise and a 6-degree angular change is certainly free of noise. The noise-free angular changes are less for sports cars or vehicles with tighter steering. However, to capture the result of the steering inputs, a 6-degree steering reversal criterion is recommended. A threshold of 6 degrees differentiates larger variations from the numerous small steering wheel reversals associated with normal driving.

An alternative threshold for defining a steering reversal is that a reversal occurs when the direction of rotation of the steering wheel changes and the initial steering wheel angular velocity (not the angular change) is greater than 3.0 deg/s (Theeuwes, Alferdinck, and Perel, 2002; deGroot, de Winter, Garcia, Mulder, and Wieringa, 2011).

To discriminate lane change maneuvers from steering wheel reversals, the recommended maximum time window for a reversal is two seconds, but the time window could be much shorter.

9.2.2 Number of Steering Reversals

Number of times over that the steering wheel rotates at least a specified amount in one direction and then rotates at least an equal amount in the opposite direction within a time window Δt, accumulated over some time span (e.g., per minute) or distance travelled (e.g., per mile or kilometer).

GUIDANCE: This measure has been used as an indicator of driver distraction, with the number of reversals decreasing as distraction increases. When distracted, drivers attend less to steering, making fewer small steering corrections but more large corrections that are classified as reversals.

REQUIREMENT: The first time *number of steering reversals* is used in a document, the angular rotation threshold Δa, and the time window Δt defining a reversal shall be reported.

9.2.3 Steering Reversal Rate (Δa, Δt, d)

Number of steering wheel reversals in a given time period, t, divided by that time period, usually per minute.

NOTE: The steering reversal rate (Δa, Δt, d) may also be computed over a specified distance traveled, d (e.g., per mile or kilometer).

GUIDANCE for Steering Reversal Rate: The lack of agreement over angular change and time window for a reversal also makes comparison of reversal rates challenging. Ostlund, Nilsson, Tornros, and Forsman (2006) report reversal rates of 33 – 36 per minute for 1-degree reversals and 18-25 per minute for 3-degree reversals for rural road driving. For motorways, the 1-degree reversal rates are about 25-27 per minute. McGehee, Lee, Rizzo, Dawson, and Bateman (2004) show the mean of steering reversal rates greater than 6 degrees to be 14, 4, and 2 for older subjects and 16, 3, and 1 for younger subjects driving for what appear to be the first, second, and third minutes of a drive on a rural road in a driving simulator. This suggests that it takes about three minutes of driving to become familiar with a driving simulator, so simulator assessments involving steering reversals should not begin until after three minutes of training is provided.

REQUIREMENT: The first time the term *steering reversal rate* is used in a document, the angular change required, the time window, and the calculation method (option) shall be reported.

9.2.4 Steering Entropy, H_P

Measure of the consistency/randomness of the steering wheel angle computed by using a series of previous steering wheel angle values to compute a subsequent steering angle.

NOTE 1: There are two methods for calculating Steering Entropy, the 1999 method and the 2005 method. See Appendix G for the equations.

NOTE 2: The MATLAB code for steering entropy is available on the UMTRI Driver Interface web site (www.umich.edu/~driving) in the near future.

NOTE 3: The steering entropy values are between 0 and 1 and are dimensionless.

NOTE 4: One steering entropy value is calculated per trial during a particular test condition.

NOTE 5: Steering entropy is a measure of driver workload. The less the driver is attending to steering, presumably because they are paying attention to something else, the less consistent the steering wheel angle.

NOTE 6: Steering entropy analyses are determined relative to a baseline condition involving no secondary task, i.e., normal driving.

REQUIREMENT: The first instance the term *steering entropy* is used in a document, the calculation method (1999 or 2005) shall be reported.

GUIDANCE for Steering Entropy: Steering entropy was first defined and used to quantify workload by Nakayama, Futami, Nakamura, and Boer (1999). See also Boer (2000) and Boer (2001). Later a revised definition was presented in Boer, Rakauskas, Ward, and Goodrich (2005). Steering entropy is generally computed using MATLAB and Excel. (See Appendix G for the computational details of the original and revised versions.) The revised (2005) definition is preferred.

Examples of studies using steering entropy include Rakauskas, Ward, Bernat, Cadwallader, Patrick, and de Waard (2005), Dawson, Cosman, Lei, Dastrup, Sparks, and Rizzon (2007), Kersloot, Flint, and Parkes (2003), Paul, Boyle, Boer, Tippin and Rizzo (2008), and Crisler (2010). For data on the effects of age, see Nemoto, Yanagshima, Taguchi,and Wood (2002). Typical values for steering entropy are about 0.4 for normal or baseline driving. Most often, what is of interest is comparing the steering entropy between a baseline condition and a condition related to performing an in-vehicle task. Table 1 provides baseline and task-related steering entropy data.

TABLE 1 -- MEASURED H_P RESULTS FOR EACH ACTIVITY BY 4 SUBJECTS
Source: Nakayama, Futami, Nakamura, and Boer (1999), p.6

	Subject				Mean
Task	1	2	3	4	
No secondary task (Baseline)	0.45	0.49	0.46	0.48	0.47
1. listen to traffic information	0.44	0.46	0.48	0.48	0.46
2. converse-repeat spoken words	0.46	0.47	0.46	0.49	0.47
3. converse-give a yes/no answer	0.47	0.49	0.46	0.46	0.47
4. converse-select among 3 choices	0.47	0.46	0.46	0.46	0.47
5. Perform mental arithmetic	0.54	0.41	0.52	0.51	0.52
6. Check a map	0.55	0.46	0.48	0.53	0.51
7. Select a name from a list	0.64	0.48	0.54	0.64	0.58
8. Operate hardware switch	0.66	0.59	0.57	0.55	0.59
9. Operate touch panel switch	0.69	0.62	0.53	0.55	0.60
10. Scroll map	0.74	0.69	0.57	0.72	0.68
11.Change map scale	0.68	0.61	0.51	0.56	0.59
12.Take out coins	0.62	0.68	0.80	0.64	0.69
13. Make cell phone call	0.61	0.67	0.80	0.63	0.68
14. Answer a cell phone call	0.81	0.64	0.66	0.59	0.68

9.2.5 Guidance Concerning Steering Performance Statistics

Relative to other statistics in this document, these statistics have seen relatively lower use. For statistics related to steering wheel reversals, additional thought is needed as to what angular change over what time period constitutes a reversal. For steering entropy, the code to calculate entropy needs to be more widely disseminated.

10. LATERAL CONTROL: OPERATIONAL DEFINITIONS OF VEHICLE-BASED MEASUREMENTS

10.1 Lateral Position Measures and Statistics

10.1.1 Lateral Lane Position

Lateral distance, usually measured in feet or meters, from a specified point on the vehicle to a specified part of the lane

NOTE: There are three ways to compute lateral lane position: Option A - with regard to the lane center, Option B - with regard to the middle of the path driven within the lane, and Option C - with regard to the lane edge towards the roadway center. Lateral position can be measured relative to two locations on a vehicle, (1) the lateral midpoint of the front axle and (2) the vehicle center of gravity. The center of gravity is commonly used for driving simulators. The front axle location is commonly used for real vehicles. If a real vehicle has multiple front axles, the most forward axle serves as the reference.

REQUIREMENT: The first instance the term *lateral lane position* is used in a document, the computational method (Option A, B, or C) shall be reported, as well as the reference location on the vehicle (front axle or center for gravity). If option C is used, the relevant lane edge (left or right) shall be reported.

10.1.1.1 Lateral Position Relative to Lane Center (Option A)

Lateral distance, usually measured in feet or meters, from the midpoint of the driven lane to the longitudinal centerline of the vehicle

NOTE 1: Using a right-handed coordinate system, distance to the right of the midpoint is positive and to the left is negative.

NOTE 2: Typically, lane position is determined by means of a camera mounted near the inside rearview mirror and aimed at the forward road scene. The lane markings are identified in the scene, and because their position, the camera location, and the vehicle's exterior dimensions are known, the lane position can be determined. In addition, GPS data may also be used in some situations to determine lane position or to improve the estimate of lateral lane position.

NOTE 3: Depending on the system for determining lane position, sometimes the position reported is what is sensed in the forward scene, which could be the lateral position at some distance in front of the vehicle, not its current position. This difference depends on details of the lateral position algorithm, something specific to each vehicle and simulator.

REQUIREMENT: If lateral position is computed using a position in the forward scene (ahead of the vehicle, not the front axle or cg), that position in the forward scene shall be reported.

10.1.1.2 Lateral Position Relative to Middle of Path Driven (Option B)

Lateral distance, usually measured in inches, feet, centimeters, or meters, from the longitudinal centerline of the subject vehicle to the mean lateral lane position for all vehicles that have traversed this lane (usually in a baseline driving condition)

NOTE: This option is included to handle the curve-cutting problem, i.e. when people drive curves on real roads, they tend to drive closer to the inside (apex) of the curve, especially if the curve radius is small (Figure 29). When the standard deviation of lane position is computed using option A to determine the mean position through the curve, the standard deviation of lane position appears to increase in the curve. In fact, the lane position distribution has shifted.

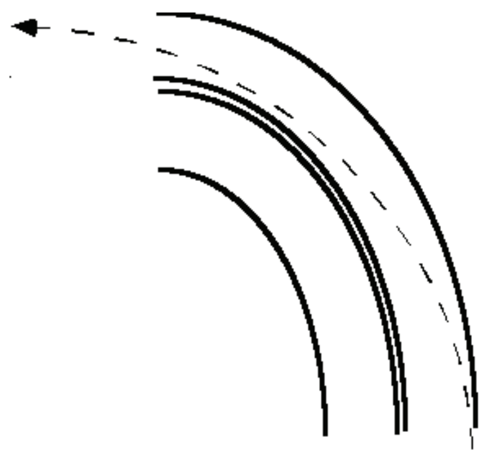


FIGURE 29 – EXAMPLE OF LANE POSITION SHOWING CURVE CUTTING
Source: U.S. Department of Transportation (1997)

10.1.1.3 Lateral Position Relative to Lane Edge (Option C)

Lateral distance, usually measured in inches, feet, centimeters, or meters, from outside edge of the tire to the inside edge of the lane boundary relative to the road centerline (Figure 30).

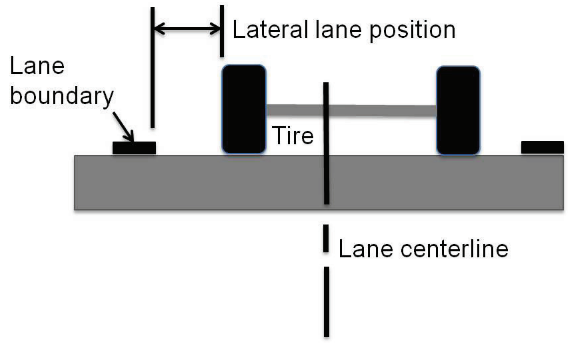


FIGURE 30 – EXAMPLE OF LATERAL POSITION RELATIVE TO LANE EDGE (OPTION C)

NOTE 1: Option C is often used when there is only one lane position camera. This camera is typically mounted either on the driver's door or on the driver-side mirror and is aimed downward.

NOTE 2: The recommended sign convention for lateral distance is consistent with the camera mounting location: positive to the left for left-hand drive; positive to the right for right-hand drive.

NOTE 3: There may be situations where two cameras are used. They are usually attached to the exterior mirrors.

GUIDANCE for Lateral Lane Position: Option A is most commonly used, though when curve cutting occurs the middle of the lane is not where people drive. Further, lane markings in some countries may be viewed by drivers as a "suggestion" and lane maintenance is poor. This argues for using the midpoint of the driven path as the lane reference. Admittedly, determining this mean path is very difficult and is rarely done.

When examining lateral lane position data obtained from a camera system, check the quality of the data. Often, quality is indicated by a confidence measure. Confidence measures, typically ranging from 0 (no confidence) to 1 (complete confidence) indicates the certainty that the lateral position data is correct. How confidence measures are computed is rarely specified. Sometimes, tar strips, rivulets of water, and other objects are misidentified as lane markings. Misidentifications may suggest physically impossible lateral position changes, such as a lane change in 0.5 s.

For most evaluations, option A is recommended, though there may be situations where option B is more appropriate. Option C is generally not recommended because lanes vary slightly in width. Roads paved using concrete forms tend not to vary in width. However, the paint crews do not necessarily align the lane markings with the paved lanes, and the markings are the most visible driving cues. Hence, relying on the distance to one lane edge increases the measurement error.

For some driving simulators, caution is also warranted when reporting lane position. Some simulators generate curves as a series of chords, which to the unsuspecting viewer may appear to be continuous curves (Figure 31). In those cases, the lateral lane position is the distance from the centerline of the chord, not the curve. To provide a number example, consider a 200 m (650 ft) radius curve, a typical curve in the DriveSafety simulator. Further, suppose that curve was approximated by 20 chords, then the angle of each chord would differ from the previous one by 4.5 degrees (90/20), so at the midpoint of each curve, the chord distance and curve radius would differ by 0.15 m, a considerable amount considering that the standard deviation of lane position is on the order of 0.2 m.

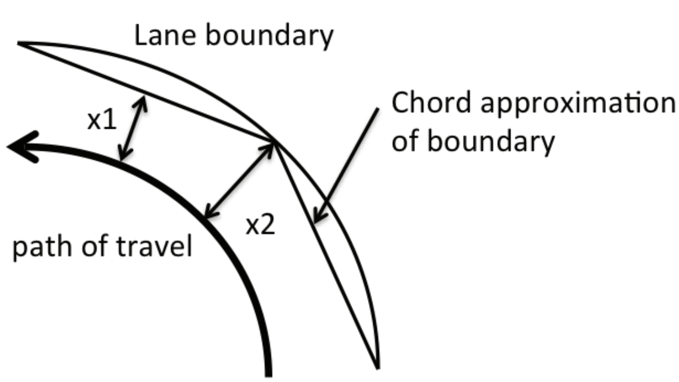


FIGURE 31 -- CHORD LANE BOUNDARY PROBLEM

Some simulators get around this problem is by drawing the lane boundary for all road segments as a cubic spline, which makes the curved sections much smoother. Cubic splines, which by definition have terms with exponents of three, are fit piecewise to the data. In some instances, such as Figure 32, the approximation is indistinguishable from the original data.

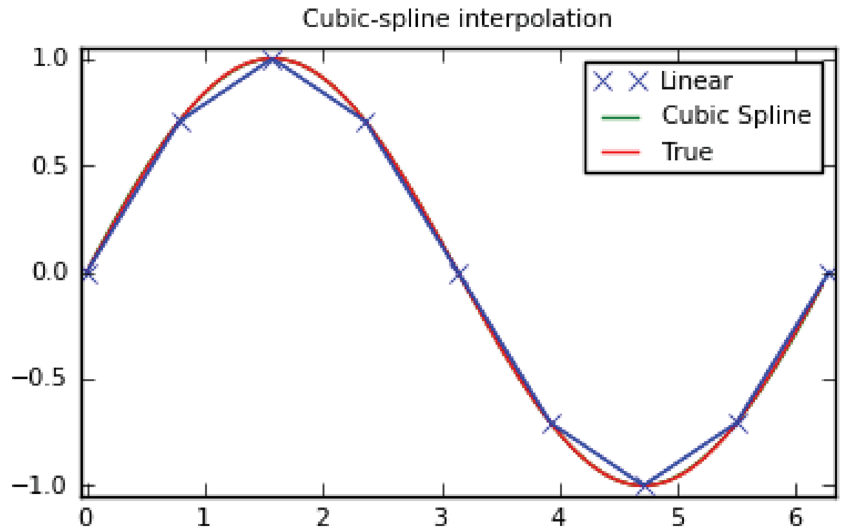


FIGURE 32 --- SPLINE APPROXIMATION OF A CURVE
Source: http://docs.scipy.org/doc/scipy-0.8.x/reference/_images/interpolate-2_00_00.png

For sample lateral position data, see Ostlund, Peters, Thorslund, Engstrom, Markkla, Keinath, Horst, Juch, Mattes, and Foehl, 2005), p 119.

REQUIREMENT: For driving simulator studies, experimenters shall report how lateral position was determined on curves, and if the computation was chord-based, report the error of the computation.

NOTE: The National Advanced Driving Simulator provides output measures for both splined and nonsplined lane boundaries (Schwarz, 2012, personal communication).

10.1.2 Mean Lateral Lane Position

Mean value, usually measured in inches, feet, centimeters, or meters, of lateral lane position of all vehicles at a given location, or across a roadway segment in the lane of travel, determined by adding up the lateral position data points (one per traverse) and dividing by the number of data points.

NOTE: Depending upon the situation, the mean could be computed for a single subject across a roadway segment, multiple subjects at a single point on the path, or multiple subjects across a roadway segment. The context will make it apparent which is being computed.

REQUIREMENT: If the term *lateral lane position* is not defined in a document before the first instance the term *mean lateral position* is used, the method used to calculate lane position (option A, B, or C) shall be reported.

GUIDANCE for Lateral Lane Position: For a plot of the distribution of lateral lane positions for light vehicles, see Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler (2011), p. 50. The mean lateral position varies with the time of day and vehicle speed, with the mean offset being about 5 cm to the left in daylight and 12 cm at night (Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler, 2011). See also Sayer, Cullinane, Zylstra, Green, and Devonshire (2003) for summaries of several studies.

10.1.3 Standard Deviation Of Lane Position (SDLP)

dispersion of the lateral lane position, usually measured in inches, feet, centimeters, or meters, computed using either of the following equations.

$$\text{SDLP} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \overline{x})^2} \quad \text{or} \quad \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2}$$

where:

x_i = i-th value of lane position

$\overline{x}$ = mean lane position of the sample

N = number of data points in the sample

NOTE 1: In most situations, N is sufficiently large so that the difference between the two equations is insignificant.

NOTE 2: In a manner similar to Mean Lateral Position, the standard deviation could be computed for a single subject across a roadway segment, multiple subjects at a single point on the path, or multiple subjects across a roadway segment. The context will make it apparent which is being computed.

NOTE 3: SDLP is the most commonly reported lateral lane position statistic.

REQUIREMENT: The first instance that *standard deviation of lane position* is used in a document, the method to calculate the standard deviation shall be reported.

GUIDANCE for Standard Deviation of Lane Position: The unbiased estimator (dividing by 1/(N-1)) is recommended.

Kircher, Uddman, and Sandin (2002) report 0.2 m as being a typical value for SDLP for an alert driver. In a driving simulator study of a rural road reported by Mullen, Bedard, Riendeau, and Rosenthal (2010), the SDLP was 0.38 m for a control condition, and 0.30 m when a lane-departure-warning system was provided. Green, Cullinane, Zylstra, and Smith (2004) summarized data from about 10 studies concerning driving performance measures and statistics. They found SDLP is typically between 0.2 and 0.3 m for normal driving, depending upon the driver age, the road type, and the speed driven. Equations for these relationships were given.

Figure 33 shows the distribution of lateral lane positions (lane offset) for all drivers in the IVBSS project (Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blanespoor, and Winkler, 2011). See also Mas, Merienne, and Kemeny (2011) for a description of line integral of the lateral position, an alternative statistic.

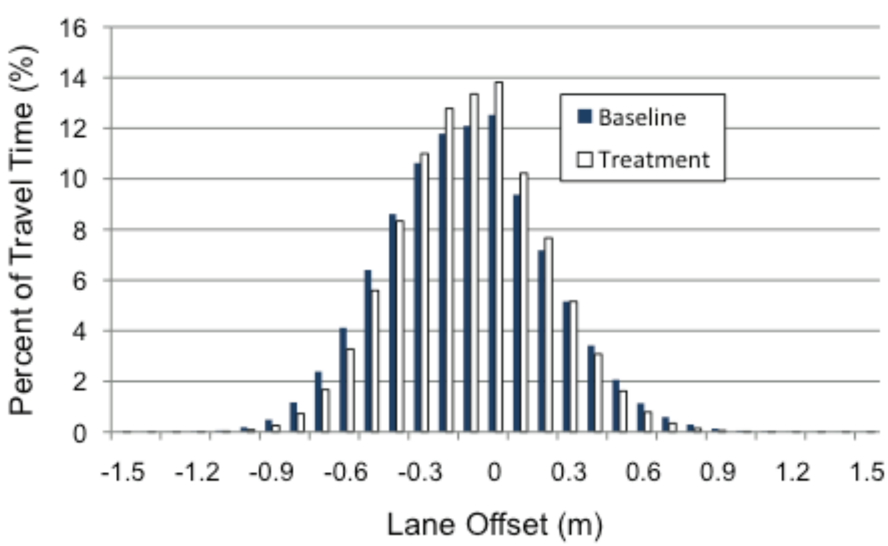


FIGURE 33 -- DISTRIBUTION OF LATERAL POSITIONS FROM THE IVBSS PROJECT

(Treatment refers to the IVBSS warning suite being on)
Source: Sayer, Bogard, Buroarosa, LeBlanc, Funkhouser, Bao, Blanespoor, and Winkler (2011), p. 50

Tarko (2012) reports that the distribution of lateral positions close to a departure (near departure) is fitted by a Pareto distribution, with the parameters depending on how a near-departure is defined (lateral distance, constant speed on straight path, constant lateral speed).

10.2 Roadway Departure Measures and Statistics

These terms are readily confused in the literature and, depending on how they are defined, could in some cases be identical.

10.2.1 Roadway Departure

Period when any part of one or more tire contact patches are no longer on the roadway until all tire contact patches are on the roadway or the vehicle has stopped without returning to the roadway.

NOTE 1: A roadway departure cannot begin in an intersection.

NOTE 2: A vehicle may come to a stop because it collides with another vehicle or a roadside object.

NOTE 3: This term is not to be confused with a lane departure. By definition, for every roadway departure there is a lane departure, but not vice versa.

NOTE 4: For information on the relationship between road geometric characteristics and crash frequency, see Hallmark, Veneziano, MacDonald, Graham, Bauer, Patel, and Council (2006); Gross, Jovanis, Eccles, and Chen (2009); and Lord, Brewer, Fitzpatrick, Geedipally, and Peng (2011).

10.2.2. Number of Roadway Departures

Count of the number of roadway departures per unit distance, often per 100,000 mi or 100,000 km.

NOTE 1: Lane changes and turning maneuvers are not road departures because they are intentional.

NOTE 2: A roadway departure ends when all vehicle tires are on the roadway, not when the vehicle is in the original or a new lane of travel. A vehicle may never get stably into a lane of travel before again departing the roadway, in which case a second roadway departure is recorded.

10.2.3 Roadway Departure Duration

Time interval of a roadway departure, usually measured in seconds.

NOTE: This measurement is much more likely to be collected in a driving simulator than in field studies.

10.2.4 Magnitude of Roadway Departure

Maximum lateral distance, usually measured in centimeters, meters, inches, or feet, from the center of the vehicle front axle to the center of the lane edge line during a roadway departure.

NOTE: This measurement is much more likely to be collected in a driving simulator than in field studies.

GUIDANCE for Number, Duration, and Magnitude of Roadway Departures: Separate analyses and reporting should be done for roadway departures from the left or right roadway edges. In addition, for the FHWA definition, separate reports shall be made for departures across a centerline or median into an opposing lane of traffic. Although there is considerable data on roadway departure crashes, the authors have not been able to find data on any of these measures of roadway departures.

10.2.5 Roadway Pavement Departure

Period when one or more tire contact patches are no longer on the paved roadway until the all tire contact patches are in the lane of travel or the vehicle has stopped or crashed without returning to the original travel lane

NOTE 1: The measures given in 10.2.1.1.1 – 10.2.1.1.3 also apply for roadway pavement departures.

NOTE 2: The start and end of a roadway pavement departure are easier to detect in the field because the pavement edge is readily identifiable, whereas the transition between traveled way and shoulder, or between the shoulder and the roadside, is not always readily identifiable. Police and other accident investigators often use pavement edges in making their determination of a roadway departure.

10.3 Lane Departure Measures and Statistics

10.3.1 Lane Departure

Period when some part of the vehicle is no longer in the travel lane until all tire contact patches are back inside the lane of travel or the vehicle comes to a stop before returning to the lane, excluding lane changes and turning maneuvers.

NOTE 1: The back part of the vehicle could be the rear half of a towed trailer.

NOTE 2: When a lane departure occurs, a vehicle could strike another vehicle or pedestrian in an adjacent lane or a roadside appurtenance such as a sign, light post, mailbox, lane barrier, curb, or retaining wall.

NOTE 3: There are three parts of a vehicle commonly used to determine a lane departure: front tire contact patch, widest part of vehicle, and any tire contract patch. They are used in combination with the inside edge, middle, or outer edge of a lane boundary marking.

NOTE 4: Where the position of the vehicle's tires are used to determine if a lane departure has occurred, and there are multiple tires on each end of the axle (for example for a dual-tire pickup truck or dual tires for the trailer of a tractor trailer), the reference tire is the outermost tire.

NOTE 5: Ideally, one would like to separate intentional departures, such as giving additional space to a nearby vehicle, from unintentional departures. However, short of asking the driver, which is often not possible to do, distinguishing intentional and unintentional departures is difficult. Should intentional and unintentional departures be identified, the criteria for the distinction shall be reported. (For example, a lateral motion of size x in response to a vehicle of size y at gap z.)

NOTE 6: When there are multiple lanes of travel in the same direction, a lane departure that ends with the vehicle traveling in a lane other than the original lane is considered a lane change and not a lane departure.

NOTE 7: Every roadway departure includes a lane departure, but not vice versa.

Guidance for Lane Departure: The preferred option for lane departure will depend upon the intended use of the data, the requirements of other standards, and other reasons, all of which can vary from instance to instance. The data may be used to determine if (1) a departure will occur soon, (2) the vehicle is departing now, or (3) a departure has occurred. Furthermore, other standards, such as NCAP Forward Crash and Lane Departure Warning System 2010 Test Procedures (U.S. Department of Transportation, 2010a, b and AAM Driver Focus Guidelines (Alliance of Automobile Manufacturers, 2006) may require the use of particular definitions.

REQUIREMENT: The first instance the term *lane departure* is used in a document, the start and end options shall be reported.

10.3.1.1 Lane Departure Start Options

10.3.1.1.1 Widest Part of Vehicle (Option A)

A departure begins when the most outward portion of a vehicle, usually the outer edge of an exterior mirror, but sometimes the body of the vehicle, cargo (e.g., a ladder) or a trailer passes over the centerline of a lane boundary. See Figure 34.

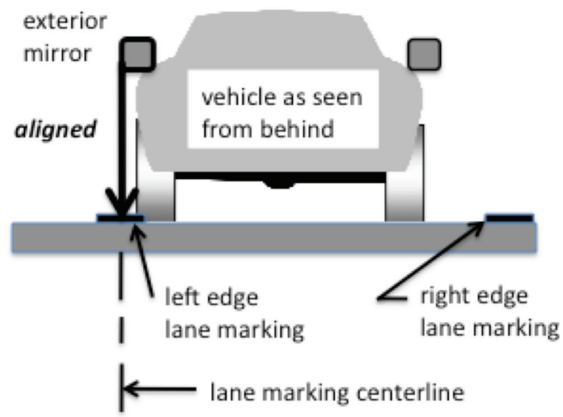


FIGURE 34 -- LANE DEPARTURE, OPTION A: WIDEST PART OF VEHICLE ABOVE LANE MARKING CENTERLINE

NOTE 1: This is the most safety-/crash-relevant departure point for a departure into an adjacent lane of travel. Two identical vehicles passing in either the same or opposite directions (depending on the vehicle configuration) could theoretically come in contact with each other.

NOTE 2: If the widest vehicle part is itself an adjustable component (for example extendable or foldable side mirrors), the widest part is determined by the outermost setting most typically used for driving. (For normal driving, the mirrors would not be folded; if the mirrors are moveable and a wide trailer is towed, they would be deployed to the outermost setting.)

NOTE 3: For sports cars the widest point is often the vehicle body, not outer edge of the exterior mirror.

NOTE 4: If no lane marking is present, then the traveled way edge, barriers, curb, or other structures serve as the lane boundary.

10.3.1.1.2 Inside Edge of Lane Marking, Front Tire (Option B)

A departure begins when any part of the tire contact patch of either front tire touches the inside edge of the closest lane marking. See Figure 35.

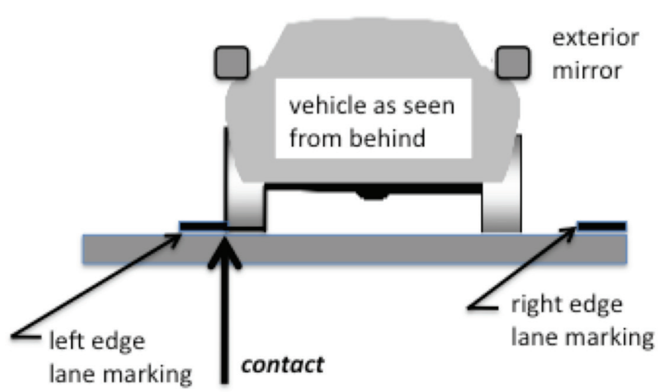


FIGURE 35 -- LANE DEPARTURE, OPTION B: FRONT TIRE TOUCHES INSIDE OF LANE MARKING

NOTE 1: This is the easiest lane departure point to measure.

NOTE 2: The difference between Options B and C is a few inches or centimeters, with the difference being larger for heavy trucks.

GUIDANCE for Option B: Lane departure can be readily determined by mounting a camera low on the front door, on the fender, or under an exterior side mirror, and aiming it at the front tire. It requires one camera per side. Contact of the tire track and lane marking is somewhat easier to see when the pavement is wet than when the pavement is dry. This version of lane departure is most consistent with the use of time-to-line crossing, which generally refers to tire contact patch.

10.3.1.1.3 Outside Edge of Lane Marking, Front Tire (Option C)

A departure begins when outer part of the tire contact patch of either front tire touches the outside edge of the lane marking. (Figure 36)

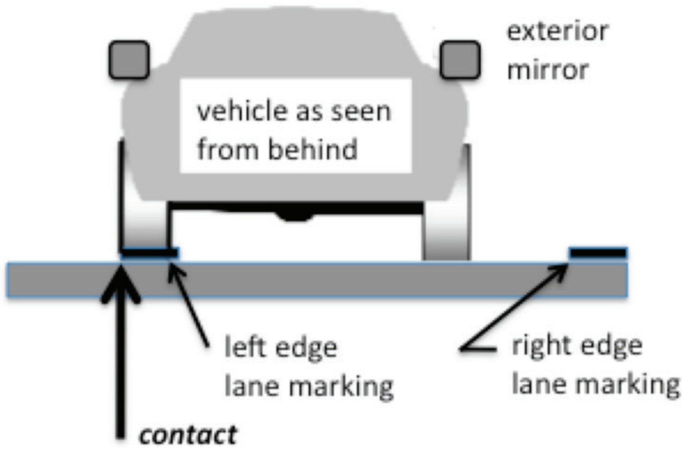


FIGURE 36 -- LANE DEPARTURE, OPTION C: FRONT TIRE TOUCHES OUTSIDE OF LANE MARKING

NOTE: The difference between Options B and C is the width of a lane marking, commonly 4 in (10 cm), but sometimes 6 in (15 cm).

10.3.1.1.4 Beyond Outside of Lane Marking, Front Tire (Option D)

A departure begins when the front tire contact patch is completely beyond the outside edge of the closest lane marking. (Figure 37)

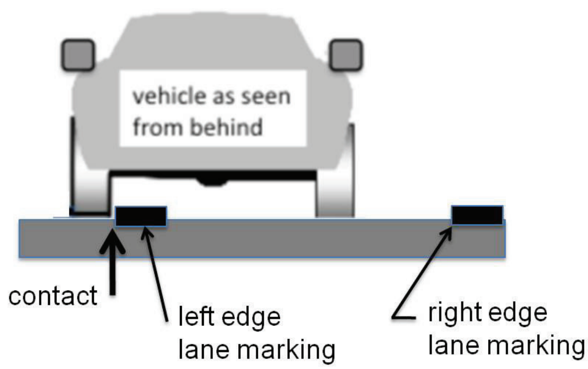


FIGURE 37 -- LANE DEPARTURE, OPTION D: FRONT TIRE OUTSIDE OF LANE MARKING

NOTE: The difference between options C and D is the width of a tire. For example, tire width for a 2012 Fiat 500 is 185 mm whereas tire width for a 2012 Cadillac Escalade EXT is 285 mm.

GUIDANCE for Option D: This option is often used by the police as it leaves little doubt the vehicle has departed the lane.

10.3.1.1.5 Inside Edge of Lane Marking, Any Tire (Option E)

A departure begins when any part of the contact patch of any tire touches the inside edge of the closest lane marking or other. See Figure 38.

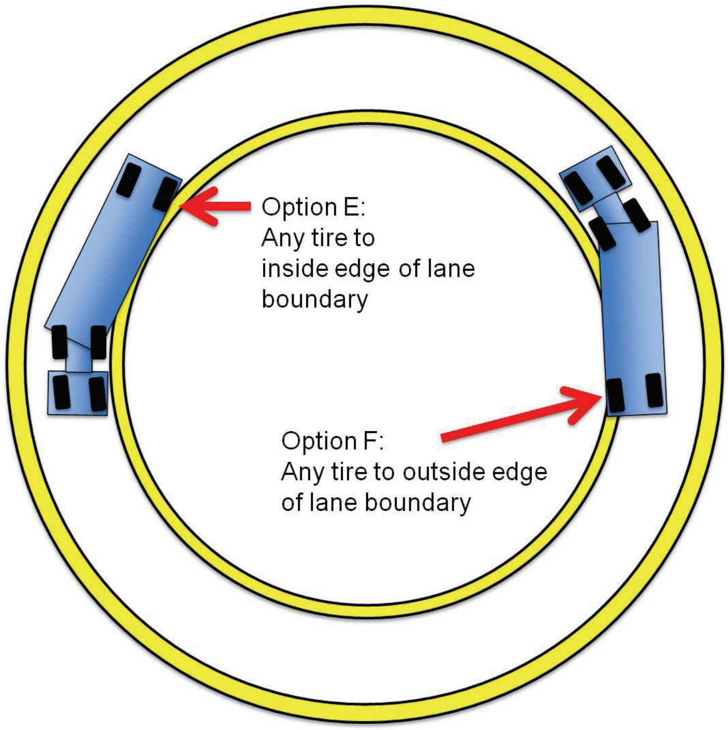


FIGURE 38 -- LANE DEPARTURE, OPTIONS E AND F:
ANY TIRE TOUCHES INSIDE/OUTSIDE OF LANE MARKING

NOTE 1: This definition is identical to option B except that it refers to any tire.

NOTE 2: There may be situations, such as when tractor-trailer drives through curves, where the cab will be in the lane but part of the trailer may have departed the lane. There may also be situations when driving curves that the driver will intentionally drive outside of the curve so the trailer does not track too far over the inside boundary, or does not go over the boundary at all.

NOTE 3: When considering when a lane departure ended, keep in mind that for a tractor-trailer, even though the cab may return to the lane before the trailer, all tire contact patches have to be inside the original lane of travel.

10.3.1.1.6 Outside Edge of Lane Marking, Any Tire (Option F)

A departure begins when the outer part of any tire's contact patch touches the outside edge of the closest lane marking. See Figures 36 and 38.

NOTE: This definition is identical to option C except that it refers to any tire.

10.3.1.1.7 Tire Fully Outside of Lane Marking, Any Tire (Option G)

A departure begins when any tire contact patch is fully the outside edge of the closest lane marking.

NOTE: This definition is identical to option D except that it refers to any tire.

10.3.1.1.8 Summary of Options

The seven start options (A-G) form a reasonably complete set of possibilities, with A referring to the lane centerline and the widest part of the vehicle, B, C, and D referring to the front tire, and E, F and G referring to all tires (and being analogous to B, C, and D (Table 2). An option analogous to A for all tires was not included because that option would not be used. Options E, F, and G are particularly important when a tractor-trailer is the subject vehicle.

TABLE 2 -- LANE DEPARTURE START OPTIONS

Start Options	End
A – Widest Part of Vehicle, Middle of Lane Boundary	All tires are inside the lane boundary, or the vehicle comes to a stop before returning to the lane of travel
B – Front Tire, Inside of Lane Boundary	
C – Front Tire, Outside Edge of Lane Boundary	
D – Front Tire, Tire Beyond Outside Edge of Lane Boundary	
E – Any Tire, Inside of Lane Boundary	
F – Any Tire, Outside Edge of Lane Boundary	
G – Any Tire, Tire Beyond Outside Edge of Lane Boundary	

10.3.2 Number of Lane Departures

Count of the number of times when some part of the vehicle is no longer in the travel lane.

NOTE 1: There may be times when a vehicle departs a lane but does not re-enter, such as in a crash.

NOTE 2: There are seven options for the start of this measure consistent with the definition of a lane departure.

NOTE 3: The number of lane departures is usually specified per unit distance, often per 100 mi or 100 km.

NOTE 4: Lane changes and turning maneuvers are not lane departures because they are intentional.

NOTE 5: A lane departure ends when all vehicle tires are back in the lane of travel. A vehicle may never get stably into a lane of travel before again departing the lane, in which case a second lane departure is recorded.

REQUIREMENT: The first instance the term *number of lane departures* is used in a document, the start option (A-G) shall be reported, if not done previously. Separate records should be kept and reported for lane departures that do not return to the lane of travel.

GUIDANCE for Number of Lane Departures: In the Road Departure Curve Warning (RDCW) project, the alert rates for light vehicle lane departures were about 12 alerts per 100 miles (LeBlanc, Sayer, Winkler, Ervin, Bogard, Devonshire, Mefford, Hagan, Bareket, Goodsell, and Gordon, 2006), with the rate depending upon the sensitivity setting. That report also provides alert rates by road type and numerous other factors. An alert does not necessarily mean a departure occurred, only that the vehicle got near enough to a lane boundary to trigger an alert.

More recently, Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler (2011) reported that the number of lane departures (option undefined) per 100 miles in the IVBSS field test for light vehicles was 7.1 for expressways, 8.4 for surface roads, 9.2 for expressway ramps, and 5.9 for unknown road types in the baseline (no warning system) condition. When a warning system was provided, the number of warnings was 15.9, 13.7, 16.4 and 11, respectively. Between 61 - 69 % of the warnings were for departures on the left side of the lane.

For heavy trucks without lane departure warning systems, the rates are about 20 departures/100 miles for limited access and surface roads for pickup and delivery routes and 16-21 departures/100 miles for line haul routes. Installing lane departure warning systems reduced those rates slightly (Sayer, Bogard, Funkhouser, LeBlanc, Bao, Blankespoor, Buonarosa, and Winkler, 2010).

10.3.3 Lane Departure Duration

Time interval, usually measured in seconds, from start to end of the lane departure.

NOTE 1: The options (A-G) are the same as that used for a lane departure. The relevant portions of the boundary are the inside edge, the centerline, and the outside edge of the lane marking.

NOTE 2: The start and end points for duration are the same as those in the lane departure definition (Table 2).

REQUIREMENT: The first instance the term *lane departure duration* is used in a document, the start option (A-G) shall be reported, if not done previously. Separate records should be kept and reported for lane departures that do not return to the lane of travel.

GUIDANCE for Lane Departure Duration: As shown in Figure 39, lane-departure durations are exponentially distributed and commonly less than 2 s (Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler, 2011).

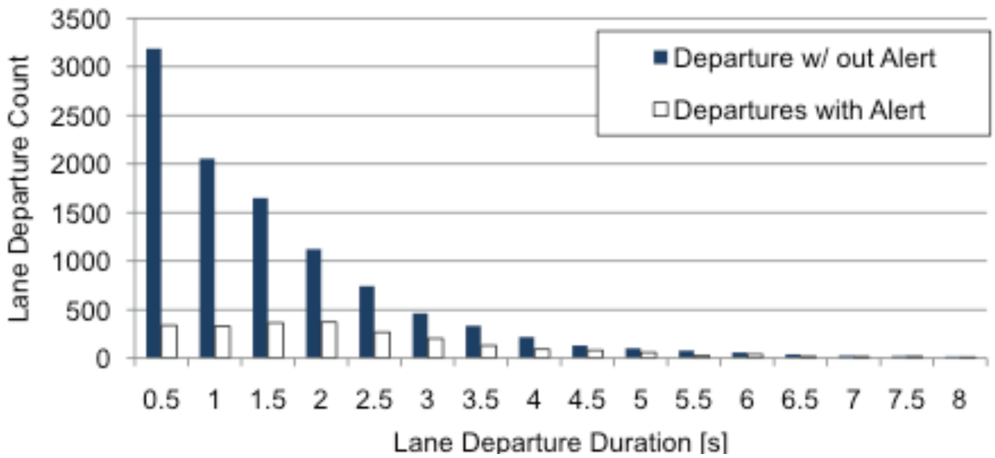


FIGURE 39 -- DISTRIBUTION OF LANE DEPARTURE DURATIONS
Source: Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler (2011), p. 56

10.3.4 Magnitude of Lane Departures

Maximum distance perpendicular to the lane boundary, usually measured in inches or centimeters, from the start to the end of the lane departure.

NOTE: The start options (A-G) are the same as that used for a lane departure. The relevant portions of the boundary are the inside edge, the centerline, and the outside edge.

REQUIREMENT: The first instance the term *magnitude of lane departures* is used in a document, the start option (A-G) shall be reported, if not done previously. Separate records should be kept and reported for lane departures that do not return to the lane of travel.

GUIDANCE for Magnitude of Lane Departures: Figure 40 shows a distribution of lane-departure magnitudes from the IVBSS report. A value of 6 cm was most common; much larger magnitudes were also found, though departures larger than 18 cm were quite rare.

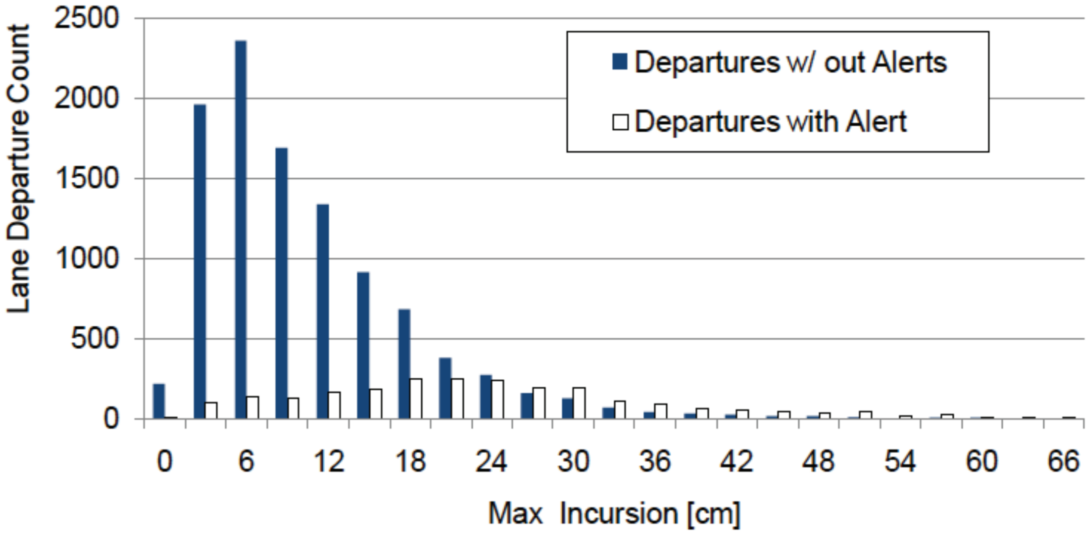


FIGURE 40 -- MAXIMUM LANE DEPARTURE MAGNITUDE (INCURSION)
Source: Sayer, Buonarosa, Bao, Bogard, LeBlanc, Blankespoor, Funkhouser, and Winkler, p. 78

10.4 Lateral Position Exposure Statistics

10.4.1 Time to Line Crossing (TLC)

Time, usually in seconds, taken for a vehicle to reach a vehicle lane boundary.

10.4.1.1 Boundary options

10.4.1.1.1 Time to Line Crossing – Inside Edge of Lane Marking (Option A)

See section 10.2.1.1.1.

10.4.1.1.2 Time to Line Crossing – Centerline of Lane Marking (Option B)

See section 10.2.1.1.2.

10.4.1.1.3 Time to Line Crossing – Outside Edge of Lane Marking (Option C)

See section 10.2.1.1.3 and Appendix H.

NOTE 1: TLC was first described by Godthelp (1984), Godthelp, Milgram, and Blaauw (1984) and Godthelp (1988). Alternative calculation methods first reported in Van Winsum, Brookhuis, and deWaard, 2000 are repeated in Appendix A. See also Mammar, Glaser, and Netto (2006) for computational details, Glaser, Mammar, Neto, and Lusetti (2005) for experimental issues, and Gordon, Kostyniuk, Green, Barnes, Blower, Bogard, Blankespoor, Leblanc, Cannon, and McLaughlin (2010) or Gordon, Kostyniuk, Green, Barnes, Blower, Blankespoor, and Bogard (2011) for its application. For information on real-time signal filtering, see Cario, Casavola, Franze, Lupia, and Brasilli (2009).

NOTE 2: TLC measures are most commonly reported for driving simulator studies, for which the center of each edge marking and mirror-to-mirror vehicle width are readily available. Exactly how various simulators compute TLC is usually not reported.

NOTE 3: A complete description of all computational methods for TLC appears in Appendix H.

REQUIREMENT: The first instance the term *time to line crossing* is used in a document, the boundary definition and computation option shall be reported.

GUIDANCE for Time to Line Crossing: Boer and Ward (2003) argue for looking at the inverse of TLC, in particular the 75th percentile. The median value for that is about 0.09 s^{-1}. For data on TLC vs. speed, see van der Horst (2004).

10.4.1.2 TLC Computational Methods

All of the following computations for time to line crossing, which have been accepted practice for years, consider when the front tire touches the edge line, which is consistent with lane departure definition B.

10.4.1.2.1 TLC Trigonometric Computation, TCL_tri (Option A)

Time, usually measured in seconds, taken for some part of the tire to contact the lane boundary, based on a theoretically-derived trigonometric calculation.

NOTE: In computing this time, road curvature, curvature in the path of the vehicle, vehicle distance to the lane edge, vehicle speed and acceleration vectors, and locations of the center of road and vehicle path are all considered, as described by Winsum, Brookhiuis, and de Waard (2000).

10.4.1.2.2 TLC First Derivative Method (Option B)

Time taken for a front tire to touch the lane boundary, estimated by using the instantaneous lateral distance and velocity.

$$TLC = y/y'$$

where y = lateral distance between the front wheel and the lane boundary
y' = lateral velocity

GUIDANCE for TLC Option B: This computation may be easier to do in a simulator than on the road or on a test track, as all of the data needed (in particular data on the curve center) are more likely to be available in a simulator. With sophisticated image processing, speed sensors, and yaw sensors, this version of TLC can be estimated using on-board information only, though it is easier if a navigation database and GPS coordinates are available.

10.6.1.2.3 Acceleration Method (Option C)

Time taken for a front tire to touch the lane boundary, estimated using the lateral distance, velocity, and acceleration.

$$TLC = y / (y' + y'')$$

where y'' is the projected lateral velocity after 1 s.

10.4.1.2.4 Guidance Concerning TLC Computation Methods

When should each of the versions of TLC be used? The first step is to determine what data are available. Option A, the most accurate, requires a great deal of data, including the exact location of the vehicle relative to the road, the radius of a curve being driven, the yaw angle relative to the road, and the difference in location between the center of the curve radius and the center of the vehicle's turning radius. For driving real roads, obtaining GPS data is now quite common, so a vehicle's location relative to the road geometric elements can be determined. Further, for real roads, curve radii are shown on as-built plans, which can be obtained, albeit with some effort. Furthermore, the calculations assume that real roads consist of only straight sections (tangents) and fixed radius curves. In fact, there are transitions between straight sections and curves (blended sections), and their presence complicates the calculations.

In driving simulators, all of the desired data can usually be obtained readily, and some simulators have built in functions for TLC, though the calculation method may not be identified.

Do the differences matter? Van Winsum, Brookhuis, and deWaard (2000) examined the accuracy of two approximations of TLC: (1) lateral distance divided by lateral velocity (option B) and (2) adding a correction for lateral acceleration (option C) in predicting the trigonometric solution (option A). They conducted several driving-simulator experiments involving normal lane keeping when driving a road with curves, performing normal lane changes, and drowsiness-induced lane departures. For normal lane keeping, they report that the TLC approximation that includes acceleration (option C) resulted in a good approximation of the trigonometrically computed value. The estimate that included only lateral distance and velocity (option B) led to poor estimates of the trigonometrically computed value.

For normal lane changes, a second experiment, the version with acceleration (option C) gave better estimates when the vehicle was 0.6 s from the lane boundary or less. However, when the vehicle was 0.8 to 1.0 s from the boundary, option B predictions more closely approximated the actual value of TLC.

In a third experiment concerning drowsiness, estimated lane departures were examined. The findings were similar to those of the prior experiment. For true TLC value less than 0.5 s, option B gave better approximations. For TLC values larger than 0.5 s, the accuracy of the two estimates was equivalent.

Thus, the TLC approximation that best estimates the true TLC value depends on the maneuver and time range of interest.

In summarizing their research, van Winsum, Brookhuis, and de Waard (2000), page 55 state the following:

"The accuracy of approximations of TLC depends on both the specific maneuver performed by the driver and the purpose for which TLC is used. In studies of driver behavior minima of TLC are sometimes computed as indices of driver performance. For the purpose of measuring TLC minima to study how the driver's steering actions are related to perceived safety margins, or for examining TLC minima as indices of lateral control performance a simple approximation does not give results of sufficient accuracy. This simple approximation of TLC, i.e. lateral distance divided by lateral speed, is probably the most frequently used method of computation in studies of driver behavior. Its drawback is that it falsely assumes a constant lateral velocity. This results in overestimation of TLC minima and a shift in the phase of the signal. Thus, the minimum that is found by the simple approximation occurs later in time than the actual TLC minimum and usually is substantially larger. A more complex approximation that applies the second derivative of lateral distance together with the first derivative resulted in a more accurate TLC approximation.

For studies of driver behavior it is then recommended to use the trigonometrically computed TLC or the second approximation as a good alternative. For predicting actual lane boundary exceedence, for example in lane keeping support systems or in systems that detect driving off-the-road as a result of drowsiness or falling asleep, the first and simple approximation gave better results than the second, more complex, approximation. However, also in this case, this simple method tends to result in an overestimation of available time for pre-incident periods larger than 0.5 s."

10.4.2 Minimum Time-to-Line Crossing (TLC_{min})

Minimum time, usually in seconds, needed for some part of a vehicle usually a front tire, to reach a lane boundary.

NOTE: Definitions of lane departure or TLC in the literature do not provide the same level of detail as this document (10.2.1) in specifying what is meant by "reaching the lane boundary".

As show in Figure 41, plots of TLC reveal a series of epochs, typically between 1 and 30 s, in which the driver is approaching either the left or right lane marking, often in a alternating pattern. So key details can be readily observed, large values of TLC (here more than plus or minus 27 s) are not shown. The minimum is typically the local TLC minimum within each epoch, which sometimes is for the left lane marking and sometimes for the right. (See Appendix H.)

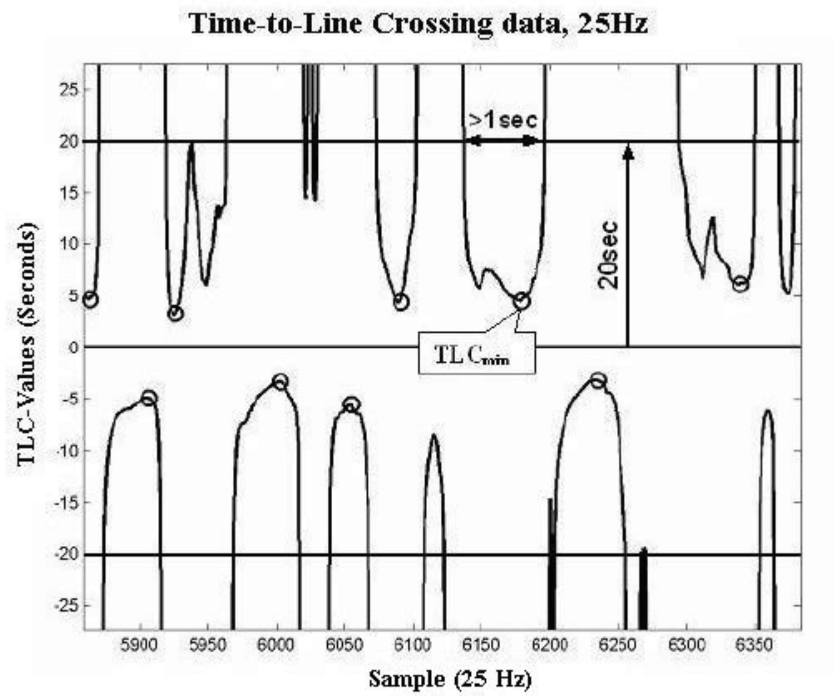


FIGURE 41 -- TLC VERSUS TIME FOR TWO LANE BOUNDARIES
Source: Östlund, et. al., (2004), page 279

NOTE 1: Negative values in Figure 34 do not indicate TLC was actually negative but rather serve to differentiate between vehicles approaching the left (positive) and right (negative) lane boundaries.

NOTE 2: Readers interested in the calculation of TLC minima should also see van Winsum, Godthelp (1996), Kircher, Uddman, and Sandin (2002), or Appendix 2 of the AIDE Methods and Metrics report (Östlund, Peters, Thorslund, Engstrom, Markkla, Keinath, Horst, Juch, Mattes, and Foehl, 2005).

NOTE 3: Additional details on TLC calculations appear in Appendix I.

REQUIREMENTS: The first instance the term *minimum time to line crossing* is used in a document, the boundary definition and computation option shall be reported. Authors shall report: (1) the maximum value of TLC in excess of which values are ignored, (2) the minimum and maximum sample durations for TLC waveforms, (3) any filtering to remove spurious signals, and (4) what constitutes reaching the lane boundary.

GUIDANCE for Minimum Time-to-Line Crossing: Shorter TLC values represent poorer lateral control. In a manner analogous to TTC, there is some point at which larger TLC values do not result in a substantial increase in driving safety. Furthermore, including them in the calculation of a mean TLC can lead to a misleading impression of driving safety. For mean TLC values, Ostlund, Nilsson, Tornros, and Forsman (2006) showed that TLC values higher than 20 s should also be ignored because they are irrelevant from a safety point of view. (See also van Winsum, Brookhuis, and de Waard, 2000).

In addition to filtering out large values, durations over which TLC is sampled shall be long enough to avoid statistical artifacts. Sometimes TLC waveforms can results in brief peaks, so Ostlund, Nilsson, Tornros, and Forsman (2006) state that TLC waveforms of duration less than 1 s should be ignored. As was noted in an AIDE project (Ostlund, Peters, Thorslund, Engstrom, Markkla, Keinath, Horst, Juch, Mattes, and Foehl, 2005), performance consequences of tasks less than 10 s long may not be reflected in the TLC data because there are too few TLC minima. Statistics such as 15th% percentile of the TLC distribution are infeasible for data less than several minutes long.

Finally, some filtering and data quality should be considered when TLC is used in field experiments to avoid amplifying noise. A low-pass filter with cut-off frequency no less than 3 Hz is regarded as a good starting point for lateral lane position, velocity, and acceleration of the vehicle (van Winsum, Brookhuis, and de Waard, 2000).

Wiethoff (2003) based on the data of Godthelp (1988) (and Brookhuis, De Waard, and Fairclough, 2003) report the TLC values shown in Table 3 as being representative of impaired driving due to inattention, fatigue, alcohol, or for other reasons.

TABLE 3 -- TLC IMPAIRED VALUES

Statistic	Speed (km/hr)	Absolute Criteria (s)
Median TLC	60	6.0
	80	5.7
	100	5.0
	120	4.2
15% TLC	60	3.8
	80	3.5
	100	3.1
	120	2.9

Ostlund Nilsson, Tomros, and Forsman (2006) report mean TLC values of 5.6 to 6.9 s for a simulated rural road, 7.2 to 8.1 for a simulated motorway, 4.9 to 5.6 for a second motorway. For additional information on TLC values and their distribution, see Lin and Ulsoy (1995).

10.4.3 Guidance Concerning Lateral Exposure Measures

Lateral exposure measures are relatively new to research, so the number of studies examining them is limited. To advance science and engineering practice, researchers are therefore encouraged to collect and report such measures.

10.5 Lane Change Measures and Statistics

10.5.1 Lane Change

Movement of a vehicle from one vehicle lane to another vehicle lane with continuing travel in the same direction in the new lane.

NOTE 1: A lane change involves a merge maneuver into another lane of travel in the same direction.

NOTE 2: Lane changes are either discretionary or mandatory (non-discretionary). A mandatory lane change occurs when a driver must leave a lane, such as when the lane in which they are driving ends (due to a lane drop or when merging from an on-ramp), to bypass a blockage downstream, or avoid entering and using a restricted lane (Yang, 1997). Mandatory lane changes can also occur at the juncture of two or more traveled ways blending together in the same direction. A discretionary lane change occurs when the driver decides another lane is preferred to the lane in which they are driving for other than mandatory reasons. See Gipps (1986) and Ahmed (1999).

NOTE 3: Lane changes are (1) most commonly made to an adjacent lane, but (2) could be to a lane two or more lanes away (which sometimes occur when drivers quickly need to exit an expressway), or (3) could be part of either a passing or an avoidance maneuver involving an adjacent lane change and then an immediate lane change returning to the original lane (Figure 19). This third option is often used in vehicle handling evaluations (ISO 3888-1:1999, ISO 3888-2:2011) where it is called a “double lane change”. In (2), a lane change two or three lanes away from the original vehicle lane is called a two-lane change or a three-lane change.

NOTE 4: Passing maneuvers where the passing lane contains opposing traffic are not analyzed with the other lane change data. They are analyzed separately.

NOTE 5: Lane changes can be intended (sometime signaled) or unintended (windblown or otherwise due to loss of control such as when skidding). Unintended lane changes are considered as a lane departure. Intentional lane changes that are aborted before completion are also considered to be a lane departure.

REQUIREMENT: The first instance the term *lane change* is used in a document, the method used to determine the start (Option A or B)`and end (Option 1 or 2) of the lane change shall be reported.

10.5.1.1 Lane Change Start – Front Tire on Inside Edge of Lane Marking (Option A)

A lane change begins when any part of the tire contact patch of a front tire touches the inside edge of the lane marking to either side of vehicle.

10.5.1.2 Lane Change Start -- Widest Part of Vehicle on Lane Centerline (Option B)

A lane change begins when the most outward portion of a vehicle, usually the outer edge of an exterior mirror, but sometimes the body of the vehicle, cargo (e.g., a ladder) or a trailer passes over the centerline of a lane marking

10.5.1.3 Lane Change End – All Tires in New Lane (Option 1)

A lane change ends when the vehicle has all its tires in the new travel lane and has no subsequent lane departures.

NOTE: Weaving in the lane is permitted so long as there are no subsequent lane departures from the new lane. If there are subsequent departures from the new travel lane, the lane change has not ended.

10.5.1.4 Lane Change End -- Stable Position in New Lane (Option 2)

A lane change ends when the vehicle is stably positioned and traveling in the new lane.

NOTE: At this point, there is no consensus on criteria defining “stably positioned”. In essence it means that the vehicle is heading straight (zero heading angle, parallel to lane markings) for 2 or more seconds in the new travel lane.

10.5.2 Number of Lane Changes

Count of the number of times a vehicle changes travel lanes over some time or distance interval.

NOTE: The number of lane changes is usually reported per 100 miles or 100 kilometers, though on occasion, the report is either per minute or per hour.

REQUIREMENT: The first instance the term *number of lane changes* is used in a document, the method used (Option A, B, or C) to determine the start and end points of the lane change shall be reported.

GUIDANCE for Lane Changes: The most extensive and recent document on lane changes is Lee, Olsen, and Wierwille (2004), who among other things, provide data on the number of lane changes per unit time reported by prior studies. Those numbers vary considerable, in part because what constitute the beginning and end points varies between studies, if those points are reported at all. Identifying a clear beginning and end point for a lane change is difficult, though this document provides three options. For the initiation point, Lee, Olsen, and Wierwille (2004), p. 36 say the following:

> *“Experience indicates that drivers ordinarily return fixation direction to the forward view (from the mirrors or direct looks to the rear) when they begin the lane change. Initiation of the lane change itself can ordinarily be detected by a steering input or by movement toward the lane boundary or both… Thus, when t = 0, the beginning of the lane change or lane change attempt can be determined by monitoring one or more of the following:*
>
> 1. *The vehicle begins to move laterally relative to the lane.*
> 2. *Driver initiates a steering input intended to change the direction of the vehicle relative to the lane.*
> 3. *Driver returns gaze to the forward view after looking in mirrors or looking directly toward the side or rear.*

4. The vehicle leaves the lane at least temporarily.

While four criteria were used to define the beginning point, they were often not all present. Thus, some judgment was necessarily required. In some cases, the driver may not look to the rear, and in other cases the vehicle may naturally drift to the left or right without a steering input. Nevertheless, it was still possible for the reductionist to locate the initiation point in time by looking for the remaining criteria.

An additional cue that was sometimes present was the actuation of the directional signals. This signal alerted the reductionist to a possible lane change, but could not be relied upon for determination of the start point. Signals are not always used, and when they are used, activation varies relative to the actual lane change start point. …"

For the end point, Lee, Olsen, and Wierwille (2004), p. 37 say the following:

"Generally speaking, a lane change or attempted lane change ends when the vehicle "settles" in the new lane (or in the original lane for a passing maneuver). … Settling point appears to provide the best concept for the end of a lane change because it allows for lane overshoot, variable lane transition time, and incomplete lane-change attempts. … when the vehicle's lateral velocity relative to the lane is below a threshold for a specified period of time, the lane change is complete. "

For other useful research on the definition and application of lane changes, see Worrall and Bullen (1970), Godthelp (1985), Finnegan and Green (1990), Chovan, Tijerina, Alexander, and Hendricks (1994), Tijerina, Garrott, Glecker, Soltzfus, and Parmer (1997), Hetrick (1997), Van Winsum, de Waard, and Brookhius (1999), Salvucci and Liu (2002), Lee, Olsen, and Wierwille (2004), Mandalia and Salvucci (2005), Choudhury (2005), Hwang and Park (2005), Lee (2006), Fitch, Lee, Klauer, Hankey, Sudweeks, and Dingus (2009), Sun (2009), Lee, Kim, Yi, and Jeong (2011), Gurupackiam and Jones (2012), and Sun and Elefteriadou (2012).

Figure 42 shows data from the IVBSS report on the number of lane changes per 100 miles for various situations. Some 20 - 25 lane changes/100 miles are typical.

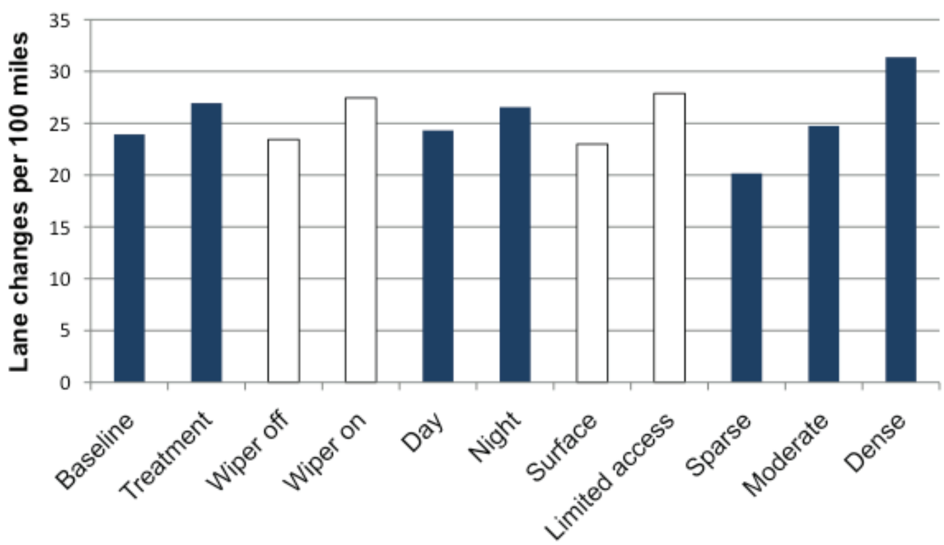


FIGURE 42 -- NUMBER OF LANES CHANGES PER 100 MILES
Source: Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler (2011), p. 70.

10.5.3 Duration of Lane Changes

Time interval, usually in seconds, over which a vehicle is moving from one travel lane to another.

GUIDANCE for Lane Change Duration: The distribution of lane change times is log normal (Figure 43) as was shown by Hetrick (1997), and Toledo and Zohar (2007). The range of times depends upon the study, the direction of the change, the vehicle type (car vs. truck), and the traffic volume. Most studies report lane change times on the order of 2.5 to 8.0 s, though the times are longer for trucks (Olsen, Lee, Wierwille, and Goodman, 2002; Lee, Olsen, and Wierwille, 2004).

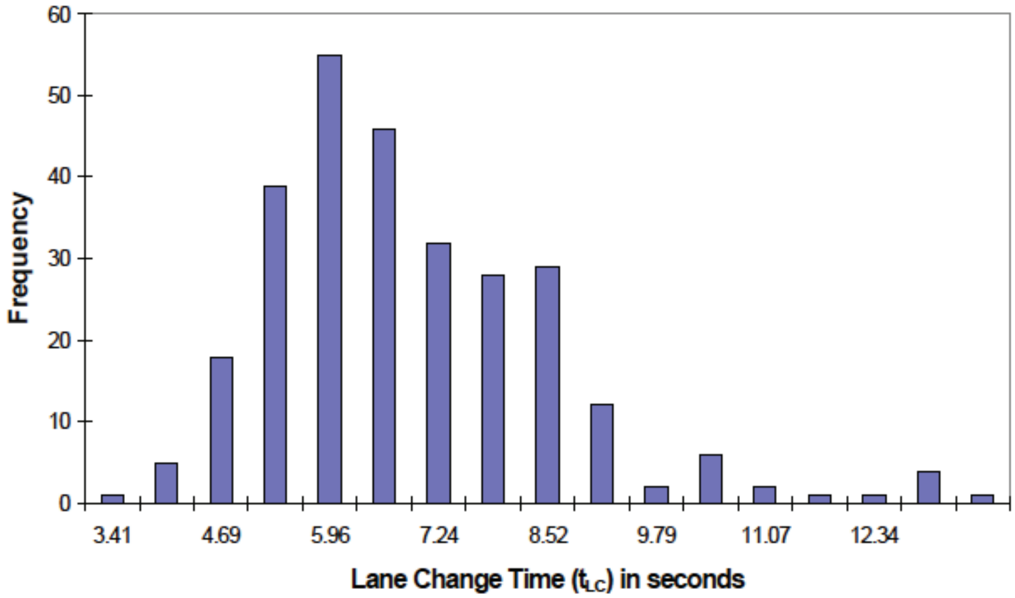


FIGURE 43 – DISTRIBUTION OF LANE CHANGE DURATIONS
Source: Hetrick (1997), p. 35.

10.5.4 Lane Change Severity

Subjective, seven-level estimate of the hazard created when a vehicle in the destination lane was cut off (Lee, Olsen, and Wierwille, 2004, p iii).

Lee, Olsen, and Wierwille (2004) describe eight types of lane changes (enter, exit/prepare to exit, lane drop, merging vehicle, other, return, slow lead vehicle, tailgated, unintended), having 4 categories of success/magnitude (single, passing, multiple, unsuccessful). They also identify 7 levels of lane change severity (1 = unconflicted, 7 = physical contact) as shown in Table 4. Severity ratings are based upon the presence of a vehicle in the proximity zone (zone in an adjacent lane 4 feet (1.2 m) in front of the subject vehicle to 30 feet (9.1 m) behind it) and the time to reach the rear of that zone by vehicles within the fast approach zone (zone in an adjacent lane 30 (9.1 m) to 162 feet (49.4 m) behind the subject vehicle).

TABLE 4 -- LANE CHANGE SEVERITY RATING
Modified from: Lee, Olsen, and Wierwille (2004), p. 33

Rating	Description
7	Physical contact/collision occurs with a vehicle (or object) in the adjacent lane into which the driver of the subject vehicle was attempting to move (no incidents observed in Lee, Olsen, and Wierwille, 2004)
6	Emergency action/unplanned sudden maneuver required to avoid a collision with a vehicle (or object) in the adjacent lane into which the driver of the subject vehicle was attempting to move
Ratings 5 through 1 are assessed at initiation of the attempted lane change with the principal other vehicle	
5	in the proximity zone
4	in the fast approach zone with time to reach closest end of zone, Tr < 1.0 s
3	in the fast approach zone with time to reach closest end of zone in the range 1.0 < Tr < 3.0 s
2	in the fast approach zone with time to reach closest end of zone in the range 3.0 < Tr < 5.0 s
1	in the fast approach zone with time to reach closest end of zone, Tr > 5.0 s, including case where there is no vehicle in the adjacent lane

10.5.5 Lane Change Urgency

Subjective, four-level estimate of how soon the lane change was needed based on TTC with the closest vehicle ahead (or behind for accelerating vehicles such as tailgaters).

NOTE: Lane change urgency rating scale is given in Table 5.

TABLE 5 -- LANE CHANGE URGENCY RATING
Modified from: Lee, Olsen, and Wierwille (2004) p. 33

Rating	Name	Description
4	critical incident/crash	collision occurs with a vehicle (or object) in the (1) same lane as the subject vehicle (2) an adjacent lane in the same direction of travel, (3) an adjacent lane in the opposite direction of travel, or (4) a sudden maneuver (braking or swerving) is required to avoid such a collision
3	forced	short TTC (TTC ≤ 3 s) and/or close headway/following distance to vehicle in an adjacent lane in the same or opposite direction of travel
2	urgent	moderate TTC (5.5 s ≥ TTC > 3 s) and/or moderate headway/following distance to vehicle an adjacent lane in the same or opposite direction of travel
1	non-urgent	minimal, infinite, or negative TTC (TTC > 5.5 s) with a vehicle in the same or opposite adjacent lane, and/or long headway distance, and/or lack of vehicles in the same or opposite adjacent lane.

10.6 Guidance Concerning Lateral Position Measures

Controlling the lateral position of the vehicle involves multiple objectives, which in a few instances may conflict. At the highest level, the driver's goal is not to collide with other vehicles or fixed objects such as lane barriers and bridge abutments. Thus, when other large vehicles are abreast of the subject vehicle but in adjacent lanes, drivers shift their lateral positions slight to provide additional clearance (Green, Kang, Alter, Best, and Lin, B. (2011). In addition, drivers attempt to minimize the number of times they depart the lane, making the number of lane departures an appropriate statistic that describes lateral control. Finally, drivers have the goal of driving smoothly, which in practical terms means they minimize lateral jerk. One could argue, that some combination of these three values is the true representation of driving performance. However, driving abreast situations are not that common, and to some extent the standard deviation of lane position is connected with both the number of lane departures and lateral jerk, which is why standard deviation of lane position is often the only measure used to assess the quality of lateral control.

An alternative perspective is that of control theory. Models of lateral control (e.g., Wier and McRuer, 1968) have two components to them, one for moment-to-moment corrections, and a second for preview control, with activity related to those components becoming apparent in a spectral analysis of the steering signal. Preview is reflected in the peaks from 0.1 to 0.3 Hz and momentary corrections in 0.35 to 0.6 Hz. Preview error is an indicator of heading error.

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