SURFACE VEHICLE RECOMMENDED PRACTICE	J2944	JUN2015
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Operational Definitions of Driving Performance Measures and Statistics

RATIONALE

A common and consistently defined vocabulary is a basic requirement for comparing evaluation procedures and their results for driving contexts, vehicles, and vehicle components. This is the reason for foundational documents such as SAE J1100 Motor Vehicle Dimensions (Society of Automotive Engineers, 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 engineering and research literature. This inconsistency makes comparing studies, test procedures, and results difficult, which in turn can compromise safety and usability. 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.

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1. SCOPE

This Recommended Practice, Operational Definitions of Driving Performance Measures and Statistics, provides functional definitions of and guidance for performance measures and statistics concerned with driving on roadways. As a consequence, measurements and statistics will be calculated and reported in a consistent manner in SAE and ISO standards, journal articles proceedings papers, technical reports, and presentations so that the procedures and results can be more readily compared. Only measures and statistics pertaining to driver/vehicle responses that affect the lateral and longitudinal positioning of a road vehicle are currently provided in this document. Measures and statistics covering other aspects of driving performance may be included in future editions. For eye glance-related measures and statistics, see SAE J2396 (Society of Automotive Engineers, 2007) and ISO 15007-1 (International Standards Organization, 2002).

1.1 Applicable Vehicles

This Recommended Practice applies to both left- and right-hand-drive wheeled vehicles having a steering control, accelerator pedal, and brake pedal. This document applies primarily to passenger vehicles, heavy trucks, and buses, including articulated vehicles and vehicles towing trailers, but may be useful for other types of vehicles. It applies to agricultural, construction, industrial, and military vehicles when those vehicles are driven on roadways, not off-road. Vehicles may be completely operated by a driver, automatically driven, or be operated by shared control.

This document does not apply to two-wheeled, three-wheeled, and tracked vehicles to avoid complicating the specification of lane-related measures and because of the unique steering controls they may have. Road vehicles operated only by hand controls and not foot controls, such as those driven by persons with physical disabilities, are also excluded to avoid complicating the specification the response time measures.

In addition, measures in section 7 concerning reaction, movement, and response time for foot pedals are not applicable for vehicles with a clutch pedal. These measures for vehicles with clutch pedals were not included in this edition of J2944 to avoid delaying its publication. However, measures in the rest of this document are applicable to vehicles with clutch pedals.

1.2 Applicable Contexts

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

1.3 Purpose

The measures and statistics defined in this document are used to describe the lateral and longitudinal control of road vehicles as part of safety and/or usability evaluations of (1) driver distraction caused by in-vehicle information 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 technical 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, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

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 Related Publications

Several definitions included in this document 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 so all relevant information appears in one document. 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.

Markkula, G. and Engstrom, J. (2006). A Steering Wheel Reversal Rate Metric for Assessing Effects of Visual and Cognitive Secondary Task Load, paper presented at Proceedings of the 13th ITS World Congress, London, United Kingdom.

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.

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-bc3712a7411b85c7/emc_horst_19900424.PDF, retrieved February 15, 2015).

Van Winsum, W., Brookhuis, K.A., and De Waard, 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.

NOTE: Most of the references cited in this document are in the Bibliography at the end of the Appendices.

3. CITING J2944 DEFINITIONS

REQUIREMENTS: The first time any terms defined in this Recommended Practice are used in a document, SAE J2944 shall be cited.

For terms for which there are parameters, for example a value greater than which data are excluded in a calculation, those parameter values shall be identified.

EXAMPLE: "The dependent statistic of interest was mean value of center of gravity (CG) distance separation, per SAE J2944. All values in excess of 120 m were omitted."

For terms with multiple definitions (options), the option used shall be identified.

EXAMPLE: "The dependent statistic of interest was mean value of time-to-collision (TTC), option B per SAE J2944. All TTC values in excess of 10 s were excluded."

4. INTRODUCTION

4.1 Background and Current Practice

Historically, there have been few comprehensive attempts to define terms used to describe driver performance, and only Savino (2009) examined 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 motivation for this document. 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 (Department of Transportation) 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 International Standards Organization (ISO) adaptive cruise control (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),
2. FHWA (Federal Highway Administration) *Highway Capacity Manual* (Transportation Research Board, 2010), and
3. MUTCD (*Manual on Uniform Traffic Control Devices*) (U.S. Department of Transportation, 2009).

The FHWA *Model Inventory of Road Elements* (MIRE) report (Lefler, Council, Harkey, Carter, McGee, and Daul, 2010) is derived from these and other documents and is often cited as a source for terms related to highway design.

A key source of definitions from the vehicle crash literature is:

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

Derived from ANSI D16, and often cited as a source for terms related to crash investigation and analysis are:

1. *Model Minimum Uniform Crash Criteria* (MMUCC, U.S. Department of Transportation, 2012b) and
2. *Fatality Analysis Reporting System* (FARS) *Analytical User's Manual (1975-2012)* (U.S. Department of Transportation, 2013b).

For a single concise review that contains data relevant to many of the measures and statistics in this document, see Yekhshatyan (2008) and Back, Jaeger, Skov, and Thomassen (2009). For background, additional measures, and related information, see Rupp (2010) and Campbell, LIchty, Brown, Richard, Graving, Graham, O'Laughlin, Torbic, and Harwood (2012).

Generally, terms relevant to driving performance measures and statistics are not consistently named and terms are not explicitly defined in publications, though there are cases where terms may be inferred from other definitions, figures, or their usage in a publication (e.g., *roadway* was not defined, but *roadway departure* was) (Savino, 2009; Green, 2012). Even when cited or provided, some of the definitions conflict with each other and others are not specific enough to allow for replication. 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).

4.2 Approach

The ultimate goal of this document is to encourage consistent use of a single name and definition for each driving performance measure and statistic. However, multiple definition options are provided for a term when there is a need to (1) reflect the potential multiple interpretations of that term, (2) be consistent with current standards and guidelines, (3) create a complete set of options, (4) support the variety of methods used in past and current studies, or likely to be used in future studies, and (5) accelerate the process of reaching agreement as to how that term is best defined. By including multiple options for defined terms, authors are more likely to find the definition they used, and are therefore more likely to cite this document, promoting its use.

Terms that represent states or processes, such as *lane departure*, *roadway departure*, and *lane change* can have multiple meanings. For example, does *lane departure* mean that a lane departure is predicted, is just starting, is in progress, or the vehicle has departed from the lane? For lane change, its initiation can be defined narrowly (when the vehicle crosses the lane boundary) or more broadly (when the driver is preparing to change lanes).

There will be instances where new alternative definitions of terms may be needed as technology advances (e.g., an additional option for what constitutes a lane departure), or new research identifies improved criteria for a definition (e.g., when braking is deemed to begin). Practitioners and researchers are encouraged to publish those improvements, reference SAE Recommended Practice J2944, and send new or revised definitions along with supporting evidence to the Driver Performance Operational Definition Subcommittee of the SAE Safety and Human Factors Steering Committee. Contact information is provided at the end of this document.

Guidance is provided to aid readers in applying the measures and statistics in this document. 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 determine if their measurements are reasonable. 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.

As users conduct evaluations using the measures and statistics in this document, they are encouraged to develop equations to predict differences between options. Further, they are encouraged to report results obtained for multiple options for the measures and statistics in the document, so that rules of thumb describing differences between options can be included in future versions of this document, enhancing its usefulness.

5. GENERAL MEASUREMENT AND REPORTING GUIDANCE AND REQUIREMENTS

Driving performance measures can be divided into at least three categories, (1) response time measures (for which means across trials are typically reported, (2) countable, discrete outcomes (such as lane and roadway departures), and (3) continuous performance measures such as steering wheel angle, lateral position, distance gap, time to collision) for which means, standard deviations, and other statistics are reported. Some of the guidance in this section applies to the measures and statistics in all three categories, whereas some apply to one or two categories. Countable outcomes can occur from a single trial (Did the vehicle depart the lane when the lead vehicle swerved?) or be aggregated over time (How many lane departures occurred in the fatigued condition?).

5.1 Good Measurement Practice

5.1.1 Specify a well-defined start point

The start point is a distinct, well-defined point indicating an event, task, or data collection has begun. Examples of event-related start points include:

1. illumination of a vehicle's brake lamps reaches a specified value,
2. illumination of a traffic signal reaches a specified value for some state or phase,
3. first word of a spoken warning begins or is completed, or an entire message is spoken,
4. lead vehicle decelerates above a specified threshold,
5. turn signal lamp flashes on, then off, and then starts to go on again, indicating a driver intends to change lanes,
6. front bumper of a vehicle on an intersecting path crossed a particular pavement marking for a pedestrian crossing, and
7. pedestrian begins to move a leg to walk in a particular direction.

In field experiments, video-based detection of events in the traffic environment is currently the most common method to determine the start point. 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, and because low resolution of the recorded video can sometimes make it difficult to perceive small objects/events far ahead of the subject vehicle.

For in-vehicle tasks, Angell, Cook, and Perez (2013) summarize discussions with human factors experts as to what constitutes the event start point, which for in-vehicle video display tasks requires identification of the first screen. That screen could be (1) the default start screen for the system function in question (the home screen, if there is one), (2) the screen used most often by the subject (often the radio menu), or (3) the screen on which the subject ended the previous task. Angell, Perez, and Garrott (2013) note that a task begins when the subject begins to interact with the device, which could be when the subject begins to move a hand to the device or when the subject first glances at the device, whichever occurs first.

For experiments that involve the driver states (e.g., fatigue), roadway, traffic, lighting, or weather conditions, the start point is generally a particular point on a roadway (e.g., a specified distance after an intersection or freeway entrance), but not immediately after the subject starts driving.

For identifying the start of foot movements, the shoe can be either on the floor, on a pedal, or suspended above the pedals. Use the lateral midpoint (x,y,z) of the shoe ball of foot to identify the initial shoe location if the shoe is not initially on a pedal. If the shoe starts on a pedal, report the geometric center of the pedal pad surface as the start point. See SAE J1100 (Society of Automotive Engineers, 2009) for pedal dimensions.

REQUIREMENTS: The start point of an event and a response shall be measurable and clearly defined when it is first used in a document. For the initial foot response, measure the position of the lateral midpoint of ball of the shoe or the geometric center of the pedal pad surface. The event and response start points shall also be reported.

5.1.2 Specify a well-defined end point

For event-initiated responses, the most significant problem in interpreting and comparing response time data is that the start point and/or end point of the response is often not clearly defined. Is the end point (1) when a specified movement of the accelerator pedal begins, or (2) when complete release of the accelerator pedal, touching the brake pedal, activating the stop lamp, full activation of the brake, or something else first occurs? Differences in the end point lead to substantial, practical differences in the values obtained.

The end point should be a distinct, well-defined point of the movement or utterance 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.

For in-vehicle task-related measurements, the end point is when the subject has truly completed the task, which could be when the final manual input has occurred, or when the last glance has occurred. Determining the end point can be difficult in situations involving significant vehicle system delays (e.g., when the driver queries a web site and the vehicle system takes several seconds to retrieve and display the information to the driver). SAE J2364 (Society of Automotive Engineers, 2004) defines a system time-out period, most of which is excluded from the determination of total task time that the subject is engaged in the task. The disengagement is partial, with the subject making glances on the order of 1.0 - 1.5 s to the display every 5 - 10 s to determine if the task is completed and to obtain the desired information.

For experiments that involve the driver state (e.g., fatigue), roadway, traffic, lighting, or weather conditions, the end point is generally a particular point on a roadway determined in a manner similar to the start point.

REQUIREMENTS: The end point of a response shall be measurable and clearly defined when it is first used in a document. The amount of movement and the time window over which the movement is detected shall be reported.

5.1.3 Measure driver control movements accurately and precisely

Steering wheel and pedal movements are generally determined in one of four ways: (1) directly from the Controller Area Network (CAN[1]) bus (which is becoming the most common method, available for all 1996 model year or newer cars), (2) from the OBD-II (On-Board Diagnostic) connector in U.S. vehicles or the EOBD (European On-Board Diagnostic) connector in European vehicles (present on gasoline engines since 2001 and diesel engines since 2004), (3) from displacement sensors installed on the accelerator and/or brake pedal to detect the onset of a driver pedal application or release; or (4) by manually or automatically coding the pedal response using frame-by-frame video analysis. For instances where the vehicle speed is controlled by the cruise control system, the beginning movement may be operating a switch to turn off the cruise control system or a foot movement towards the brake or accelerator.

Placing markers on the steering wheel rim (such as a ring of white adhesive tape) 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 Gelau, 2004).

The accuracy of movement timing depends upon the inverse of the frame rate of the video system. So, a system recording at 30 Hz is accurate to the nearest 33 ms, whereas a system recording at 5 Hz, as could be the case in a contemporary naturalistic driving study, is only accurate to the nearest 200 ms, which may be precise enough in many circumstances. In Europe and elsewhere, some video systems have frame rates of 50 Hz, in which case event times are accurate to the nearest 20 ms. Accordingly, measurement accuracy and precision shall be reported. A potential further complication is that to reduce processing requirements and minimize video storage requirements, the various cameras used may have different frame rates.

Of particular importance when sampling rates are low is the decision rule for identifying when movements appear to begin or end, (1) the frame in which there is clearly no movement, (2) the frame for which there is closest to no movement (indicated by minimal blur), or (3) some other rule. Often, the start and end points are determined manually by repeatedly replaying the frames around where the start/end point occurs to identify the key frame or frames. Whatever process and rules are used, they should be reported.

[1] CAN systems may not meet bandwidth requirements for connected or autonomous vehicles. Future systems may use Ethernet, FlexRay, LIN, or something else. See Schmid (2006), Talbot and Ren (2009), and Dello (2011) for a description of automotive serial buses.

Given concerns about the precision of video-based measurements when sampling rates are low, those measures may be complemented by displacement sensors that 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 5.1.6, contemporary automated 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 now than in the past and can sometimes be found online.

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 of the foot contacting the brake pedal provides accurate timing. This method is not often used and will be used less often in the future where brake-by-wire systems may provide the desired signal.

REQUIREMENTS: The accuracy and precision with which data were collected and the information used to determine such (e.g., video frame rates) shall be reported.

5.1.4 Eliminate sensor noise

Sensor noise can be intermittent or continuous. Intermittent noise includes shorts, disconnects, and failures that can be identified in plots of sensors outputs, where these failures are associated with outputs that are fixed (“flat lined”, generally at zero or maximum values) for periods of time and may be caused by a sensor being disconnected, shorted, or failing for other reasons. Continuous noise includes AC electrical noise (50 or 60 Hz, depending on the recording system) and should be removed as it may result in signal values that appear to vary randomly when they are actually fixed. For example, when driving parallel to a lane marking, the distance to the lane marking over 100 m should only change by a few centimeters if the lane marking is straight. Plots of sensor output will reveal such problems. DC noise may result in upward or downward shifts of all values recorded for a sensor. When examining plots of data, the maneuver the driver is performing (e.g., car following on a straight section, driving through curves, braking in response to a traffic signal) needs to be considered.

In addition to electrical interference and sensor failures, there are other types of sensor noise that are inherent to the measures and groups of measures (GPS, vehicle speed, brake pressure, etc.) and how they are communicated to the data collection systems (dedicated digital or analog inputs, one of the CAN buses). Filtering is quite common for electrophysiological data (e.g., Healey and Picard, 2005; Mehler, Reimer, and Coughlin, 2012), but less so for driving performance data.

In addition to efforts to deal with specific errors, driving data are often filtered to eliminate random noise in the data. In filtering data consider the bandwidth of interest for each signal (e.g., for driver variables other than eye fixations, often less than 10 Hz for some tire characteristics, up to 100 Hz). The Nyquist folding frequency, which is double the frequency for which accurate measurement is desired, should be used to select filter cutoff frequencies. The most appropriate filter will depend on errors expected and the correction needed, with moving average, Kalman, Bessel, and Butterworth filters often being used. For examples, see Chen, Bas, and Bajpai (2009) and Chen, Shih, and Lin (2014).

REQUIREMENTS: Electronic noise from each sensor and out-of-range inputs shall be filtered out. Actions taken to deal with sensor noise shall be reported. When filters are used, the type of filter, whether the filter is low-, high- or band-pass, the cutoff frequency or frequencies, and any other relevant characteristics shall be reported.

5.1.5 Eliminate sensor and sensor integration lags

There are inherent time 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 are collected. U.S. video data is often 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 100 ms.

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. Delays can also occur when signals from multiple sensors are integrated.

REQUIREMENTS: Adjustments of response times to account for lags shall be reported because delays associated with lags can be a substantial fraction of response time.

5.1.6 Separate vehicle automated actions from driver actions

Automated functions include conventional and adaptive cruise control, lane keeping assistance systems, crash avoidance braking systems, and other systems that control some or all of the driving tasks.

When conventional cruise control and adaptive cruise control systems are actively controlling the throttle, the driver's foot does not have to be on the accelerator pedal. For adaptive cruise control there will be periods of time where changes in speed occur without any driver input. Lane-keeping and stability-control systems may apply the brakes to some or all of the wheels, and/or provide mild steering actions to maintain lane position or prevent unintended lane departure, partially overriding driver actions. Pre-crash braking systems and forward collision warning systems with braking capability 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 cut off or reduce the throttle (Marshek, Cuderman, and Johnson, 2002; Forkenbrock, Snyder, and Jones, 2010). Consequently, there may be periods of time where changes in speed or lateral control may occur automatically without any driver input.

Other systems augment vehicle deceleration response to driver inputs. Pre-charging the brakes reduces the pedal displacement required for driver braking. Regenerative braking systems, or engine retarder systems in heavy trucks, may slow the vehicle without any change in brake pressure.

Keep separate of actions taken by automated functions and actions taken by the driver. This may require the foot pedal responses (and possibly steering responses) to be coded manually or automatically using frame-by-frame video analysis. The initial position of the foot (usually the right foot) should be taken from its position just before movement is initiated.

If automated functions are part of a steering or braking system, carefully examine the steering and brake pedal position data to ensure that the appropriate steering or braking start time is recorded. There are four cases to consider, (1) only the driver responded, (2) only the automated function responded, (3) the driver responded first but then the automated function took control, or (4) the automated function responded first but then the driver took control. Analysts have the option of (1) pooling trials in which either the driver or automated function responded, (2) analyzing the four cases separately, or (3) if there are only a few trials involving an automated response, ignoring the trials in which the automated function responded. To adequately assess the benefits of the automated function, analyze the four cases separately.

REQUIREMENTS: The automated systems (e.g., adaptive cruise control (ACC), lane keeping assistance (LKA)) installed in a test vehicle or in a driving simulator shall be reported as well as their state (off, standby, partially on, fully on, etc.) during each portion of an evaluation. Where automated functions take over from drivers or augment driver inputs, the conditions under which take over occurs (for example, the minimum operating speed for cruise control) shall be reported. Periods of automated or augmented control (e.g., cruise control is operating, regenerative braking is operating) shall be analyzed and reported separately from those of manual control.

5.1.7 Exclude preparatory movements from the accelerator or brake as well as random movements

Sometimes drivers will move their 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. However, if the driver rests a foot on the brake pedal, the brake sensor will indicate some displacement prior to a response event and even possibly 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 displacement of the brake pedal associated with the desired action occurs. When timing the driver's 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 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 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 backwards from the maximum braking pressure to ensure that the initial braking response is accurately captured. A foot camera view of the accelerator and brake pedals is useful to validate initial accelerator pedal and brake pedal movements.

An alternative approach is to use regression to determine the relationship between brake pedal position or brake line pressure and time, and to find the point at which the regression line intercepts the time axis, where position or pressure is estimated to be zero. See Fitch, Blanco, Morgan, Rice, Wharton, Wierwille, and Hanowski (2010) for an example of this approach.

Another challenging sequence that is revealed by video occurs when the driver removes their foot from the accelerator pedal, is uncertain what to do and waves the foot above either or both pedals, and then depresses a pedal. Such indecision can only be detected from video recordings.

REQUIREMENTS: Instances when drivers do not have their foot or hand on a control at the beginning of a response sequence shall be reported. The location of the hand or foot at the movement beginning shall also be reported. These data shall be analyzed and reported separately from trials where the hand or foot rests on a control or pedal at the beginning of a response sequence.

5.2 Good Reporting Practice

5.2.1 Identify when drivers have both hands off of the steering device

Sometimes drivers will remove both hands from the steering device, possibly 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., with a knee), (2) limit steering device 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.

RECOMMENDATIONS: Situations when both hands are off the steering device in any test condition should be analyzed separately from trials where drivers always have at least one hand on the steering device. Data can be pooled if no differences are found.

5.2.2 Identify when drivers use both feet to drive

For vehicles with clutch pedals, the driver uses two feet to manipulate the pedals. Driving with two feet is common for racecar drivers. As noted in 1.1, this document assumes the vehicle does not have a clutch pedal, an assumption made to simplify the development of response time measures and statistics related to foot pedals.

Some drivers, usually older drivers, rest their left foot on the brake pedal while they use their right foot to operate the accelerator pedal (Figure 1). At times they may even use both feet to operate the brake pedal (Figure 2). As noted in 5.1.7, the left foot resting on the brake pedal may lead to a non-zero brake pedal pressure, possibly enough to activate the brake lamps, so it cannot be taken as an indication that braking has begun. The brake pedal response to an event begins when the brake pedal moves downward and/or brake pressure increases beyond a resting or threshold value.

Figure 1 - Using both feet to drive
Source: Pettinato and Best (2012), personal communication

Figure 2 – Two-foot braking
Source: Pettinato and Best (2012), personal communication

In addition, for two-footed pedal operation, the release of the accelerator pedal may partially overlap with application of the brake pedal. In that case, the actions of the brake pedal are considered the defining action.

RECOMMENDATIONS: Instances when the left foot, the right foot, or both feet are used to brake should be analyzed and reported separately. Where automated functions for braking are provided, the four cases (in 5.1.6) should be analyzed and reported separately when assessing the benefits of the automated braking function. However, in lieu of a separate analysis, analysts may either (1) pool the trials in which either the driver or automated function responded, or (2) ignore the trials in which the automated function responded, if it rarely occurred.

5.2.3 Match the roadway segments for conditions being compared

When comparing conditions, such as a baseline with a test condition, select conditions that match for all important respects except for the difference of interest (though there may be exceptions when using Taguchi methods (Taguchi, Chowdhury, and Wu, 2004; Roy, 2010)). For experiments on real roadways, the ideal baseline condition is often taken on the same roadway just before or after the location where the test data were collected, or, if feasible, test conditions are interspersed between segments of the roadway. The baseline segments should match the test segments in terms of roadway geometry (e.g., curve radii, lane width, and speed limits) and traffic, though matching moment-to-moment changes in traffic is not easy. Ideally, each section should be of just one geometry type and one traffic condition. Usually, traffic changes between days or between roadways are often more pronounced than those within days and roadways. In a driving simulator, where roadway geometry and traffic can be specified, obtaining matching conditions is much easier.

Roadway sections where different test vehicle maneuvers occur should be analyzed separately (e.g., sections where drivers accelerate, decelerate, turn, change lanes, or back up). Walker, Alicandri, Sedney, and Roberts (1991) and Green, Williams, Hoekstra, George, and Wen (1993) are examples of studies where such separations were implemented.

RECOMMENDATIONS: When comparing conditions, such as a baseline with a test condition, users should select conditions that match as best as possible in terms of roadway geometry, signs, traffic signals, traffic (often measured by Level of Service), surface condition (using roadway roughness indices), visibility (using sight distance), vehicle mix, and drivers, and differ only in the treatment condition of interest.

5.2.4 Make the sample durations equal

Some statistics, such as the variability of a continuous measure (e.g., standard deviation of lane position), may depend on the sample duration. This can be a challenge when comparing activities that naturally have different durations, e.g., street address entry usually requires much more time to complete than dialing a phone number. To equalize duration, one can confine the analysis to the duration of the shortest task, and select samples from the longer tasks equal to that of the shortest duration (often, the first n seconds). Performance may not be stable over a longer task (e.g., destination entry), with drivers slowing down as the task progresses.

RECOMMENDATIONS AND REQUIREMENTS: The durations of tasks being compared should be approximately equal when measures of variability, skewness, or kurtosis are being determined. In all cases, the sample duration shall be reported.

5.2.5 Adjust for extreme responses

Many driving-related human performance measures are computed from censored distributions. For example, very long response times (e.g., beyond the four seconds) or situations where drivers fail to respond may reflect a response process that is different from when the response time is one or two seconds. Furthermore, for other measures, such as *distance gap* (8.1.1), *time to collision* (8.2.1) and *time to line crossing* (10.3.2), there is no practical difference in driving behavior when the response values are large versus very large. To be specific, whether a lead vehicle is 0.1 mile (0.16 km) or 1 mile (1.6 km) in front of a driver will have no substantial differential effect on how the following vehicle is driven, though the value does affect the computation of the mean gap. Furthermore, the sensors for some of these measures have range limitations. For example, current sensors for forward collision warning and adaptive cruise control have a range of about 120 m (almost 400 ft) under ideal conditions.

Censoring, ignoring values about some threshold, is one way to omit these values from the distribution of interest so as to focus the data analysis on the more relevant responses.

A much more complex alternative is to use survival analysis to make inferences about the underlying distributions, including the responses not observed (Cox and Oates, 1984; Ratliff, 1993; Ulrich and Miller, 1994; Palmer, Horowitz, Torralba, and Wolfe, 2011; Parmet, Avinoam, Oron-Gilad, Yael, and LItal, 2012).

A third alternative, most appropriate if all the data were generated by the same response process, is to examine the inverse of the response measure. In this alternative, responses that are inferred to take extremely long times or have extremely large values (essentially infinite) when inverted have values of zero, and the range of the inverse is from zero to one.

RECOMMENDATIONS AND REQUIREMENTS: When dealing with extreme or unusual responses, some method (e.g., censoring, identification of the number of missing responses, survival analysis, or inverses) should be used to adjust for the extreme responses. The method used shall be reported.

5.2.6 Percentiles are sometimes the most revealing statistic

Sometimes what may be of interest is only part of the range of a measure or a particular percentile. For example, when studying the effect of time or distance gap on crash risk or vehicle following performance, what matters is the fraction of time the gap is small, say a few car lengths (with the exact value depending on the speed driven). Thus, some percentile value of the distribution (say 5^{th} or 10^{th}) may be most important (or in this example, crash-relevant), but there is usually little theoretical justification for a particular percentile.

REQUIREMENTS: When what is important is a shift of some part of a distribution, analysts shall select a percentile relevant to that part of the distribution. The rationale for selecting that percentile shall be provided. That rationale may be consistency with prior publications (that are cited) or some other reason.

5.2.7 Report distribution parameters to aid modeling

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

RECOMMENDATIONS: For the major dependent measures, their distribution type (e.g., normal, log-normal, double exponential) and the distribution parameters (e.g., mean, standard deviation, skewness, and kurtosis) should be reported. The rationale for the distribution type should be reported.

5.2.8 Select response measures and statistics appropriate for the question(s) posed

Prior to data collection, clearly define the specific questions to be investigated. From these questions, the analyst can determine the most suitable response measures. Most well designed experiments make specific quantitative predictions regarding the outcome. Mere directional predictions (A will be better than B) are insufficient.

For example, in an experiment to test the effectiveness of alternative brake lights, suppose the subject was instructed to (1) follow a lead vehicle and maintain a specific distance gap, a longitudinal control task, and (2) brake as rapidly as possible when the lead vehicle braked. For this experiment a specific hypothesis could be "as predicted by … in the literature (or some human performance theory), the response time to design B will be 10% less than design A." In that case, there is no need to examine lateral control measures, such as standard deviation of lane position, unless there was another hypothesis that brake lamp design would affect lateral control.

Furthermore, an insightful analyst would consider the entire sequence of actions in this case (initial release of the accelerator pedal, the point at which the accelerator pedal travel is zero, the point at which the brake pedal is first contacted, etc.) and make specific predictions about how each portion of the response sequence is expected to change.

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

REQUIREMENTS: For each research question, analysts shall identify the measures and statistics used to answer that question.

5.3 Summary of General Measurement and Reporting Requirements

If available, 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, (e.g., when a warning sound begins and ends),

2. The (a) salience of the triggering event, (b) if it is expected, and (c) how often it has been seen before, (e.g., the luminance, area, and contrast ratio of a traffic signal),

3. The (a) alertness/fatigue of the driver, and (b) where the driver is looking,

4. The (a) start and (b) end points of the sampling period or response (the time window over which data are collected),

5. How the data were collected,

6. Quantification of the (a) lags and (b) noise in the data collection devices,

7. How drivers are using their (a) hands and (b) feet to drive, and (c) if there were any extraneous motions,

8. The roadway geometry, traffic, surface condition, and visibility for the data collection period,

9. The duration of the data collection period,

10. If the data were censored, and if so, how the censoring was done, and

11. The filter and its parameters, if used, to remove noise from the raw data.

Analysts should report the distribution type for each measure and statistic and the distribution parameters to aid modeling.

6. GENERAL DEFINITIONS

This section contains definitions of terms that are not performance measures or statistics, but are parts of vehicles or trafficways that are needed to define performance measures and statistics. For example, *leading and trailing surfaces*, defined in this section, are used in the operational definition for *gap* provided later. Other terms defined in this section, such as *response time*, are given more application-specific definitions in the operational definitions. For example, *response time until brake lights 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 3).

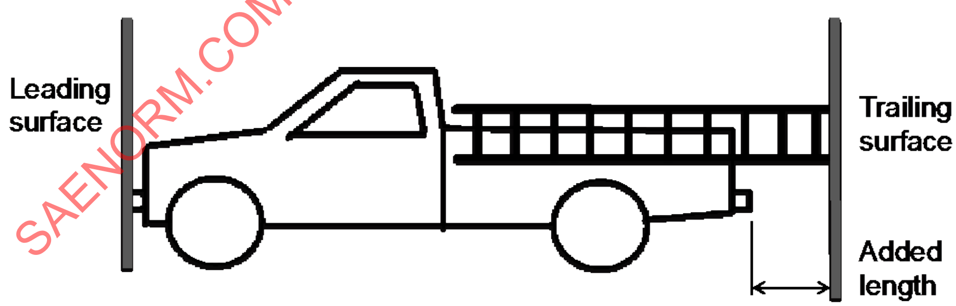

Figure 3 - Truck with a ladder that adds a trailing surface to its length

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

REQUIREMENTS: 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 3).

6.2 Trafficway Elements

In the literature there are many terms related to *trafficway* - such as *highway, roadway, road,* and *traveled way* - that can have conflicting or multiple meanings and often are confused with each other. To ensure consistent descriptions in technical reports, proceedings papers, and journal articles, this document (1) recommends use of terms such as *trafficway, traveled way*, and other terms described in this section, (2) defines the recommended terms, and (3) describes how they should be cited and used. Alternative definitions in current use are provided in the notes associated with some of these terms to aid in understanding how these terms have been defined and used elsewhere, and to encourage harmonization.

The two core documents for the definitions in 6.2 are (1) AASHTO's A Policy on Geometric Design of Highways and Streets (the Green Book, AASHTO, 2011 and Errata, 2012) and (2) ANSI D16.1-2007 (7th 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.

For additional information on the definitions and explanations of trafficway elements, and the functional classifications of the roadway networks that should be used in publications, see the *Highway Performance Monitoring System Field Manual* (U.S. Department of Transportation, 2014).

GUIDANCE for Trafficway Elements: To provide for consistent descriptions in technical reports, proceedings papers, and journal articles, this document recommends use of the terms defined in 6.2, particularly the terms *trafficway, traveled way, roadway, shoulder, usable shoulder*, and *lane expansion.*

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 4).

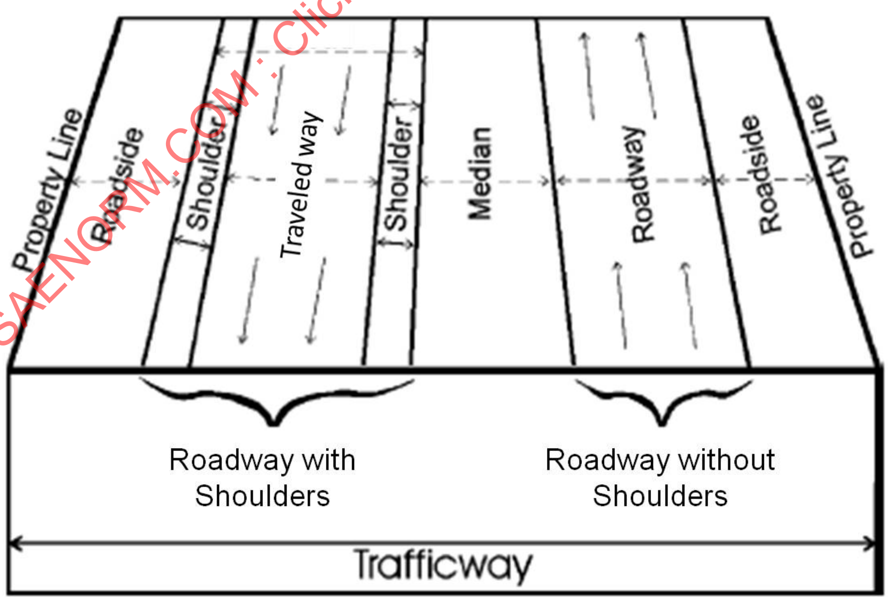

Figure 4 - Trafficway, traveled way, and roadway
Source: Modified from American National Standards Institute (2007), p. 3

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, p. 364) of *National Transportation Statistics* published by the Bureau of Transportation Statistics (U. S. Department of Transportation, 2013e, 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, p. 14) calls this the *highway* (definition 83). The AASHTO Green Book uses *highway, road* or *street* instead of *trafficway*. The *Highway Capacity Manual* (Transportation Research Board, 2010) 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)."

NOTE 4: *Right-of-way* has both common usage and usage as a legal term. Right-of-way is determined by ownership (who owns the land) and by access (such as the easements of cable, electric, and phone companies).

6.2.1.1 Street

Trafficway in a city or town.

6.2.1.2 Highway

See trafficway (6.2.1).

Guidance for Trafficway: Use of the term *trafficway* is recommended because it is consistently defined wherever it is used. Terms such as *highway* and *street* may be used but they are not as consistently defined or are more often used in a way that means something different from trafficway. The term *road* is defined later and is not recommended to be used in lieu of trafficway because it has a variety of other meanings. The term *right-of-way* is sometimes used to mean trafficway, but such usage often includes legal implications that are beyond the scope of this document. Users should be careful when using the term *trafficway* because it sounds like *traveled way*, but has a very different meaning.

6.2.2 Traveled way

Portion of the *trafficway* for the movement of vehicles, exclusive of shoulders and bicycle lanes (Figures 4, 5).

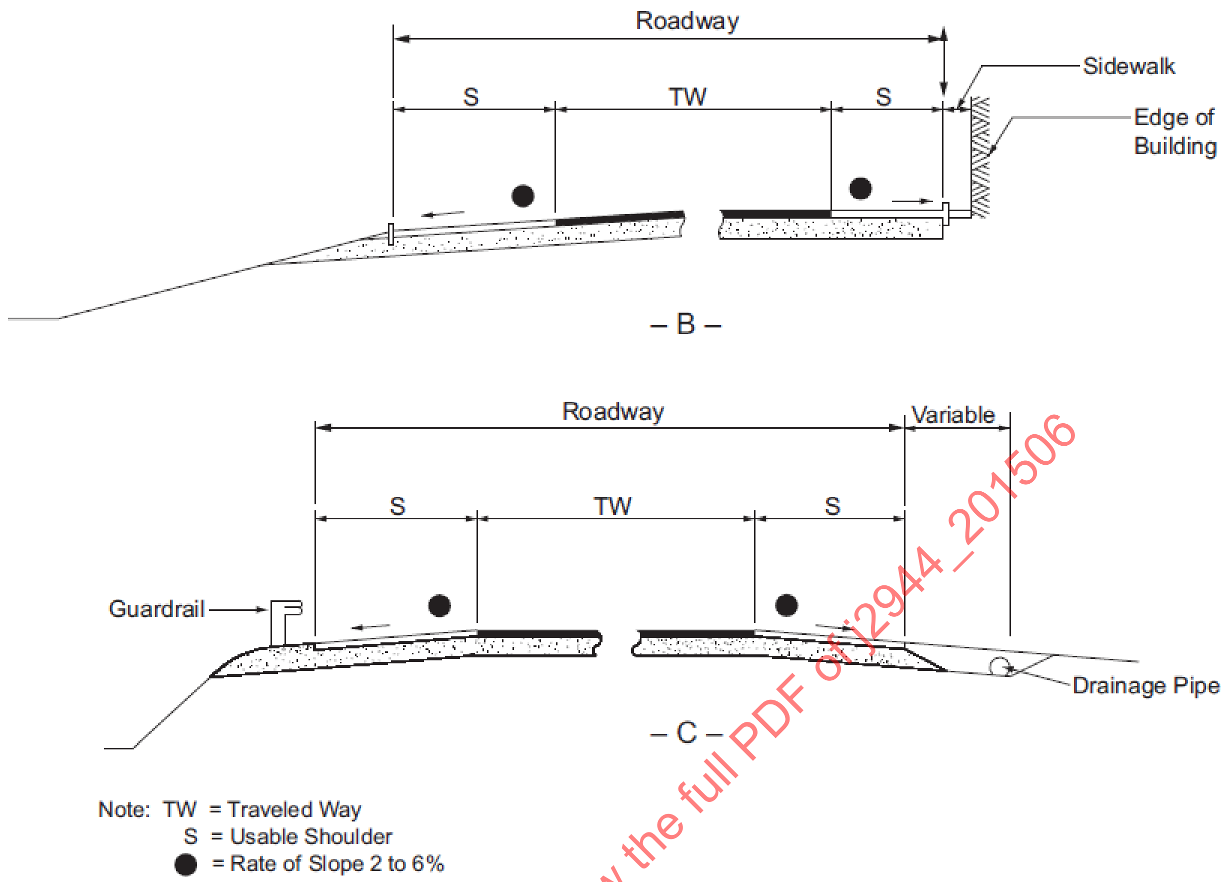

Figure 5 - Traveled way, roadway, and usable shoulder
Source: AASHTO (2012 errata)

NOTE 1: The definition in the AASHTO Green Book (2011, p. 4-1 and errata 2012) states the *traveled way* is the "portion of the trafficway for the movement of vehicles, exclusive of shoulders, and bicycle lanes." The MUTCD (2009, p. 22) states the *traveled way* is "the portion of the roadway for the movement of vehicles, exclusive of the shoulders, berms, sidewalks, and parking lanes." Figure 5 shows the traveled way using the corrected figure found in the 2012 Green Book errata. *Traveled way* is not defined in ANSI D16.1-2007 or in the *Highway Capacity Manual*.

NOTE 2: A traveled way includes the visually contiguous surface beyond the lane edge line. The *traveled way* is the portion of the trafficway that is designed to support the movement of motor vehicles on their intended path of travel. Vehicular traffic may be in the same or opposing directions. In Figure 6, the concrete surface from the lane to the paved asphalt shoulder is considered part of the traveled way. In Figure 7, 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 6 - Example of visually contiguous paved traveled way, a paved shoulder, and a partially usable unpaved shoulder
Source: http://www.deldot.gov/information/community_programs_and_services/DSHSP/roadway_departure_crashes.shtml

Figure 7 - Example of a U.S. urban traveled way with a contiguous 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 8).

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 et al., 2011; see also http://www.youtube.com/watch?v=asy33BGQwUw). For additional information on shoulder design, shoulder drop offs, and loss-of-control crashes, 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).

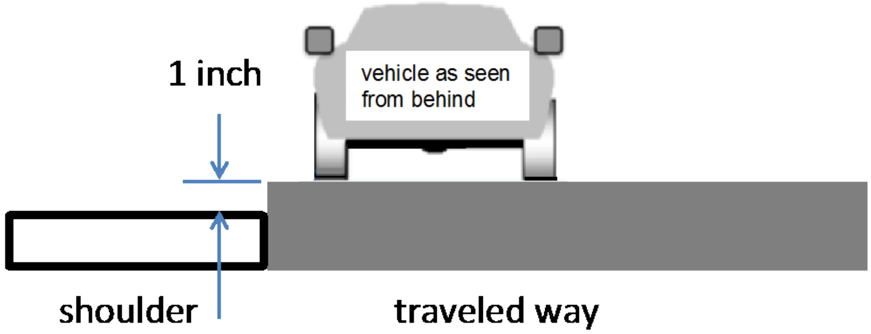

Figure 8 - Illustration of vertical drop off

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 Parking lane

Lane contiguous to a traveled way designed to provide temporary or emergency parking for motor vehicles (Figure 9).

NOTE 1: Parking lanes are considered part of the shoulder by AASHTO. They are not part of the traveled way but are considered part of the *roadway* by all agencies.

NOTE 2: Parking lanes are common on city streets, and parking may be parallel to or angled relative to the traveled way. Scenic outlooks along traveled ways can also provide parking lanes.

Figure 9 - Parking lanes
Source: http://www.denverinfill.com/images/blog/2007-08/2007-08-27_portland3.jpg

6.2.4 Bicycle lane

Lane that has been designated for preferential or exclusive use by bicyclists via pavement markings (and possibly by signs), and is either contiguous with (but marked off from) the traveled way (Figure 10 right), or physically separated from the traveled way (Figure 10 left).

NOTE: The definition used here is similar to that in the MUTCD (2009, p. 11) “a portion of a roadway that has been designated for preferential or exclusive use by bicyclists by pavement markings and, if used, signs” except that here reference is made to the traveled way because there are multiple options for the definition of *roadway* (6.2.5).

Figure 10 - Bicycle lanes separated by a barrier (left panel) and not separated (right panel) from the traveled way
Sources:
http://www.bikexprt.com/bikepol/facil/images/9107N10R16Barrier%20bike%20lane.jpg (left)
http://rvelo.files.wordpress.com/2011/08/seattle-bike-lane.jpg?w=584&h=389 (right)

6.2.5 Roadway

Portion of a trafficway improved, designed, or ordinarily used for vehicular travel, which may or may not include the usable shoulder (or a part of it).

NOTE 1: The term *roadway* has a variety of meanings in common usage. One meaning, not used in this document, but often used in roadway construction and repair, broadens the above definition to include the entire trafficway - shoulders, drainage, and roadside.

NOTE 2: A divided trafficway has two or more roadways.

NOTE 3: There are four commonly used, well-entrenched, and conflicting sources of definitions of the term *roadway* – (A) AASHTO, (B) MUTCD/FARS/HCM, (C) ANSI, and (D) FHWA. The AASHTO definition (option A, 6.2.3.1) includes the usable shoulders. The MUTCD/FARS/*Highway Capacity Manual* definition (option B, 6.2.3.2) excludes the usable shoulder, except for parking lanes. The ANSI definition (option C, 6.2.3.3) excludes the usable shoulder, mirroring the *traveled way* definition. The distinction is important because it influences what is used to determine a roadway departure.

NOTE 4: The AASHTO Green Book (2011, p. 4-1) states the *roadway* is "the portion of a highway, including shoulders, for vehicular use."

NOTE 5: The MUTCD (2009, p. 19) states the *roadway* is "that portion of a highway improved, designed, or ordinarily used for vehicular travel and parking lanes, but exclusive of the sidewalk, berm, or shoulder even though such sidewalk, berm, or shoulder is used by persons riding bicycles or other human-powered vehicles. In the event a highway includes two or more separate roadways, the term *roadway* as used in this Manual shall refer to any such roadway separately, but not to all such roadways collectively." The *Highway Capacity Manual* (2010, p. 9-16) uses verbatim the definition that appears in MUTCD. This definition includes the traveled way plus parking lanes. See 6.2.5.2.

NOTE 6: ANSI D16.1 (2007, p. 12, definition 2.2.28) defines the *roadway* as "that part of a trafficway designed, improved and ordinarily used for motor vehicle travel or, where various classes of motor vehicles are segregated, that part of a trafficway used by a particular class." An associated figure shows exclusion of the shoulder from the roadway. The ANSI definition of *roadway* is identical to the AASHTO definition of *traveled way*.

NOTE 7: FHWA has at least three definitions for *roadway* depending on their application. First, the *Model Inventory of Roadway Elements* (MIRE) report (Lefler, Council, Harkey, Carter, McGee, and Daul, 2010) does not directly define what a *roadway* is. However, included among the roadway elements are the number of through lanes, left and right 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. Second, the FHWA *Highway Performance Monitoring System Field Manual* (U.S. Department of Transportation, 2014, p. 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. Third, for roadway departures FHWA explicitly excludes shoulders and opposing lane(s) of vehicles, so crossing a lane centerline into an opposing lane of traffic is viewed as a roadway departure (option D, 6.2.5.4).

NOTE 8: The third FHWA definition suits FHWA's 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 contiguous 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, though FHWA is unlikely to revise their definition of *roadway departure* unless it contributes to improving road safety (Sutherfield, 2012, personal communication). See 6.2.5.3.

NOTE 9: In the NHTSA *Model Minimum Uniform Crash Criteria* (MMUCC, U.S. Department of Transportation, 2012b, p. 6), *roadway* is defined by implication to exclude shoulders. Variable C8 (Location of First Harmful Event Relative to the Trafficway) has 10 attributes including "on roadway" and "shoulder." FARS, whose users' manual 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.

NOTE 10: Definitions of *roadway* in other publications either lack sufficient detail or are not consistent as a set. For example, SAE M105 (*Glossary of Automotive Terms*) defines *roadway* as, "the surface or plane which is supporting the vehicle, and on which it is moving" (Society of Automotive Engineers, 1992, p. 322). The glossary cites SAE J1451 as the source.

6.2.5.1 Roadway including usable shoulders (Option A)

Portion of a trafficway improved, designed, or ordinarily used for vehicular travel, <u>including</u> the usable shoulders (which can contain parking lanes and contiguous bicycle lanes).

NOTE 1: This definition is based on the definition of *roadway* in the AASHTO Green Book (AASHTO, 2011, p. 4-1), and the definition of *road* in ANSI D16.1 (2007). It consists of the traveled way plus the usable shoulder.

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

NOTE 3: The AASHTO Green Book (2012), p 4-3 specifies the cross slope of the traveled way cannot differ from that of the usable shoulder by more than 8 %.

NOTE 4: The term *road* has many definitions. The definition in 6.2.5.1 is the most useful one for defining and applying terms such as *on-road* and *off-road*, terms that are often used in a vehicle or human factors context. Off-road includes areas beyond the road that can extend past any trafficway boundaries.

NOTE 5: SAE J2808, definition 3.1 defines *road* as "the surface that a vehicle would be expected to travel along in the absence of any obstruction" (Society of Automotive Engineers, 2007, p. 4). On that same page, further clarification comes from definition 3.2, *road boundary*, "the borderline of the road that is determined by incidental visible road features or other means such as GPS. This definition lacks sufficient detail.

6.2.5.2 Roadway including parking lanes (Option B)

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

NOTE: This definition is based on the definition of *roadway* in the MUTCD (*Manual on Uniform Traffic Control Devices*, 2009, p. 19). MUTCD specifically excludes bicycle lanes.

6.2.5.3 Roadway excluding usable shoulders (Option, C)

Same definition as *traveled way.*

NOTE: Use of the term *traveled way* is recommended.

6.2.5.4 Roadway excluding shoulders and opposing lanes (Option D)

Portion of a traveled way that excludes opposing lanes of traffic and is bounded by edge lines or a centerline/median separating opposing lanes of traffic.

NOTE: This definition is derived by implication from the FHWA definition of a roadway departure. FHWA defines *roadway departure* as, "A non-intersection crash in which a vehicle crosses an edge line, a centerline, or leaves the traveled way" (U.S. Department of Transportation, 2014, p. 3).

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

Guidance for Roadway: How *roadway* is defined is important because it affects how roadway departures will be counted (10.5.2). Option D, the most restrictive definition of a *roadway*, is used in FARS and will identify the largest number of departures. Options C, B and then A successively include more paved surface area, and therefore using those definitions will decrease the number of departures counted. For all four definitions of *roadway*, all tires remain on a paved surface, so there is an opportunity to use the full handling capabilities of the vehicle to recover from a loss of control should that occur. However, as one moves farther from the traveled way (for option B and then A), the probability of encountering or crashing into objects to be avoided (e.g., pedestrians, bicyclists) increases. Further, parking lanes, bicycle lanes and shoulders, even though paved, may not be of the same surface quality as the traveled way.

Because the alternative definitions of roadway are so different, phrasing to reinforce the definition used (including usable shoulders, excluding shoulders, etc.) should be provided. For FHWA projects involving roadway departures, use of their definition (option D) is likely to be required and is consistent with existing practice. Where feasible, use of option A (traveled way plus usable shoulders) to count road departures is recommended in addition to option D. Including option B as well is less critical because option B is nearly synonymous with traveled way, and use of the term *traveled way* is preferred.

6.2.6 Paved roadway

Portion of a roadway, including usable shoulders and parking lanes, that is paved with asphalt or concrete or some other similarly rigid material (e.g., brick, cobblestone) 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) usable shoulders that are partially paved, and (4) usable shoulders that are completely paved. As maneuvering is 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) report refers to the "total paved surface width" (Lefler, Council, Harkey, Carter, McGee, and Daul, 2010, p. 26).

6.2.7 Shoulder

Paved or unpaved part of a trafficway that is contiguous with the traveled way for emergency use, for accommodation of stopped road vehicles, and for lateral support of the traveled way structure (Figures 7–9, 11).

NOTE 1: The AASHTO Green Book (2011, p. 4-8) defines the *shoulder* as "the portion of the roadway contiguous with the traveled way that accommodates stopped vehicles, emergency use, and lateral support of subbase, base, and surface courses. In some cases, the shoulder can accommodate bicyclists." The Green Book also provides details on the side slope of shoulder and materials to surface them.

NOTE 2: The *Highway Capacity Manual* (2010, p. 9-17) defines the *shoulder* as that “portion of the roadway contiguous with the traveled way for accommodation of stopped vehicles; emergency use; and lateral support of the subbase, base, and surface courses,” identical to the AASHTO definition, but without the comment on bicyclists (or bike lanes). ANSI D16-2007 (p. 13, definition 2.2.32) defines the shoulder as “that part of a trafficway contiguous with the roadway for emergency use, for accommodation of stopped road vehicles, and for lateral support of the roadway structure,” language very similar to that used in the *Highway Capacity Manual.*

NOTE 3: 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 4: 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 5: 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.

6.2.8 Usable shoulder

Portion of the shoulder, available for the driver to make an emergency stop or for parking.

NOTE 1: This definition is taken from AASHTO (2011, p. 4-8). See Figure 5.

NOTE 2: Parking lanes are part of roadway options A and B.

NOTE 3: The width of the usable shoulder is measured, usually in feet or meters, 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 the beginning of rounding to slopes steeper than 1:4. See the AASHTO Green Book (2011, p. 4-8) for details.

NOTE 4: FHWA recommends but does not require that usable shoulders be paved (U.S. Department of Transportation, 2007). A paved usable shoulder can have a cross slope of 2–6 %.

6.2.9 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.

NOTE: SAE 2808: 2007 and ISO 17361: 2007 define a *lane* as, “the area of roadway that a vehicle would be expected to travel along in the absence of any obstruction without the driver’s desire to change the path of travel” (Society of Automotive Engineers, 2007, p. 4; International Standards Organization, 2007, p. 1). SAE J2808 and ISO 17361 do not define the term *roadway*.

6.3 Trafficway Element Boundaries

Depending on the trafficway element and its design, a boundary could be identified by (1) a painted line, (2) objects abutting the road surface (drainage ditch, curb, gutter, gutter cover), (3) objects extending above the road surface (bridge abutment, tunnel or retaining wall, guardrail, fence, Jersey barrier), (4) a decrease in pavement elevation (drop off), change in cross slope, (5) a change in the traveled way surface material, or (6) other means.

The terms in 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 1: Boundaries may be defined by edges of pavement markings, edge drop offs, changes in paving materials, or barriers such as curbs, gutters, guardrails, bridge abutments, or other roadside appurtenances.

NOTE 2: See 6.2.3.1, 6.2.3.2, and 6.2.3.3 for the three options to define the term *roadway*.

REQUIREMENTS: The first instance the term *roadway boundary* is used in a document, the option used to identify the roadway (A, B, C, or D) 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 vehicles move in a single file in the same direction 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) or some other horizontal surface such as Botts dots. As noted in 10.2.1, the part of a lane marking that defines a departure (the inner edge, centerline, or outer edge) depends on the applicable definition for a lane departure.

NOTE 2: Unpaved traveled ways usually do not have an outside edge line marking or a centerline marking.

NOTE 3: 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 4: For U.S. practice on pavement markings, see Chapter 3 (Markings) in the MUTCD (U.S. Department of Transportation, 2009).

NOTE 5: For European data on national road markings, see ISO 17361:2007, Annex A.

NOTE 6: SAE J2808, definition 3.4, using language from ISO 17361:2007 (also definition 3.4), defines a *lane boundary* as “the borderline of the lane that is determined by a visible lane marking and in the absence of a visible lane marking by incidental visible road features or other means such as GPS, electromagnetic nails, etc. In the case of a visible lane marking, the boundary shall be at the centre thereof” (Society of Automotive Engineers, 2007, p. 4; International Standards Organization, 2007, p. 2).

NOTE 7: Where vertical surfaces such as barriers (e.g., guard rails, Jersey barriers, bridge abutments, tunnel walls, etc.) restrict travel along the vehicle lane, the vertical surface closest to the lane center that actually restricts travel is the lane boundary.

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

6.3.3 Lane expansion

Distance, in inches, centimeters, feet, or meters, computationally added to the lane width(s) for very narrow lanes of a traveled way in order to reduce the number of minor lane departures.

NOTE: For wide vehicles, such as heavy trucks and buses, sometimes their width is almost the legally specified width of a lane of the traveled way (Jahns, 2010, personal communication). In those cases, always maintaining vehicle travel within the specified lane boundary may not be possible. Therefore, in those cases, small departures from the lane boundaries may be accepted because they routinely occur and are likely not safety-relevant. Such departures can also occur for passenger cars if the lanes are very narrow (Dijkstra, Drolenga, and van Maarseveen, 2007; Dijkserthuis, Brookhuis, and de Waard, 2011).

REQUIREMENTS: The amount of lane expansion, if provided, shall be specified for at least four cases: (1) traveled way to an adjacent shoulder, (2) traveled way to adjacent bike lanes and parking lanes, (3) traffic lanes to traffic lanes in the same direction, and (4) traffic lanes into traffic lanes in the opposite direction.

GUIDANCE for Lane Expansion: Artificially increasing lane widths should only be done with great caution. The amount of lane expansion should not alter conclusions about the safety of driving on that traveled way. The amount of lane expansion that is routinely accepted is a matter of local convention. Expansion values are on the order of 5 % to 10 % of the width of the traveled way.

6.4 Terms Relating to Data Types

To be consistent with ISO nomenclature and provide clarity, only the terms *measure, measurement*, and *statistic* are used to refer to data and data collection. The term *metric* is not used because the term is not well defined or consistently used. At various times in the literature, the term *metric* has been used to represent a measurement, a measure, a statistic, or collections of those terms.

6.4.1 Measure

As a noun, a variable, either categorical, integer, or real, that represents the size, amount, or degree of a property of interest.

NOTE: Sometimes a *measure* is called a *channel*.

EXAMPLES: distance gap, time to collision, and lane departure

6.4.2 Measurement

As a verb, the process of collecting the values of a measure; as a noun, a single data point.

NOTE: The International Vocabulary of Metrology (JCGM 2000:2012, p. 16, definition 2.1) defines *measurement* as "the process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity." Furthermore, the term *quantity value* is defined as "the value of a quantity" (definition 1.19, p. 12) and *quantity* is defined as "the property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference" (definition 1.1, p. 2).

6.4.3 Statistic

Attribute that characterizes one or more measurements, typically a single value representing or summarizing multiple measurements.

NOTE 1: Statistics include count, mean, minimum, maximum, sum, standard deviation, and so forth. Examples include mean distance gap, mean time to collision, and the number of lane departures.

NOTE 2: ISO 3534-1:1993, definition 2.45, defines a *statistic* less specifically as "a function of the sample random variables," and notes that "a statistic, as a function of random variables, is also a random variable and as such it assumes different values from sample to sample." The value of the statistic obtained by using the observed values in this function may be used in a statistical test or as an estimate of a population parameter, such as a mean or a standard deviation.

6.5 General Terms for Driver Reactions to Events and Movements

6.5.1 Event

Stimulus in the environment surrounding the driver that leads to a driver response involving steering, braking, or acceleration of the vehicle being driven.

EXAMPLES – An event could be the movement of other vehicles (e.g., braking, accelerating, or merging) or pedestrians, animals or other objects, a change in the state of a traffic signal, a change in environmental conditions (such as a crosswind, ice on the road, etc.), or the onset of a warning sound (or other stimulus).

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

REQUIREMENTS: The number of times drivers do not respond to each type of event shall be reported by event.

GUIDANCE for Event: Some consider no response to indicate an infinite response time, a value not compatible with computing the arithmetic mean time. However, an infinite time can be included in a computation of the mean if the analysis is done using the inverse time.

6.5.2 Reaction time (RT)

Time interval, usually measured in seconds or milliseconds, from onset of an initiating event to the first observable response to that event, such as a movement of the driver's hand (on the steering wheel) or foot (on a pedal or from the floor), or, the beginning or end of an utterance by the driver (for voice-activated controls).

NOTE 1: *Steering reaction time* (9.1.2) is a related term.

NOTE 2: The SAE Glossary of Automotive Terms (1992, p. 121) defines *driver reaction time* as "the time elapsed between the instant the driver perceives a demand for braking and the start of brake application." The Glossary refers to the now cancelled SAE J834a as the source. The Glossary definition is in conflict with the accepted scientific use of the term reaction time and the definition used in this document, which uses the first movement as the endpoint, not brake application. Usually, the foot would be initially resting on the accelerator, so the Glossary definition also includes the time for movement to the brake pedal.

NOTE 3: Although not often used, there may be instances where the reaction is an eye movement or a head movement.

NOTE 4: Reaction time values depend on the salience of the stimuli, the number of stimuli from which the driver is to choose, the probability of each stimulus, and other factors (Hick, 1952; Hyman, 1953; Teichner and Krebs, 1974).

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

6.5.3 Movement time (MT)

Time interval, usually measured in seconds or milliseconds, for the responding foot or hand to move from one location to another.

NOTE 1: Foot movements can start and/or end with foot in contact with the accelerator pedal (option A), the brake pedal (option B), or on neither of these pedals, for example on a dead pedal, in the air, or on the floor (all option N).

NOTE 2: When moving the foot, a driver may unintentionally make contact with another pedal, e.g., accelerator pedal or brake pedal, prior to moving to and applying one of them. If a pedal misapplication occurs, this movement time is added into the total movement time.

NOTE 3: Movement time is determined by the movement distance travelled, the accuracy required at the end location, the extent to which vision is available to guide the movement, as well as other factors (Fitts, 1954; MacKenzie, 1992; Seow, 2005). Most foot movements are not visually guided; they are blind movements and often ballistic in nature.

NOTE 4: *Steering movement time* (9.1.2) is an analogous term involving hand movements of the steering wheel. Head or eye movement times, or vocal response times, are not covered in this document, nor are hand movements to controls.

GUIDANCE for Movement 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 - 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 traveled way.

REQUIREMENTS: The first instance the term *movement time* is used in a document, both the movement start and end points (options A, B, N) shall be reported. For example, the duration of a movement that starts on the accelerator pedal and ends on the brake pedal would be *movement time option AB*.

6.5.4 Response time (RspT)

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

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* (9.1.1) is a related term.

NOTE 3: The abbreviation RspT was chosen to distinguish *response time* from *reaction time* (RT), the abbreviation more common in the psychological literature (e.g., Welford, 1980).

NOTE 4: When there is no movement, the reaction time and the response time are equal.

NOTE 5: When seeking a measure to more generally describe a subject response, the term response time is used. However, in the literature, some mistakenly use the term *reaction time* when the term *response time* should have been used, and vice versa.

REQUIREMENTS: The first instance the term *response time* is used in a document, the initiating event, and the start and end points of the movement shall be reported.

GUIDANCE for Response Time: When a pedal response time is reported but is not defined, the measure is usually brake response time, not accelerator response time, primarily because brake response time is easier to measure and braking is often the intended end response. However, accelerator response time provides a clearer indication of the type response that has occurred. For that reason, reporting the end point is essential.

6.5.5 Types of movement response end points

Movement responses can end in three different ways:

1. initial (at the earliest indication of a response),
2. intermediate (at a point between the initial and final), and
3. final (when the movement stops or reaches a maximum value).

In the common situation of maximum braking starting with the foot on the accelerator pedal, the initial response will be the initial movement to release the accelerator pedal. Intermediate response end points include when accelerator pedal is completely released, when the brake is contacted, and when the brake lights illuminate - this could be an initial movement, if foot was initially on the brake pedal. The final response is when maximum braking occurs. However, if the driver action, starting with the foot on the accelerator pedal, was only to coast down, the initial response would end with the first movement of the accelerator pedal, the final response would be end when the accelerator pedal is completely released, and there would be no intermediate response. These terms are explained in greater detail in the text that follows.

6.5.5.1 Initial driver response

Earliest reliable indication that a driver movement response has begun.

NOTE 1: This term is used to determine the end of driver reaction time and the start of the movement time.

NOTE 2: For pedal movements, the most common initial actions are (1) the foot begins to move off of the floor toward a pedal or (2) the foot is on a pedal and the pedal movement is greater than the normal variation to maintain speed (e.g., going from riding the brake to emergency braking).

6.5.5.2 Intermediate driver response

Reliable indication that a meaningful driver movement response is underway, past the movement start point but not to completion.

NOTE 1: This includes responses such as moving the foot from floor to pedal, or movement of a pedal away from its initial position. It indicates a response is in progress.

NOTE 2: Response times associated intermediate driver responses are collected because: (1) they are easier to collect than alternatives or (2) to provide a connection to other research. For example, determining the brake lamp is on by detecting an electrical signal may be easier than decoding the CAN bus signals that contain information concerning accelerator and brake pedal position.

6.5.5.3 Final driver response

Reliable indication that a pre-determined driver movement response is completed.

NOTE 1: The pre-determined end point is often a value such as maximal or x percent of maximum response. Maximum responses include fully depressing the accelerator or brake, or suddenly and completely releasing the accelerator or brake. Even though drivers may be instructed or intend to respond maximally, they often do not. So, for example, in emergency braking by a particular driver on a particular trial, only 75 % and not 100 % of maximum brake line pressure is often chosen as the movement endpoint. In some instances, the preferred method to identify a maximum response time may involve examining the maximum response of each subject for each trial.

NOTE 2: Whether a particular response is intermediate or final can depend on the context. For example, if the driver has their foot on the accelerator and engages in emergency braking, then foot contact with the brake pedal is an intermediate response. However, if the situation is less urgent, then merely contacting (or tapping) the brake could be the final response.

6.5.6 Perception-response time (PRT)

Time interval, usually measured in seconds or milliseconds, between when an initiating event (e.g., obstacle in the roadway) can be physically sensed and when braking begins.

NOTE 1: This term is often called perception-reaction time in the roadway design and accident reconstruction literature, even though it involves an intermediate movement to the brake, and is more than just reaction time as defined here. PRT includes the time needed to (1) see/perceive the roadway element or obstacle, (2) to complete relevant cognitive operations (e.g., recognize hazard, read sign, decide how to respond, etc.), and (3) initiate a maneuver (e.g., take foot off accelerator and step on brake pedal).

NOTE 2: A major ambiguity in this term is what is meant by “when braking begins.” It could mean (1) response time until brake pedal is contacted, option A (7.2.7), (2) response time until the brake lights illuminate, option A (7.2.8), or (3) when the brake line pressure reaches a point that the vehicle begins to decelerate or when a specified initial deceleration threshold is reached.

NOTE 3: The rationale for including the movement to the brake pedal in the PRT is that during the PRT period the vehicle generally maintains its current speed and trajectory. During the maneuver period the vehicle trajectory or speed changes. This makes PRT a useful measure for designing roadways or analyzing crashes. For example, roadway designers use PRT in their model of stopping sight distances (SSD = PRT distance traveled + braking distance).

NOTE 4: The term PRT has most often been applied to vehicle braking responses. However, some authors have used the term PRT to describe non-braking responses. Campbell, Lichty, Brown, Richard, Graving, Graham, O’Laughlin, Torbic, and Harwood (2012) describe a number of these applications as does Lerner (1994).

REQUIREMENTS AND RECOMMENDATIONS: When the term *Perception-Response Time* (PRT) is used, the initiating event and associated test conditions, as well as the response endpoint shall be clearly defined and reported. Use of the term PRT should be restricted to situations involving an emergency braking response by the driver. Terms defined in section 7 involving brake response times may be used in lieu of PRT as they have more clearly defined response endpoints.

GUIDANCE for Perception-Response Time: The AASHTO Green Book (AASHTO, 2011, p. 111-113) recommends a perception-reaction time of 2.5 s. The Green Book cites research by Johansson and Rumar (1971), who found a mean PRT of 0.66 s when drivers were aware an event might occur (alerted), with 10 percent of drivers having PRT's of 1.5 s or longer (Figure 11). The distribution is roughly log-normal (Figure 11). If drivers were not alerted (such as when responding to an unexpected event), then their response times increased by approximately 1 s. Accordingly, the AASHTO Green Book concluded that the 90th percentile PRT for unexpected braking is approximately 2.5 s. They state that a PRT of "2.5 s is considered adequate for conditions that are more complex than the simple conditions used in laboratory and road tests, but it is not adequate for the most complex conditions encountered in actual driving, such as those found at multiphase at-grade intersections and at ramp terminals on through roadways."

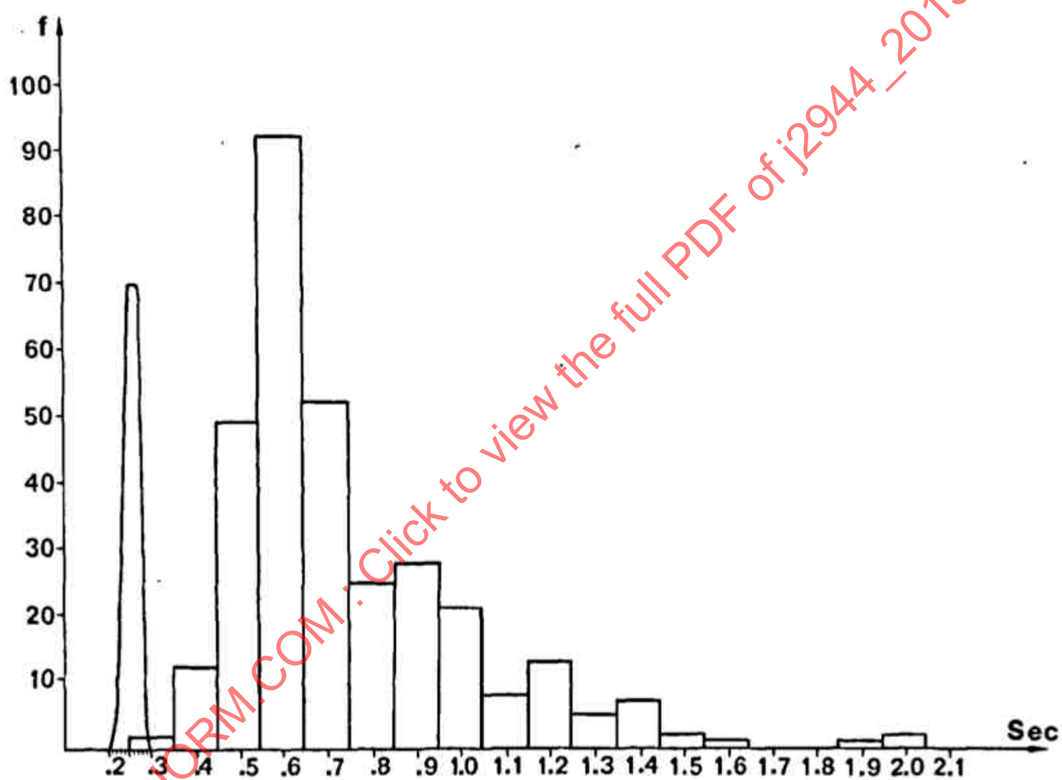

Figure 11 – Perception-response time distribution for 321 drivers
Source: Johansson and Rumar (1971), p. 26

In a study often quoted by accident reconstructionists, Olson and Sivak (1986) had young and older drivers brake in response to a foam block they unexpectedly encountered when cresting a hill. They estimated a median PRT of about 1.1 s to contact the brakes, with a 90th percentile value of about 1.6 s for both young and older drivers (Figure 12). Based on this data, accident reconstructionists often use 1.5 - 1.6 s as the perception-reaction time to an "unexpected" obstacle. The figures provided allow alternative percentiles to be selected.

For a web site on this topic that is regularly updated, see http://www.visualexpert.com/Resources/realprt.html (Let's Get Real about Perception-Reaction Time). See also Muttart (2003a, 2003b), Muttart, Messerschmidt, and Gillen (2005), and Krauss, Todd, and Heckman (2012) for a list of variables that affect PRT and for attempts to develop models to describe or predict PRT based on data from prior empirical studies.

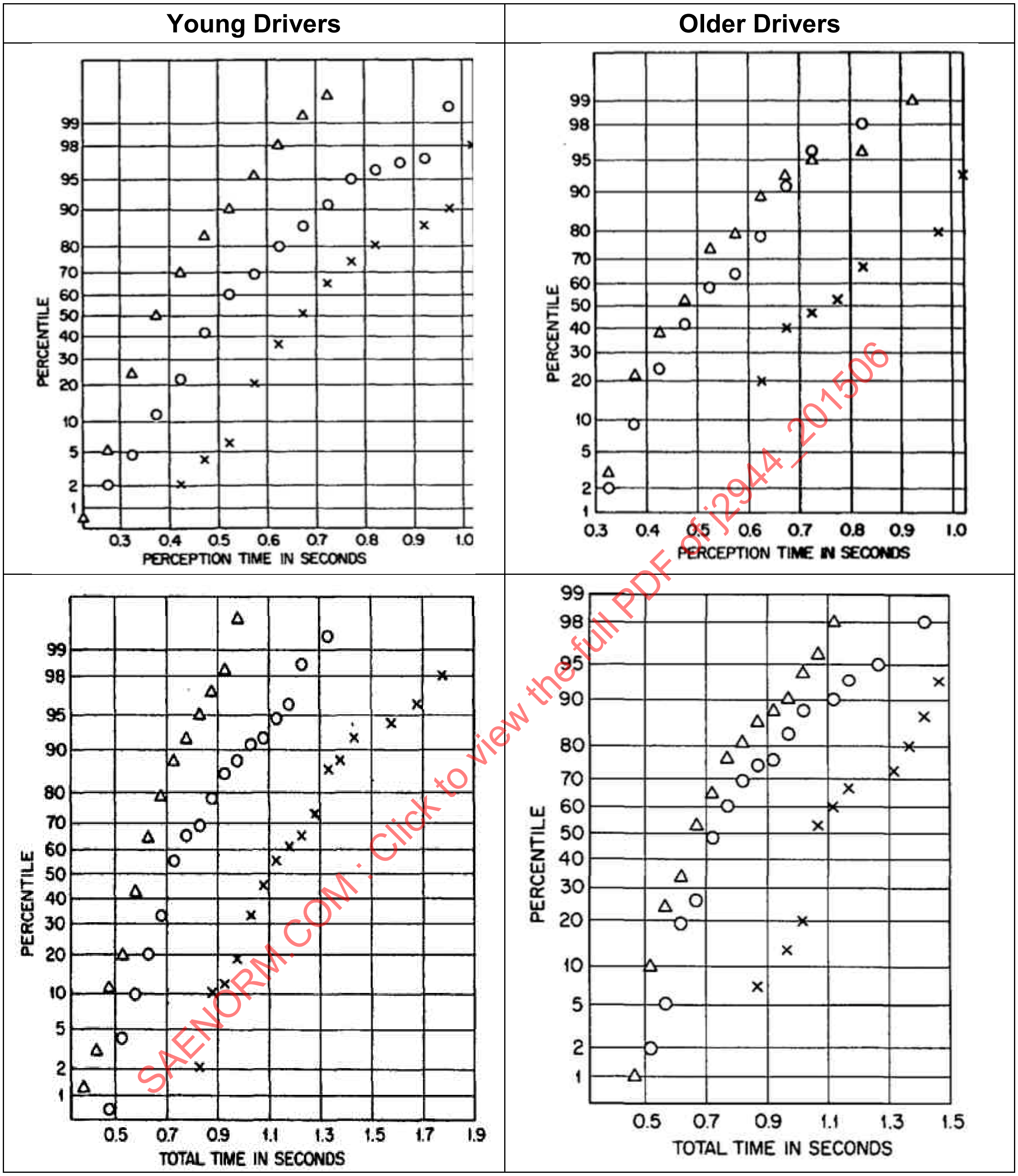

Figure 12 – Normal probability plot for perception time (top row) and PRT (bottom row) for younger and older drivers

X = surprise response to object on road, O = alerted response to object on road,
Triangle = brake in response to light on hood
Source: Olson and Sivak (1986), p. 93-95

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

7.1 Response Time Classification Scheme

7.1.1 Scheme overview

To eliminate ambiguity concerning the specification of pedal responses, this section provides a scheme to identify them. This scheme assumes the driver is responding using one foot, though the scheme can be applied to two-foot responses. Pedal responses are classified in 6.5.5 based on where the foot starts in the response sequence, the location where the foot ends the response sequence, and type of movement being examined (initial, intermediate, or final. It is important to determine the when response first began (the initial response), what response is most convenient to measure (generally intermediate response), and when the ultimate goal of the response has been achieved (the final response).

Pedal responses can start with the foot on the accelerator pedal (option A), on the brake pedal (option B), or in neither location (option N). Option N includes (1) on the floor (likely when a cruise control is engaged) or possibly even resting on a dead pedal (currently only provided for the left foot in left-hand drive cars), and (2) hovering over either the accelerator pedal or the brake pedal. Option N will become more common as vehicles become increasingly automated. See 5.1.1 for details about specifying the foot start point.

If the foot is releasing a pedal, the detectable actions include (1) the initial pedal movement, (2) for the brakes, the brake lights going off, and (3) pedal release. For pressing a pedal the detectable actions are (1) contact with the pedal, (2) for the brakes, the brake light illuminating, (3) some threshold or maximum pedal value being reached, either an accelerator or brake value, or (4) a vehicle acceleration (or jerk) value being reached.

The scheme that follows incorporates those actions into variable names in current use (e.g., response time until accelerator moved), supplemented by an option to indicate the initial location of the foot (A, B, or N) to provide a complete description the driver's response. The complete scheme appears on Table 1. Each of these terms is explicitly defined in the section that follows. It is important to emphasize the focus is on driver responses, either by themselves, or combined with automated functions. See 5.1.6 for guidance concerning automated functions.

At this point, the responses associated with partial release or application of the accelerator or brake are not formally defined because there is no consensus operational definition for those terms, though they are included in Table 1. Examples of such actions include easing up on the accelerator pedal after seeing a vehicle ahead slow down, and accelerating to cross the intersection before the yellow signal changes to red.

Table 1 - Response time measures classification scheme

Foot Position		Driver Response		
Initial action	**Final action**	**Initial Response Time Until…**	**Intermediate Response Time Until…**	**Final Response Time Until…**
on accelerator pedal (Option A)	depress accelerator pedal partial let up or depression of accelerator pedal release accelerator pedal	Accelerator Moved (7.2.1)		75 % Throttle Value, option A (7.2.10) Maximum Jerk while Accelerating, option A (7.2.12) Maximum Accelerator Value, option A (7.2.14) Accelerator Completely Released (7.4)
	move to brake pedal ”maximal” brake	Accelerator Moved (7.2.1)	Accelerator Completely Released (7.2.4) Brake Contacted, option N (7.2.7) Brake Lights On, option A (7.2.8)	75 % Brake Value, option A (7.2.11) Maximum Jerk while Braking, option A (7.2.13) Maximum Brake Value, option A (7.2.15)
	move to not on any pedal 7.1.1.1 vehicle coasts	Accelerator Moved (7.2.1)	Accelerator Completely Released (7.2.4)	The final position may be in the air or on the floor; the exact final position is not important.
on brake pedal (Option B)	depress brake pedal partial let up or depression of accelerator	Brake Moved (7.2.2)		75 % Brake Value, option B (7.2.11) Maximum Jerk while Braking, option B (7.2.13) Maximum Brake Value, option B (7.2.15)
	move to accelerator pedal depress accelerator	Brake Moved (7.2.2)	Brake Lights Off (7.2.8) Brake Completely Released (7.2.5) Accelerator Contacted, option A (7.2.6)	75 % Accelerator Value, option B (7.2.10) Maximum Jerk while Accelerating, option B (7.2.12) Maximum Accelerator Value, option B (7.2.14)
	move to not on any pedal vehicle coasts	Brake Moved (7.2.2)	Brake Lights Off (7.2.9) Brake Completely Released (7.2.5)	The final position may be in the air or on the floor; the exact final position is not important.
not on any pedal (Option N)	move to accelerator pedal depress accelerator	Foot First Moved (7.2.3) As the initial position may be in the air or on the floor, the initial position is often difficult to determine.	Accelerator Contacted, option N (7.2.6)	75 % Accelerator Value, option N (7.2.10) Maximum Jerk while Accelerating, option N (7.2.12) Maximum Accelerator Value, option N (7.2.14)
	move to brake pedal panic brake	Foot First Moved (7.2.3) As the initial position may be in the air or on the floor, the initial position is often difficult to determine.	Brake Contacted, option N (7.2.7) Brake Lights On, option N (7.2.8)	75 % Brake Value, option N (7.2.12) Maximum Jerk while Braking, option N (7.2.13) Maximum Brake Value, option N (7.2.15)

7.1.2 The 1/5/75 rule to identity response movement start or end point

One of the challenges in analyzing response time data is to decide whether to visually analyze when certain pedal responses occurred on a trial-by-trial basis for each movement. Although this can provide a very accurate assessment as to what occurred, the time and cost required to obtain this information may be prohibitive. As an alternative, this section describes some rules of thumb concerning the percentage of maximum response to categorize initial or maximal movements of the destination pedal. A 1 % movement response of the destination pedal is used to define the initiation of destination pedal movement when the foot is not originally on the destination pedal. This also represents the end of the initial foot movement from its origin point, either the floor or another pedal. A 5 % movement response of the destination pedal is used to define the initiation of pedal movement when the foot is originally on the destination pedal. A 75 % movement response of the destination pedal is used to define a maximal movement or the end of the response. *Maximal* not *maximum* is used here, as the approximation does not guarantee it is the largest value, only that is it among the largest values – and a reasonable ending point for the pedal movement. This is called the 1/5/75 rule of thumb to aid in remembering the rule.

7.1.2.1 Initial movement when the foot is not on the destination pedal

The criterion that the destination pedal has moved is a 1 % change in either pedal travel, or some other relevant output signal such as throttle motion for the accelerator pedal or brake pressure for the brake pedal.

NOTE 1: There is not a one-to-one mapping between accelerator pedal travel and the throttle signal. Small initial movements of the pedal can map into large throttle changes to make a vehicle seems peppier. For accelerator travel near maximum, the opposite is true. Likewise for braking, there is not a one-to-one mapping between brake travel and brake pressure. For either pedal, the measure selected for analysis (e.g., accelerator travel or throttle percent) does not matter because the time differences between moving from pedal contact to 1 % of accelerator travel or 1 % of throttle signal are on the order of a few milliseconds, too small to matter.

NOTE 2: The 1 % change can be reliably detected with contemporary sensors and distinguished from signal noise.

NOTE 3: The initial pedal movement could be detected by a contact sensor or microphone, from the throttle signal or brake pressure signal, or by some other means.

7.1.2.2 Initial movement when the foot is on the destination pedal

When the foot is on the destination pedal, the criterion that the destination pedal has moved is a 5 % change in either pedal travel, or some other relevant output signal (e.g., throttle percent, change in brake pressure).

NOTE: The 5 % value was chosen because it allows for reliable separation of the moment-to-moment pedal movements from overt responses to an initiating event.

7.1.2.3 Final movement is maximal braking or acceleration

The criterion for a maximal response of the destination pedal is 75 % of maximum possible response for both the accelerator and the brake.

NOTE 1: For the accelerator, the 75 % can refer to either the percentage of maximum pedal travel or the percentage of maximum throttle signal.

NOTE 2: For the brake, the 75 % can refer to either the percentage of maximum pedal travel or the percentage of maximum brake pressure.

NOTE 3: Determining the threshold for a maximal response requires some consideration as drivers may not actually respond maximally when they need to do so. For example, even if the driver needs to accelerate by “flooring it” or use full braking authority, they may only use some of the vehicle capability. It is for that reason that brake assist systems (Fitch, Blanco, Morgan, Rice, Wharton, Wierwille, and Hanowski, 2010) have been developed. Complicating matters is that sometimes brake assist systems respond sooner than drivers do. Those instances should be treated separately in the data analysis.

Otherwise, the maximum response can be identified by using some value less than 100 % (here 75 %) or by determining the maximum response individually for each driver for each trial.

7.1.3 Final movement is maximum response of each driver

The criterion for a maximal response is the actual maximum response value produced by each driver for both the accelerator and the brake.

NOTE 1: For the accelerator, the measure can be the driver's maximum pedal travel or maximum throttle signal.

NOTE 2: For the brake, the measure can be the driver's maximum pedal travel or maximum brake line pressure.

NOTE 3: Rather than using a percentage of system maximum to identify a response endpoint, the response endpoint can be the actual maximum value produced by a driver. In this case the maximum response has to be uniquely determined on each trial, which is usually much more time consuming than the fixed percentage method.

NOTE 4: This method is most appropriate when the actual maximum pedal response of the driver is itself a measure desired by the experimenter.

7.2 Response Time Measures

7.2.1 Response time until accelerator moved

Time interval, usually measured in seconds or milliseconds, from an initiating event until the accelerator pedal (on which the foot is resting) is moved 5 %, if the movement is in response to that event.

NOTE: That 5 % can refer to either 5 % of maximum accelerator pedal travel or 5 % of maximum throttle signal.

GUIDANCE for Response Time until Accelerator Moved: Reported mean times for *response time until accelerator pedal movement* 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).

7.2.2 Response time until brake moved

Time interval, usually measured in seconds or milliseconds, from an initiating event until the brake pedal (on which the foot is resting) is moved 5 %, if the movement is in response to that event.

NOTE: That 5 % can refer to either 5 % of maximum brake pedal travel or 5 % of the range of the brake pressure.

7.2.3 Response time until foot first moved

Time interval, usually measured in seconds or milliseconds, from an initiating event until the foot (which was not on the brake or accelerator pedal) is moved towards the accelerator or brake pedal, if the movement is in response to that event.

NOTE: The foot could initially be resting on the floor, on a dead pedal or suspended above a pedal.

GUIDANCE for Response Time until Foot First Moved: Because the foot is not resting on a moveable pedal, the time when the foot is first moved will often be determined using video analysis. See 5.1.1 for details.

7.2.4 Response time until accelerator completely released

Time interval, usually measured in seconds or milliseconds, from an initiating event until the foot (initially on the accelerator pedal) is no longer in contact with the accelerator pedal or when the accelerator position signal reaches zero, if the movement is in response to that event.

NOTE 1: For some vehicles, even if the accelerator pedal is completely released, there may be some small residual throttle signal so that a stopped vehicle does not drift backwards excessively when starting to move uphill.

NOTE 2: Position or travel measurements should not be used to determine response time if the accelerator does not return to an un-depressed position when released. In this case, use video recording to determine the foot release point. Data analysts may have to work backward to determine when the final release occurred.

GUIDANCE for Response Time until Accelerator Completely Released: 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 Curry, Greenberg, and Kiefer (2005) and McGehee and Carsten (2010) for use of this measure.

Response time until accelerator pedal completely released is usually determined from the throttle signal on the CAN bus. That signal is also accessible from the OBD-II port.

7.2.5 Response time until brake completely released

Time interval, usually measured in seconds or milliseconds, from an initiating event until either the foot (initially resting on the brake pedal) is no longer in contact with the brake pedal, the brake position signal reaches zero, or the brake pressure signal reaches its resting (undepressed) value, if the pedal movement is in response to the initiating event.

NOTE 1: For most brake systems, the brake pressure is not zero when the brake pedal is not depressed.

NOTE 2: For some brake systems, even if the brake pedal is completely released, some time may be required for the brake pedal to move to the undepressed position. As with the accelerator (7.2.4), video analysis may be required.

NOTE 3: Figure 13 shows an example time history of a driver braking and then releasing the brake. A figure showing brake pressure versus time would be similar in shape although the y-axis would be shifted vertically slightly as the brake system may be slightly pressurized and never zero.

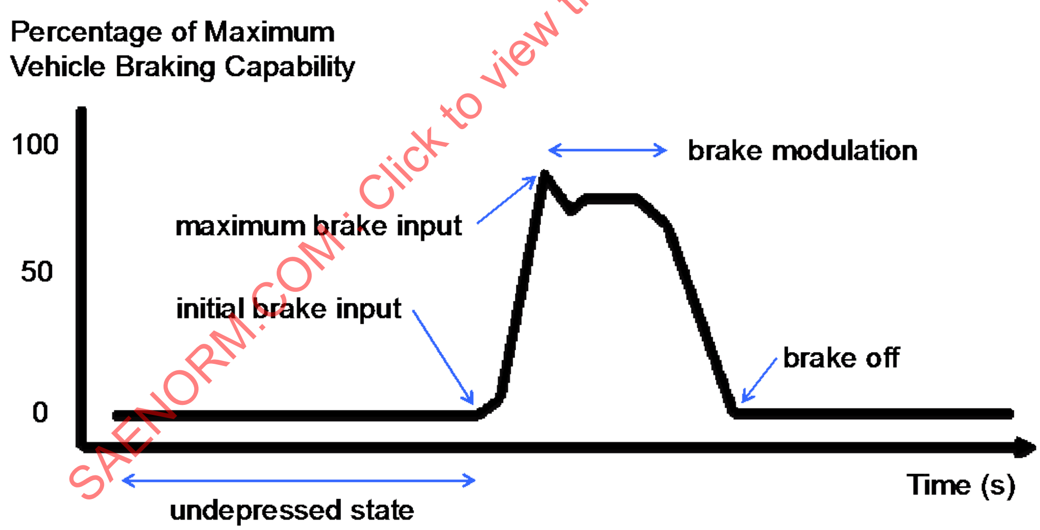

Figure 13 - Example of brake application and release

GUIDANCE for Response Time until Brake Completely Released: Response time until brake completely released is usually determined from the brake pressure signal.

7.2.6 Response time until accelerator contacted

Time interval, usually measured in seconds or milliseconds, from an initiating event until the accelerator pedal is contacted, if the movement is in response to that event.

NOTE: For option N, the foot can start on the floor or be hovering near the accelerator or brake pedal.

REQUIREMENTS: The first instance the term *response time until accelerator contacted* is used in a document, the foot start option (B (on the brake pedal) or N (neither on the brake or accelerator pedal)) shall be reported. See 5.1.1 for details. The data from the two options should be analyzed separately.

GUIDANCE for Response Time until Accelerator Contacted: For data on floor location start points, see McLaughlin and Serafin (1999). The response end point is often determined from the throttle signal on the CAN bus.

7.2.7 Response time until brake contacted

Time interval, usually measured in seconds or milliseconds, from an initiating event until the brake pedal is contacted, if the movement is in response to that event.

NOTE 1: For option N, the foot could be on the floor or hovering near the brake or accelerator pedal.

NOTE 2: Brake pedal contact point may be determined from a video recording, contact switch, brake pedal force sensor, brake line pressure, or by other means. In some cases, the indication of the first contact could be some small amount of displacement, with that amount being system specific.

NOTE 3: Of the various response time end points, this time is one of the most accurate, because contacts between objects can be readily detected.

NOTE 4: The term *brake response time* has been used in the literature to refer to a variety responses described in this document, though it is usually undefined. In the literature, the *brake response time* has meant *response time until brake contacted* (7.2.7), *response time until brake lights on* (7.2.8), *response time until maximum brake value* (7.2.15), or possibly something else. Furthermore, sometimes the term *perception-response time* or more often, *perception-reaction time* is used, especially in crash reconstruction (Triggs and Harris, 1982; Olson and Sivak, 1986; Olson, 2002). See 6.5.6.

REQUIREMENTS: The first instance the term *response time until brake contacted* is used in a document, the foot start option (A - on the accelerator pedal or N - neither on the accelerator pedal nor the brake pedal) shall be reported. See 5.1.1 for details.

GUIDANCE for Response Time until Brake Contacted: This measure may be particularly useful when maximum braking does not occur. For example, drivers may modulate their brake pedal if there is uncertainty in the collision threat (e.g., a lead car is spinning out of control and the driver does not know whether to brake, steer, or both) (Lee, McGehee, Brown, and Reyes, 2002).

As was noted previously, brake pedal contact can be determined acoustically, from video images, from a contact switch, from brake pressure data, or by other means. A typical hydraulic brake system has a maximum value of 1500 psi. To trigger the brake light switch, the pressure usually must reach 60 to 120 psi (414 to 826 kPa) or 4 to 8 % of maximum pressure, though it could be less.

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 (CHMSL) in a driving simulator, Warshawsky-Livne and Shinar (2002) report brake response times of 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 - 2.4 s with a mean of 1.08 s and a median of 0.96 s. The figure they provide suggests the distribution of response times is log normal. For additional data see Kiefer, LeBlanc, Palmer, Salinger, Deering, and Shulman (1999), Krishnan, Gibb, Steinfeld, and Shladover (2001), Najm and Lam (2003), Berndt, Wender, and Dietmayer (2007), Aust, Engstrom, Vistrom, Nabo, Bolling, Hjort, and Kallgren (2011), and Smith, Markkula, Benderius, Wolff, and Wahde (2012).

For related data on the braking performance of vehicles, information useful for predicting crash risk, see Marshek, Cuderman, and Johnson (2002a, b, c).

7.2.8 Response time until brake lights on

Time interval, usually measured in seconds or milliseconds, from an initiating event until the brake lights are illuminated, if the braking is in response to that event.

REQUIREMENTS: The first instance the term response *time until brake lights on* is used in a document, the foot-start option (A - on the accelerator pedal or N - neither on the accelerator pedal nor the brake pedal), the type of brake lamp, and the rise time to 90 % of steady state lamp luminance output shall be reported. See 5.1.1 for details.

GUIDANCE for Response Time until Brake Lights On: The time for a brake lamp to illuminate, and when it is detectable by a driver, depends on the type of lamp. For non-halogen incandescent brake lamps, no measurable light appears until about 50 ms after the voltage is applied, and it typically takes 250 ms for the lamp to reach 90 % of maximum output. For halogen incandescent bulbs, rise times are slightly faster but can still have measurable effects on overall human response times (Flannagan, 2014, personal communication). For all incandescent bulbs, the illumination vs. time function is an ogive. For LED lamps, the rise times to 90 % output are much less than 1 ms, a value too small to affect response time measurements (Flannagan, 2014, personal communication; Sivak, Flannagan, Sato, Traube, and Aoki, 1993).

7.2.9 Response time until brake lights off

Time interval, usually measured in seconds or milliseconds, from an initiating event until the brake lights are extinguished, if the foot is initially resting on the brake pedal and the movement is in response to that event.

REQUIREMENTS: The first instance the term response *time until brake lights off* is used in a document, the type of brake lamp and the fall time to 10 % of steady state incandescent lamp luminance output shall be reported.

GUIDANCE for Response Time until Brake Lights Off: LEDs extinguish very quickly, on the order of a millisecond, a value too small to affect response time measurements. However, incandescent lamps take time to extinguish, reaching 10 % of the illumination of the on state in about 100 ms. The decay is roughly exponential (Flannagan, 2014, personal communication).

7.2.10 Response time until 75 % accelerator value

Time interval, usually measured in seconds or milliseconds, from an initiating event until the accelerator response reaches 75 % of maximum, if the movement is in response to that event.

NOTE 1: See 7.1.3 for the rationale for the 75 % value.

NOTE 2: A common example of this response is when a traffic signal changes to yellow and a driver decides to accelerate through an intersection.

NOTE 3: The accelerator value could be the percentage of maximum accelerator pedal travel, the percentage of maximum throttle signal, or some other signal that describes the accelerator pedal use.

REQUIREMENTS: The first instance the term *response time until 75 % accelerator value* is used in a document, the foot start point (option A - on the accelerator pedal, B - on the brake pedal, or N - on neither the accelerator pedal nor the brake pedal) shall be reported. See 5.1.1 for details. The value that is used (e.g., percentage of maximum accelerator pedal travel, percentage of maximum throttle) shall be reported.

GUIDANCE for Response Time until 75 % Accelerator Value: Alternatives to this measure are *response time until maximum jerk while accelerating* and *response time until maximum accelerator value*. These two measures may provide a more accurate indication of a maximum accelerator pedal response, but are more difficult to determine.

7.2.11 Response time until 75 % brake value

Time interval, usually measured in seconds or milliseconds, from an initiating event until the brake response reaches 75 % of maximum, if the movement is in response to that event.

NOTE 1: See 7.1.3 for the rationale for the 75 % value.

NOTE 2: A common example of this response is when a closely followed vehicle suddenly brakes and the driver has to aggressively brake to avoid a crash.

NOTE 3: The brake value could be percent of maximum brake pedal travel, percent of maximum brake pressure signal, or some other signal that describes the brake pedal use.

REQUIREMENTS: The first instance the term *response time until 75 % brake value* is used in a document, the foot start point (option A - on the accelerator pedal, B - on the brake pedal, or N - on neither the accelerator pedal nor the brake pedal) shall be reported. See 5.1.1 for details. The value that is used (e.g., percentage of maximum brake pedal travel, percentage of maximum brake pressure) shall be reported.

GUIDANCE for Response Time Until 75 % Brake Value: Alternatives to this measure are *response time until maximum jerk while braking* and *response time until maximum brake value*. These two measures may provide a more accurate indication of a maximum brake pedal response, but are more difficult to determine.

7.2.12 Response time until maximum jerk while accelerating

Time interval, usually measured in seconds or milliseconds, from an initiating event until the maximum accelerator jerk, if the movement is in response to that event.

NOTE 1: Jerk is the time derivative of acceleration and is positive if the vehicle is accelerating, negative if decelerating. Specifically, ISO 2041 (2009) definition 1.5, defines jerk as “a vector that specifies the time-derivative of acceleration.”

NOTE 2: This value is determined for each subject for each trial.

NOTE 3: Previously, this measure and other measures related to jerk have not been collected very often (e.g., response time until maximum jerk while braking). However, as comfort issues related to adaptive cruise control and other automated systems supporting longitudinal control become increasingly common, so too will the use of jerk-related measures.

REQUIREMENTS: The first instance the term *response time until maximum jerk while accelerating* is used in a document, the foot start point (option A - on the accelerator pedal, B - on the brake pedal, or N – on neither the accelerator pedal nor the brake pedal) shall be reported. See 5.1.1 for details.

GUIDANCE for Response Time until Maximum Jerk while Accelerating: This measure is appropriate for situations where large changes in longitudinal acceleration can occur. Maximum jerk while accelerating for real vehicles can be determined directly from the speed and acceleration sensors, or more likely from data available on the CAN bus by differentiating the acceleration signal or by twice differentiating the speed signal. For driving simulators, vehicle speed is a default measure, and longitudinal acceleration may be available directly or be determined by differentiation of the speed signal.

Large jerk values increase riding discomfort. However, data on the magnitude of jerk values causing discomfort are limited (Rehnberg, 2008). For studies in which jerk is examined, see Nygard (1999), and Bagdadi and Varhelyi (2011, 2012).

7.2.13 Response time until maximum jerk while braking

Time interval, usually measured in seconds or milliseconds, from an initiating event until the maximum negative jerk, if the movement is in response to that event.

NOTE 1: This value is determined for each subject for each trial.

NOTE 2: See 7.2.12, *response time until maximum jerk while accelerating*, for related notes.

REQUIREMENTS: The first instance the term *response time until maximum individual jerk while braking* is used in a document, the foot start point (option A - on the accelerator pedal, B - on the brake pedal, or N – on neither the accelerator nor the brake pedal) shall be reported. See 5.1.1 for details.

GUIDANCE for Response Time until Maximum Jerk while Braking: This measure is appropriate for situations where large changes in longitudinal deceleration can occur. Maximum jerk while braking for real vehicles can be determined directly from the speed and acceleration sensors, or more likely from data available on the CAN bus by differentiating the acceleration signal or by twice differentiating the speed signal. For driving simulators, vehicle speed is a default measure, and longitudinal acceleration may be available directly or be determined by differentiation of the speed signal.

For studies in which jerk while braking is examined, see Nygard (1999), Bagdadi (2013), Bagdadi and Varhelyi (2011, 2013). For data on jerk while braking and accelerating, see Jensen, Wagner, and Alexander (2011).

7.2.14 Response time until maximum accelerator value

Time interval, usually measured in seconds or milliseconds, from an initiating event until the maximum individual accelerator value, if the movement is in response to that event.

NOTE 1: This value is determined for each subject for each trial.

NOTE 2: The maximum accelerator value could be the maximum accelerator pedal travel, the maximum throttle signal, or some other signal that describes the accelerator pedal use.

REQUIREMENTS: The first instance the term *response time until maximum accelerator value* is used in a document, the foot start point (option A - on the accelerator pedal, B - on the brake pedal, or N - on neither the accelerator pedal nor the brake pedal) shall be reported. See 5.1.1 for details.

GUIDANCE for Response Time until Maximum Accelerator Value: Because this measure is time consuming to determine (potentially requiring visual inspection of each trial of interest to identify local maxima), *response time to 75 % throttle* may be preferred.

7.2.15 Response time until maximum brake value

Time interval, usually measured in seconds or milliseconds, from an initiating event until the maximum individual brake value, if the movement is in response to that event.

NOTE 1: This value is determined independently for each subject for each trial.

NOTE 2: In fixed-base driving simulators (but not motion-based simulators), people tend to accelerate and brake more aggressively than in real driving, so the maximum acceleration values and maximum braking values are greater (McGehee, 2014, personal communication).

NOTE 3: The brake value could be the maximum brake pedal travel, the maximum brake pressure, or some other signal that describes the brake pedal use.

REQUIREMENTS: The first instance the term *response time until maximum brake value* is used in a document, the foot start point (option A - on the accelerator pedal, B - on the brake pedal, or N – on neither the accelerator nor the brake pedal) shall be reported. See 5.1.1 for details.

GUIDANCE for Response Time until Maximum Brake Value: Because this measure is time consuming to determine (potentially requiring visual inspection of each trial of interest to identify local maxima), *response time to 75 % brake value* may be preferred.

7.3 Guidance for Use of Accelerator Pedal and Brake Pedal Measures

Response times are generally reported in seconds (usually to nearest 0.01) or milliseconds, often reflecting the accuracy to which response time is measured. When response time is obtained using video data, accuracy is no greater than the inverse frame rate. See 5.1.3.

When selecting response measures, initial response measures (the earliest indication of a response) and final response measures (the desired pedal movement has occurred) are preferred over intermediate responses because of their safety consequences. However, for practical reasons, *response time until brake contact* or *response time until brake light on* are often used because those terms (1) communicate information to other drivers, (2) are easy to measure in a real vehicle, and (3) are useful in roadway design and crash litigation. Simulators and advanced instrumented vehicles may have more sophisticated methods to measure pedal deflection to determine the time of initial pedal contact.

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 comparing stationary (parked) and while driving response times, see Makishita. and Matsunaga (2008). For a study simultaneously examining multiple measures of pedal responses, see Lerner, Jenness, Robinson, Brown, Baldwin and Llaneras (2011).

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

In analyzing and reporting longitudinal distance measures, values above a user-specified maximum are sometimes excluded from the data set, such as when the lead vehicle is so far away that it has no practical effect on the driving behavior of the following vehicle. See 8.1.10 for details.

8.1 Vehicle Longitudinal State Measures

The arithmetic mean is the statistical measure most often reported for the state measures in 8.1.1 - 8.1.8. These means are not explicitly defined, but guidance for each mean is reported with the state measures. Standard deviations of those measures are often of interest, but only limited guidance is provided in this version. Additional guidance will appear in the next version.

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 Alliance of Automobile Manufacturers *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* (2010, p. 9-8).

NOTE 2: The distance along the traveled way is not always a straight-line distance. See Figure 23 for an illustration of the difference between distance gap and range.

NOTE 3: The two vehicles are usually the subject vehicle and a vehicle immediately ahead in the same lane traveling in the same direction (Figure 14). Often in the literature, but especially for forward crash warning studies, the term *headway* is used when the context indicates *gap* should have been used.

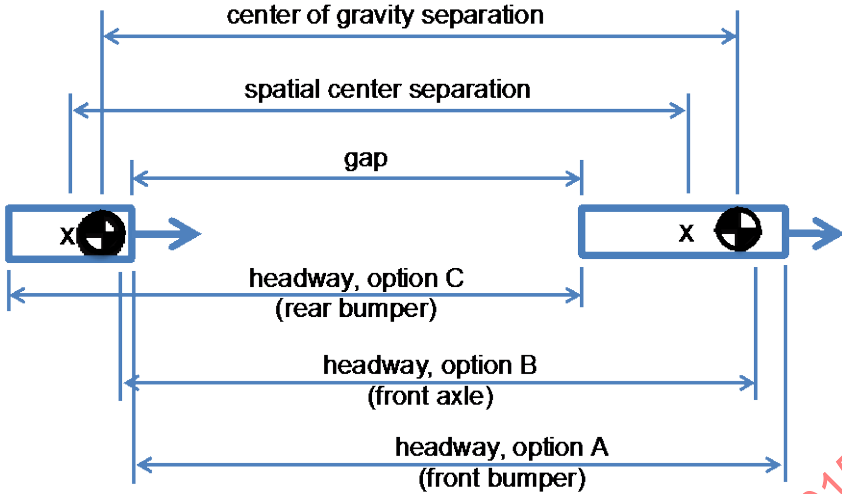

Figure 14 - Longitudinal distance or time measures

NOTE 4: When the gap between vehicles is the straight-line distance (not the distance along a curved section of the traveled way), the term range (8.1.7) can be used.

NOTE 5: Although these measures are intended to apply to vehicle-to-vehicle separation, they could also be applied to vehicle-to-pedestrian and pedestrian-to-pedestrian separation.

NOTE 6: *Distance gap* is called *clearance* in SAE J2399: 2003. The time equivalent of distance gap is time gap, defined in 8.1.2.

NOTE 7: The gap measure that is reported (e.g., distance gap (8.1.1), time gap (8.1.2) or range (8.1.9)) will likely depend on how the gap was determined (ground-based sensors or on-board sensors) and the curvature of the road. For straight roads, distance gap and range are identical.

NOTE 8: When the gaps refer to vehicles immediately ahead of and behind the subject vehicle, the terms front and rear gap are used (Figure 15), though the term following gap has often been used instead of front gap. See Hidas (2005) for use of front and rear gap.

NOTE 9: 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 (called the front and rear gaps), (2) the distance between the subject vehicle and a leading or trailing vehicle in another lane (called the *lead* and *lag gaps*), or (3) the distance gap between two vehicles in a lane adjacent to the subject vehicle, called the *adjacent lane gap* (Figure 15). The gap between the two vehicles in the adjacent lane (adjacent lane gap) is important if the subject wants to change into that lane.

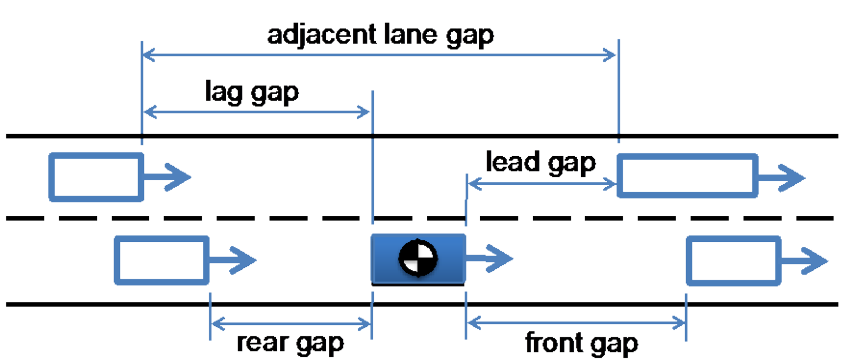

Figure 15 - Gap alternatives in a multi-lane traveled way

NOTE 10: Figure 16 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 (Lee, 2004).

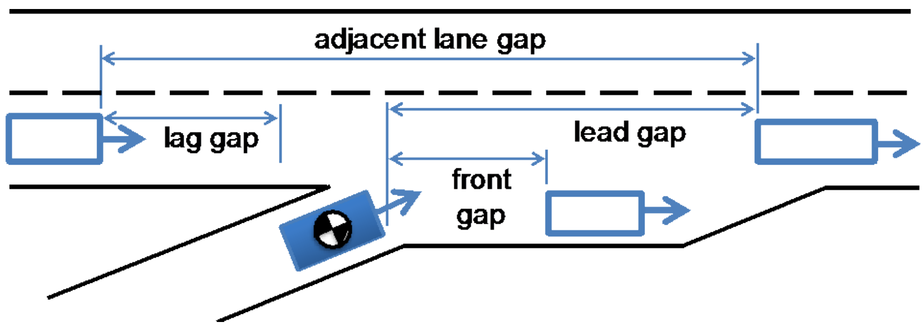

Figure 16 - Merging onto a multi-lane traveled way

NOTE 11: Figure 17 shows the gaps a driver would need to consider when passing a lead vehicle on a two-lane traveled way (Farah, Bekhor, Polus, and Toledo, 2012). When the subject vehicle is in the passing lane, then the gap for merging between the two vehicles in the original lane is the return lane gap.

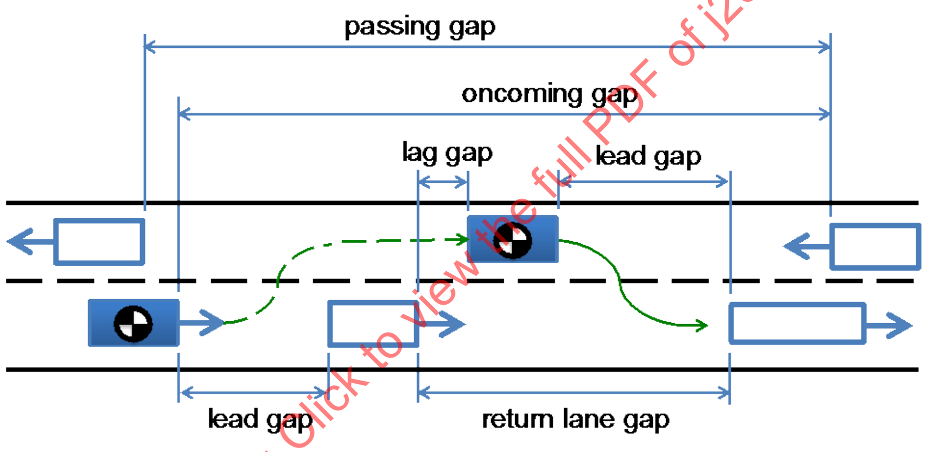

Figure 17 - Passing maneuver on a two-lane traveled way

NOTE 12: The term *gap* can also refer to the distance between the subject vehicle and approaching vehicles in intersecting lanes of travel (Figures 18 and 19). 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 18 and 19 can also be applied for the case of a pedestrian at a crosswalk.

Figure 20 shows an example of a left turning vehicle, where the driver of the subject vehicle is deciding if it's safe to turn left in front of an oncoming vehicle. Oncoming gap has sometimes been referred to as "lag" in the literature (Alexander, Barham, and Black, 2002). For additional information on the use of intersection gap measures, see, Brilion, Koenig, and Troutbeck (1999), Alexander, Barham and Black (2002), Cody, Nowakowski, and Bougler, (2007), and Yan, Radwan, and Guo, (2007).

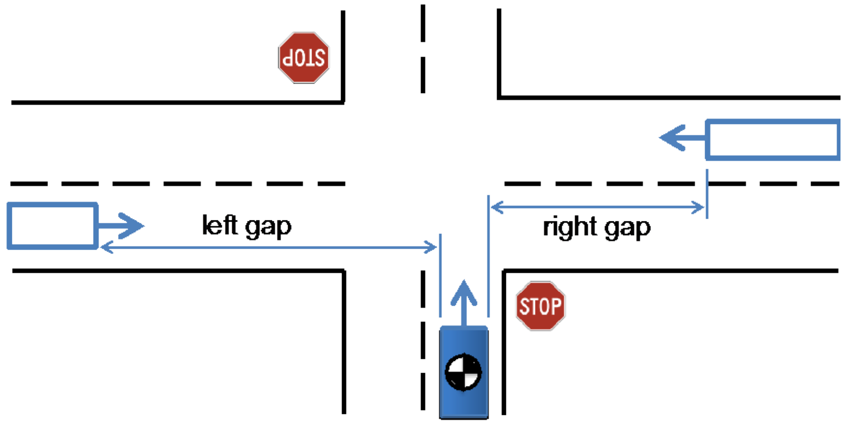

Figure 18 – Gaps when proceeding from stop to cross a right-angle intersection

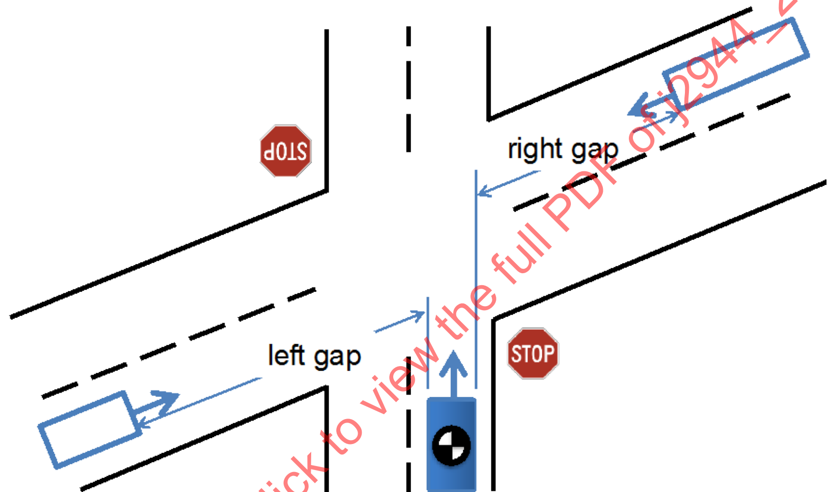

Figure 19 - Gaps when proceeding from stop to cross an angled intersection

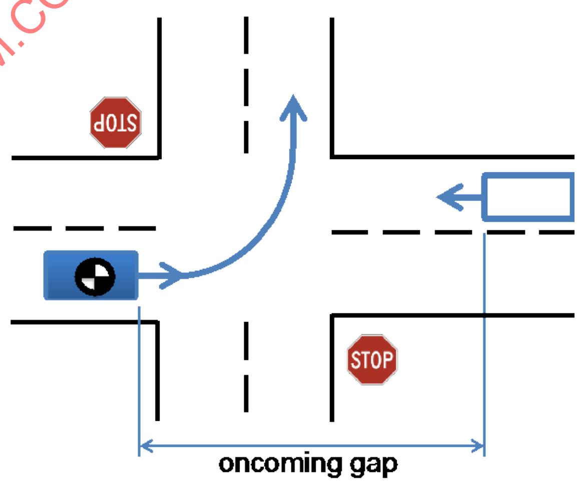

Figure 20 - Gap for left turn across path

REQUIREMENTS: 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

GUIDANCE for Distance Gap: The 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 in front of vehicles traveling perpendicular to the subject's direction of travel (gap acceptance studies) (Gibbs, 1965; Farber and Silver, 1967; McLean, chapter 8, 1989; Cooper and Zheng, 2002; U.S. Department of Transportation, 2010a; Rossi, Gastaldi, Gecchele, and Meneguzzer, 2014). For additional information on gaps in lane changes, see 10.5.1.

Table 2 shows the "average spacing" between vehicles as a function the Level of Service, a categorical indication of the volume of traffic, per Wikipedia. The original source for these data is the 2000 *Highway Capacity Manual*. Level of Service A corresponds to free flow. Level F corresponds to a lack of free flow, and levels B - E correspond to intermediate amounts of traffic flow. For additional information on the definition of Level of Service, see the *Highway Capacity Manual* (Transportation Research Board, 2010) and the AASHTO Green Book (AASHTO, 2011). Furthermore, using the service volume data in the *Highway Capacity Manual* along with assumptions about the relative fractions of car and truck traffic, and the mean lengths of each vehicle type, the mean gap can be estimated as a function of road type (e.g., expressway, urban), number of lanes, and level of service. For information on the factors that influence the distance and time gaps drivers select when following a vehicle, see Kitajima, Marumo, Hiraoka and Itoh (2008) and Wada, Doi, Tsuru, Isaj, and Kaneko (2012).

Table 2 - "Average spacing" (distance gap) between vehicles for highways
Source: modified from http://en.wikipedia.org/wiki/Level_of_service, retrieved May 22, 2012

Level of Service (LOS)	Average Spacing (ft, m)
A	550, 168
B	330, 101
C	220, 67
D	160, 49
E	130, 40
F	highly variable

8.1.2 Time gap

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

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

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

NOTE 3: Time gap is equal to distance gap divided by the speed of the following vehicle, assuming following vehicle speed is constant.

NOTE 4: Time gap can be measured for the scenarios defined in Figures 14-20.

NOTE 5: Consistent with the definition specified herein, SAE J2399:2003, 3.17, defines *time gap* as "time interval for traveling a distance equal to the clearance 'c' to the immediately forward vehicle, given the current vehicle speed." Time gap is represented by the symbol τ.

REQUIREMENTS: 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.

GUIDANCE for Time Gap: There is a considerable body of literature that refers to time headway and related measures (e.g., Mitra and Utsav, 2011). However, if it is measured using radar or LIDAR mounted on the subject vehicle and reflected by the rear of the lead vehicle, what is identified in publications as time headway is actually time gap (if the traveled way is straight).

Some of the most extensive data on time gap appears in Ervin, Sayer, LeBlanc, Bogard, Mefford, Hagan, Bareket, and Winkler, (2005). See Figure 21. Across all of the on-road conditions they examined (speeds greater than 25 mi/hr (40 km/hr)), they reported time gaps ranging from about 0.3-3.0 s with a median of 1.4 s and a mode of about 1.0 s. The distribution of time gaps appears to be log normal. They also provide data that show the effect of driver age and other factors. Michael, Leeming, and Dwyer (2000) show time gaps for urban driving to be between 1.4 and 2.2 s. 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 time gaps in work zones, see Wang, Benekohal Ramezani, Nassiri, Medina, and Hajbabaie (2011).

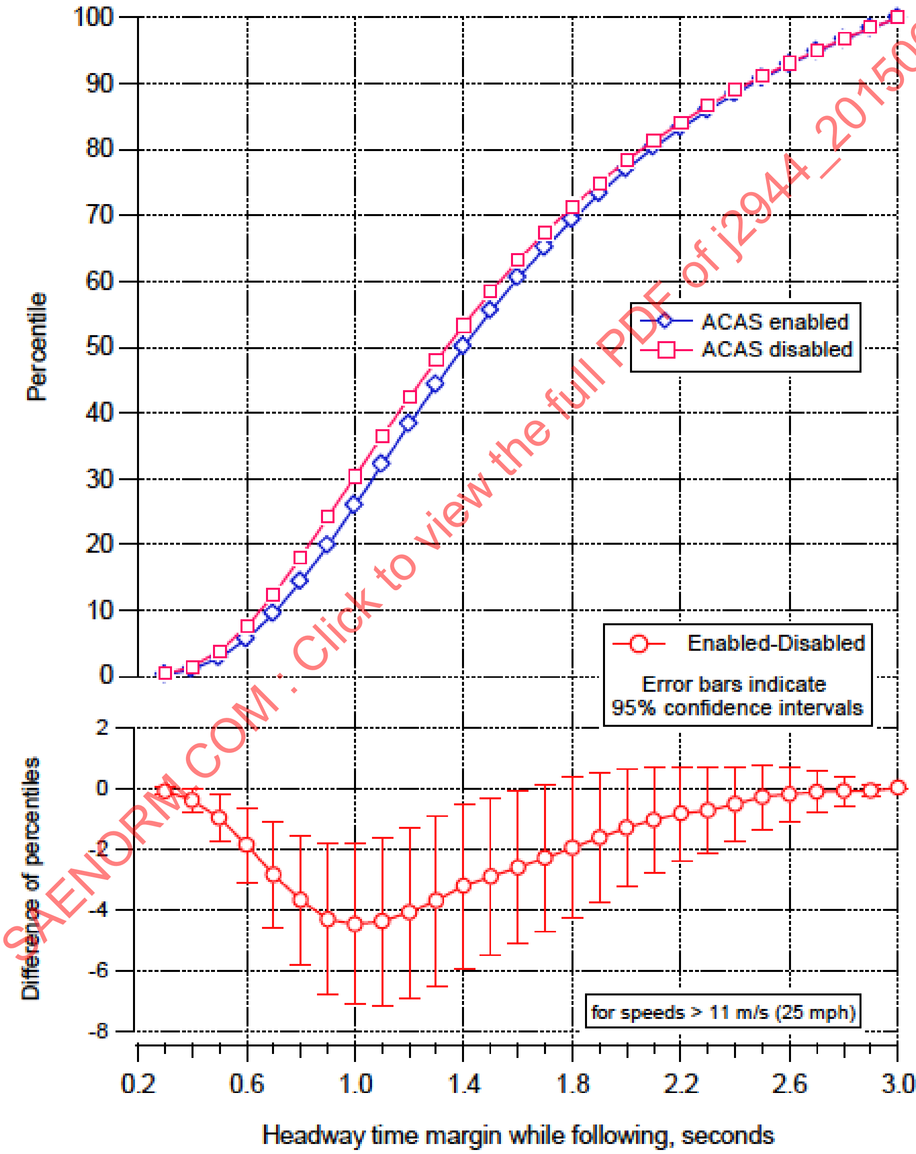

Figure 21 - Time gap distribution

(Ervin et al (2005) refer to time gap as headway.)

Source: Ervin, Sayer, LeBlanc, Bogard, Mefford, Hagan, Bareket, and Winkler (2005), p. 7-6

Of 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 fitted by a Pearson-III, mixed-vehicle-type Generalized Queuing 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 of day (morning, noon, evening). For the use of time gap to estimate crash avoidance, see 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 to deal with the problem posed by very large time gaps when computing a mean value. Another option is to focus on the median time gap. Either option is acceptable.

For data on gaps when driving on real (not simulated) traveled ways, 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 external feature of both vehicles (Figure 14).

NOTE 1: The two vehicles are a subject vehicle and a vehicle immediately ahead in the same lane (Figure 15).

NOTE 2: The three options for the external feature are: (1) the front bumper (option A), (2) the front axle or tires (option B), or the rear bumper (option C).

NOTE 3: The definition presented here is similar to the definition used in the *Highway Capacity Manual* with the added qualification that the common feature is on the outside of the vehicles.

NOTE 4: *Distance gap* and *distance headway* often differ by one "vehicle" length. For option A (front bumper), the difference is the length of the lead vehicle. For option C (rear bumper), the difference is the length of the following vehicle. However, for option B (front axle), the difference is some combination of both vehicle lengths.

NOTE 5: As noted in 8.1.1, the term headway is often erroneously used when gap is the correct term. See Figure 14 and 8.1.10 for the distinction between them.

REQUIREMENTS: The first instance the term *distance headway* is used in a document, the two vehicles in the distance headway measurement, the common external feature (option A, B, or C), and the value above which distance headway is ignored, if any, shall be reported. The method for sensing the distance headway shall also be reported.

GUIDANCE for Headway: The common external feature (option A, B, or C) used for the measurement is usually determined by which sensors are readily available.

Klein, Mills, and Gibson (2006) describe several ways for detecting vehicles passing a particular point. The methods that they and others describe for sensing external features (e.g., video image processing, active and passive infrared beams) can provide accuracy sufficient for human factors studies. Other methods that do not rely on those features (e.g., inductive loops, magnetometers, road tubes, etc.) primarily have value for counting traffic and assessing traffic flow.

There are particular concerns about the accuracy of inductive loops (Nihan, Zhang, and Wang (2002). There are also concerns about the accuracy of magnetometers and road tubes for human factors studies. When road tubes are used, the distance will be measured from front axle to front axle. When light beams are used, the distance will usually be measured from front bumper to front bumper, but it could be from rear bumper to rear bumper.

8.1.4 Time headway

Time interval, usually measured in seconds, separating two vehicles measured between the same common external feature of both vehicles (Figure 14).

NOTE 1: The three options for the common external feature are: (1) the front bumper (option A), (2) the front axle (option B), or the rear bumper (option C).

NOTE 2: This definition was modified from the *Highway Capacity Manual* (2010) to be consistent with the wording of other vehicle separation and headway measures. Specifically, the *Highway Capacity Manual* (2010, p. 9-9) defines *headway* as, "the time between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles (for example, the front axle or the front bumper)."

NOTE 3: Distance headway is equal to time headway multiplied by the speed of the following vehicle assuming the following vehicle speed is constant.

NOTE 4: This term is often used in the traffic 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 to determine the inter-arrival time. Using that procedure, acceleration can be a factor. However, this measure is generally determined when the following vehicle speed is constant, so acceleration is not an issue.

REQUIREMENTS: The first instance the term *time headway* is used in a document, the two vehicles in the measurement, the common external feature (option A, B, or C), and the value above which *time headway* is ignored, if any, shall be reported. The method for sensing the time separation shall also be reported.

GUIDANCE for Time Headway: The time headway distribution of vehicles on a traveled way has received extensive study. For example, Al-Ghamdi (2001) reports that for arterials 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. Ha, Aron, and Cohen (2012) report that gamma-based semi-Poisson and gamma-based Generalized Queuing Models provide good fits to a variety of time headway samples. For other research concerning modeling time headway distributions, see Luttinen (1992, 1996); Neubert, Santen, Schadschneider and Schreckenberg (1999); Cowan (2002); Hoogendoorn (2005); and LeBlanc, Bao, Sayer, and Bogard, (2013).

8.1.5 Center of gravity (CG) distance separation

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 14).

NOTE 1: The phrasing of this definition (but not the reference points) is based upon the definition for *distance gap* in the *Highway Capacity Manual* (2010, p. 9-9).

NOTE 2: The two vehicles are the subject vehicle and a vehicle immediately 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: The important distinction between headway and separation measures is that headway measures (A – front bumper, B – front axle, and C – rear bumper) utilize external physical landmarks on vehicles whereas separations (spatial center, center of gravity) are not based on external physical landmarks. Furthermore, separations are used almost exclusively for driving simulators.

REQUIREMENTS: 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.

GUIDANCE for Center of Gravity (CG) Distance Separation: This measure is only used by driving simulators. In fact, what DriveSafety and Realtime simulators report as *headway* is actually *center of gravity distance separation.*

This makes sense for other simulators as well 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.

8.1.6 Center of gravity (CG) time separation

Time interval, in seconds, for one vehicle's center of gravity to reach the center of gravity of a vehicle ahead (Figure 14).

NOTE 1: The phrasing of this definition (but not the reference points) is based upon the definition for *time headway* in the *Highway Capacity Manual* (2010, p. 9-9).

NOTE 2: The two vehicles are most often the subject vehicle and a vehicle immediately ahead in the same lane.

REQUIREMENTS: 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 Spatial center (SC) distance separation

Longitudinal distance along a traveled way, usually measured in feet or meters, between the geometric center of one vehicle and the geometric center of another vehicle (Figure 14).

NOTE 1: The geometric center is located at the length of the vehicle divided by two and the width divided by two.

NOTE 2: The spatial center and center of gravity can be confused because they tend to be located close to each other, and in some cases may be identical locations.

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

GUIDANCE for Spatial Center (SC) Distance Separation: The NADS MiniSim driving simulator reports the distance between vehicles using their spatial centers as headway.

8.1.8 Spatial center (SC) time separation

Time interval, in seconds, for a vehicle's spatial center to reach the spatial center of a vehicle ahead (Figure 14).

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

8.1.9 Range

Straight-line (vector) distance between two vehicles, usually 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.

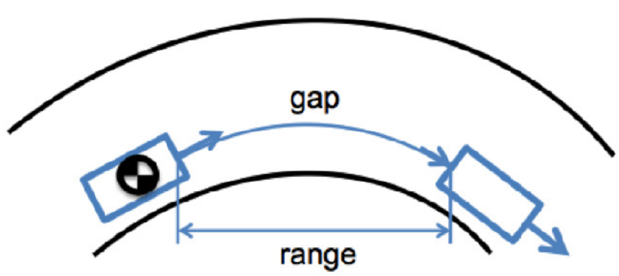

Figure 22 - Gap versus range

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.

REQUIREMENTS: When providing range data, the sensor used, its maximum range, and information about its accuracy shall be reported.

8.1.10 Guidance for longitudinal state measures

Time gap and distance gap, time headway and distance headway, and CG time separation and CG distance separation 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 typically 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 ft, a significant difference. In general, if the topic is drivers responding to lead vehicles, especially stopping, then gap (time or distance) is the preferred measure. If the topic is traffic flow, then headway measures (time or distance) are preferred.

Furthermore, there is a common misperception that simulators measure distance gap, when in fact some measure center of gravity distance separation (Stoner, 2012, personal communication) and others report the spatial center distance separation.

For all of the longitudinal state measures in this section, the most important scenarios occur 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* ranging from 10 - 30 s (or equivalently *distance gaps* of 310 - 930 m or 1020 - 3050 ft). The lead vehicle is too far away in these instances to have any immediate effect on how someone drives. However, the effect of a difference between a 0.5 s versus 1.0 s time gap is substantial. What is "small" depends upon the measurement of interest - crash risk, comfortable following distance or time, and the test conditions - the traffic volume, weather, road geometry, driver age, and many other factors.

In the past, authors have sometimes reported the mean time or distance to vehicles ahead as an 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 have no major impact on the risk of a forward crash or vehicle following behavior. There is no discussion in the literature as to what these cutoff values should be.

However, as a starting point, a reasonable maximum value is the maximum distance than can be reliably sensed by adaptive cruise control and forward collision warning sensors (LIDAR, radar, or video, or some combination of them, depending on the vehicle). In the future, depending on U.S. DOT decisions, that range may be determined by requirements for short-range communications. That distance is also affected by road geometry, traffic, and weather conditions.

To provide some reference points, the LIDAR forward sensors in the Advanced Collision Avoidance System (ACAS) project had a maximum effective range of about 120 m (400 ft). In the Intelligent Vehicle Based Safety System (IVBSS) project, heavy truck radars were reported to have a maximum range of 250 m (820 ft) under good conditions and the radar on cars truncated its reported ranges at 150 m (490 ft). The vision system for the Safety Pilot project worked well out to 100 m (330 ft). To provide another perspective, if one is driving at 70 mi/hr, the total stopping distance, including perception-response time, will approach 400 ft (http://www.csgnetwork.com/stopdistinfo.html). Collectively, this suggests using 120 m (400 ft) as the maximum distance cutoff threshold.

Obviously, for driving simulations, the maximum effective range is infinite, though typically cutoff planes may be at a quarter mile (1320 ft or 400 m) or so. The maximum time can be determined by dividing those distances by the speed traveled.

At the present time, the accuracy of sensors for measuring ranges is approximately ± 1m. Accuracy depends on the amount of metal in the vehicle body, with range estimates for fiberglass body vehicles being less accurate. For data on the radar returns of a number of vehicles, see Buller and Leblanc (2012) and Buller, Wilson, van Nieuwstadt and Ebling (2003).

RECOMMENDATIONS AND REQUIREMENTS: For human factors studies related to crash avoidance, *time gap* and *distance gap* shall be the longitudinal measures reported. For traffic and highway engineering, *time headway and distance headway (with their options, A, B, or C)* should be the longitudinal measures reported. Other measures may be reported as well. When any of these longitudinal measures is 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 if both objects continue on their current paths at their current accelerations.

NOTE 1: TTC is the time period over which the driver (or automated vehicle control system) has to act to avoid a collision.

NOTE 2: The “struck” object is often a lead vehicle, but it could be a crossing vehicle or fixed object (e.g., lamppost, tree, parked car).

NOTE 3: There are two methods to compute time to collision: (1) acceleration and velocity (Option A, 8.2.1.1) and (2) velocity only (Option B, 8.2.1.2). The computation of TTC for both cases appears in Appendix A and is described in van der Horst (1990).

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).

8.2.1.1 Acceleration based TTC (Option A)

Time interval, usually measured in seconds, required for a vehicle to strike an object (usually another vehicle) if the vehicle and object continue on their current paths and accelerations.

NOTE 1: This measurement was first proposed by Hayward (1972). He called it *time-measure-to-collision* and referred to it as a “scale of danger.”

NOTE 2: Kiefer, LeBlanc, and Flannagan (2005) refer to this as *enhanced TTC*. Ozbay, Yang, Bartin, and Mudigonda (2008) refer to *modified time to collision*.

8.2.1.2 Velocity based TTC (Option B)

Time interval, usually measured in seconds, required for a vehicle to strike an object (usually another vehicle) if the vehicle and object continue on their current paths at their current speeds.

REQUIREMENTS: The first instance the term *TTC* is used in a document, the option used (A or B) and value greater than which TTC is ignored shall be reported. When TTC refers to other than the lead vehicle, that vehicle or object shall be reported.

GUIDANCE for Time to Collision: A large value of TTC often indicates a greater degree of safety, but it does necessarily mean driving conditions are safe. For example, if a lead and following vehicle were moving at the same velocity and same acceleration, then TTC would be infinite. However, if the distance gap was small, a sudden deceleration of the lead vehicle could result in a small TTC value and possibly a collision. Furthermore, the crash consequences of various TTC values depend upon the velocities at which the two vehicles are moving. A TTC of 1 s at 10 mi/hr (16 km/hr) has very different safety consequences versus the same TTC value at 70 mi/hr (113 km/hr). This suggests that the cutoffs for the maximum range, headway, and gap, as well as the cutoff for TTC need to be considered together.

What are typical TTC values? 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).

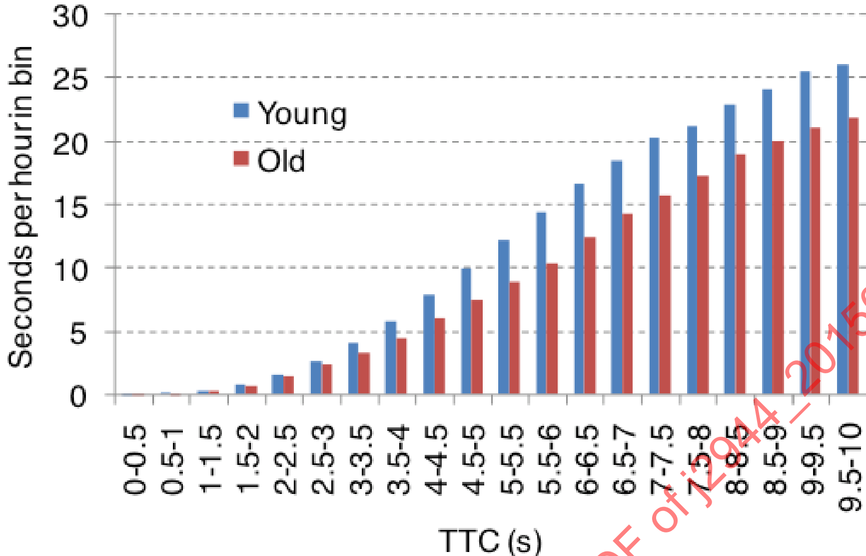

Figure 23 - Distribution of TTC from 0 - 10 seconds
Source: McLaughlin, Hankey, and Dingus (2009), p. 410

TTC can be calculated at any time during a response. McGehee, Brown, Lee, and Wilson (2002) collected data from several cut-in crash scenarios on a limited access traveled way. They reported the TTC was 2.56 s to accelerator release when no warning was provided (and 3.18 and 2.27 s for various warnings) and 2.38 s at final accelerator release (and 2.88 and 2.52 s for various warnings), values that are much less than when just driving in traffic.

In some cases, what may be most useful is not a point estimate (e.g., a mean of TTC), but the probability distribution of TTC values. For those values, see Berthelot, Tamke, Dang, and Breuel (2012).

Is option A (including acceleration) or B (velocity only) preferred? Option A is the recommended option for computing TTC. Option A is used most often and is specifically referenced in several publications (Godthelp and Koning, 1981; Godthelp, Milgram, and Blaauw, 1984; van der Horst and Hogema, 1994; van der Horst, 1990). The difference between the two options depends on the extent to which the vehicles in question are accelerating/decelerating, which is usually minimal in car following, but substantial in crash avoidance situations.

How can filtering improve TTC data? Chen, Das, and Bajpai (2009) show how an interacting multiple model-based (IMM) Kalman filter can be used to improve the quality of TTC data by reducing the effect of errors in the distance estimates.

Above what value should TTC be ignored? There is no general agreement as to what that value should be. Ostlund, Nilsson, Tornros and Forsman (2006) ignore TTCs in excess of 15 s, though as was noted earlier in this section, TTC and gap need to be considered jointly when assessing safety (Figure 24). In brief, when drivers are following a lead vehicle, drivers make decisions about their speed and following distance based on crash risk. When a vehicle ahead is close (the gap is small), the driver is primarily concerned about having enough time to stop should the vehicle ahead suddenly brake. As either the gap or TTC increases, the movements of the lead vehicle become less important, as reflected in the hypothesized tradeoff function shown in Figure 24. At some point (proposed here as a gap of 200 m, the maximum detection range of on-board sensors), the lead vehicle is so far away that drivers may ignore it. All of this is likely to depend on road geometry, traffic, and individual differences as is the case for many measures of driving performance.

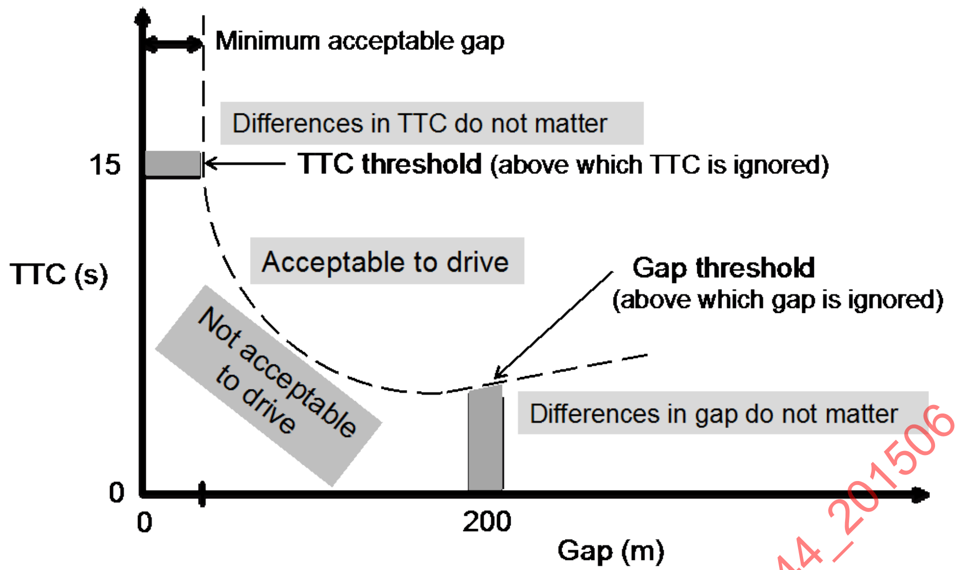

Figure 24 – Hypothetical tradeoff between gap and TTC including areas of indifference

Larger TTC values are often censored because of their effect on the calculation of mean and standard deviation of TTC, and secondarily for determination of TTC percentiles. If the velocities and accelerations of the lead and subject vehicle are closely matched, TTC values are very large (e.g., 15). Keeping these large values in the derived TTC statistics could cause misleading conclusions about driver behavior.

What other studies should be examined? For open road driving, Van der Horst and Hogema (1993) provide extensive data for TTC from both simulator and on-road studies, for both approaching and following other vehicles. For an intersection, Vogel (2003) provides extensive data looking at the relationship between TTC and headway measures, two primary measures of crash risk. In contrast, Archer (2005) and Lundgren and Tapani (2006) examined TTC using simulation. Balas and Balas (2006) provide a complementary perspective, examining the relationship between TTC, crash risk, and traffic flow. Similarly, Schmidt, Khanafer, and Balzer (2009) provide data on the relationship between TTC, urgency of response, and lead vehicle speed.

For noteworthy studies in which TTC was a dependent measure, see Gettman and Head (2003). Kusano and Gabler (2011) refer to its use for crash avoidance and Ostlund, Nilsson, Tomros, and Forsman (2006) describe research concerning using TTC assess cognitive load (and distraction). In contrast to the previous studies, Bachmann, Roorda, and Abdulhai (2011) provide specific data for medium and heavy trucks on “truck-only highway” in greater Toronto, Canada.

8.2.2 Minimum time to collision (Minimum TTC, TTC_{min})

Minimum time, usually measured in seconds, during an encounter with another vehicle or object required for one vehicle to strike another vehicle (or object).

NOTE 1: The encounter can be (option 1) a specific braking event (Donmez, Boyle, and Lee, 2010) or (option 2) more generally, as any type of traffic conflict in which the vehicle is on a collision course with another object (Ostlund, Nilsson, Tomros, and Forsman, 2006; Sayed and Zein, 2007). Sometimes this first option is represented as TTCbr (van der Horst and Hogema, 1994). Figure 25 illustrates TTC_{min} for the second option.

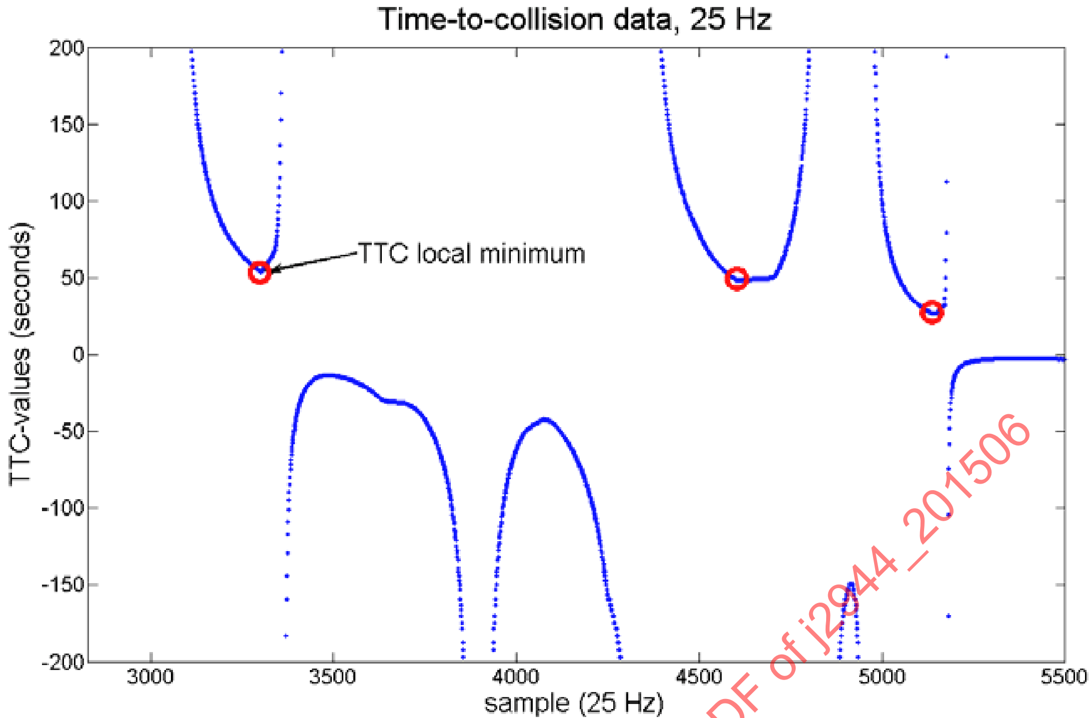

Figure 25 - Minimum time to collision
Source: Ostlund, Nilsson, Tomros, and Forsman (2006), p. 15

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

REQUIREMENTS: The first instance the term *minimum TTC* is used in a document, (1) how TTC is computed (option A – acceleration and velocity, option B – velocity only) (2) what constitutes an encounter (option 1 – a specific braking event, option 2 – any type of conflict), and (3) the value greater than which *TTC* is ignored shall be reported. When TTC refers to other than the lead vehicle, that vehicle or object shall be reported.

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

8.2.3 Minimum adjusted time to collision (Adjusted TTC)

Minimum time, usually measured in seconds, during an encounter with another vehicle or object required for one vehicle to strike another vehicle (or object) or, if striking occurs, the relative velocity at collision (as a negative value) divided by the mean acceleration at the point of collision (indicating collision severity).

NOTE 1: The adjustment to deal with striking vehicles distinguishes minimum TTC from minimum adjusted TTC and provides some advantages because the adjusted TTC is a continuous value applicable for all encounters, not just those where there is no crash.

NOTE 2: A negative value of minimum adjusted TTC indicates how much sooner a vehicle would have had to brake to avoid a collision.

NOTE 3: This term was defined by Lee, McGehee, Brown, and Reyes, (2002) (p. 317, 328) with the Brown (2007), p. 42 definition often being cited 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. This definition and the computation of minimum adjusted time to collision appear in Appendix C.

REQUIREMENTS: The first instance the term *minimum adjusted TTC* is used in a document, (1) how TTC is computed (option A – acceleration and velocity, option B – velocity only) (2) what constitutes an encounter (option 1 – a specific braking event, option 2 – any type of conflict), and (3) the value greater than which TTC is ignored shall be reported. When TTC refers to other than the lead vehicle, that vehicle or object shall be reported.

GUIDANCE for Minimum Adjusted Time to Collision: This safety-benefit statistic is particularly useful where the outcomes of a series of events (1) 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)

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

NOTE 1: Minderhoud and Bovy (2001) originally defined this term. Appendix D describes the computation of *time exposed time to collision.*

NOTE 2: There are two time thresholds, (1) the time greater than which TTC is ignored (a maximum), and (2) an exposure threshold considered to be the boundary identifying safety-critical approaches. TTC values below the exposure threshold are considered as safety-critical. The exposure threshold is used to compute TETTC.

NOTE 3: *Time exposed time to collision* is sometimes abbreviated as TET in the literature.

REQUIREMENTS: The first time the term *time exposed TTC* is used in a document, (1) how TTC is computed (option A – acceleration and velocity, option B – velocity only), (2) what constitutes an encounter (option 1 – a specific braking event, option 2 – any type of conflict), (3) the value greater than which *TTC* is ignored, and (4) the exposure threshold shall be reported. When TTC refers to other than the lead vehicle, that vehicle or object 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 roadways. 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 exposure threshold because "traffic situations less than 4 s are considered to be dangerous" (Kassner (2008), p. 330). Van Driel, Hoedemaeker, and Van Arem (2007) used TTC values below 4 s as the exposure threshold, and ignored TTC values greater than 20 s. Ostlund et al. (2004) also used 4 s as the exposure threshold. Hirst and Graham (1997) considered 3 s to be an adequate level for discriminating dangerous approach situations from acceptable situations.

Thus, for TET, 3 - 4 s is a reasonable initial recommendation for an exposure threshold. There is some difference of opinion as to what the maximum time threshold should be. Considering the above studies, the maximum threshold is observed to be three to five times the exposure threshold.

For data on the relationship between TET and road geometry, see Bella and D'Agnostini (2010). For additional studies in which TET was a dependent measure, see Jamson, Batley, Portouli, Papakostopoulos, Tapani, Lundgren, Huang, Hollnagel and Janssen (2004).

8.2.5 Time integrated time to collision (TITTC)

Weighted time interval, usually measured in seconds, over which the *time to collision* is less than some exposure threshold, with times 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). The computation of integrated time to collision is given in Appendix E.

NOTE 2: *Time integrated time to collision* is sometimes abbreviated as TIT in the literature. The abbreviation TITTC is used here to be consistent with how other TTC related terms are represented.

REQUIREMENTS: The first instance the term *time integrated TTC* is used in a document, (1) how TTC is computed (option A – acceleration and velocity, option B – velocity only) (2) what constitutes an encounter (option 1 – a specific braking event, option 2 – any type of conflict), (3) the value greater than which *TTC* is ignored, and (4) the exposure threshold shall be reported. When TTC refers to other than the lead vehicle, that vehicle or object shall be reported.

GUIDANCE for Time Integrated Time to Collision: This measure indicates exposure to various TTC values and is used less than minimum TTC. Curiously, inverse TTC has repeatedly been shown to be an important measure of exposure to crash risk (e.g., Gettman and Head, 2003; Oh and Kim, 2010), but Time Integrated Inverse TTC, a relevant exposure measure, has yet to be used.

Generally the values of TITTC are highly correlated with TTC, but there are times when TITTC 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. For additional examples in which TITTC served as a dependent measure, see Jamson, Batley, Portouli, Papakostopoulos, Tapani, Lundgren, Huang, Hollnagel and Janssen (2007).

8.2.6 Inverse time to collision

Reciprocal of *time to collision*, usually measured in inverse seconds

NOTE 1: The object is often a lead vehicle, but it could be a crossing vehicle or fixed object (e.g., lamp post, tree, parked car).

NOTE 2: There are two methods to compute the *inverse time to collision*: (1) based on velocity and acceleration (Option A, 8.2.1.1) and (2) based on velocity only (Option B, 8.2.1.2).

NOTE 3: The computation of TTC for both cases appears in Appendix A and is described in Van Der Horst (1990).

NOTE 4: Inverse TTC is an important indicator of the risk of a collision (Kondoh, Kitazaki, Kuge, and Boer, 2008) for three reasons. First, as the driver approaches a distant lead vehicle traveling at a constant velocity, the visual angle subtended by the lead vehicle will steadily increase prior to undergoing a rapid expansion when nearing a collision, called “visual looming” of the approaching object (Lee, 1976; Summala, Lamble, and Laasko, 1998; Groeger, 2000; Kiefer, LeBlanc, and Flannagan, 2005). Second, the inverse TTC measure appears as a term in the time derivative of required deceleration to avoid a collision. Third, the Evans and Rothery (1974) in-traffic study found inverse TTC to be a robust measure for describing driver’s judgments of whether the spacing to the lead vehicle was closing or opening under near threshold, relative speed conditions.

REQUIREMENTS: The first instance the term *inverse time to collision* is used in a document, (1) how TTC is computed (option A – acceleration and velocity, option B – velocity only) (2) what constitutes an encounter (option 1 – a specific braking event, option 2 – any type of conflict), and (3) the value greater than which *TTC* is ignored shall be reported. When inverse TTC refers to other than the lead vehicle, that vehicle or object shall be reported.

Guidance for Inverse Time to Collision: Kiefer, LeBlanc, and Flannagan (2005) report findings from an experiment in which drivers following a lead vehicle were asked to brake and/or steer at the last possible moment to avoid a crash, by braking normally and by braking hard. The lead vehicle could be stationary, decelerating (-0.15 g or -0.39 g), or moving at a constant speed less than the subject vehicle (moving-braking). As shown in Figure 26 for the -0.39 g (hard braking) scenario, inverse TTC values ranged from approximately 0.2 - 0.6 s^{-1}.

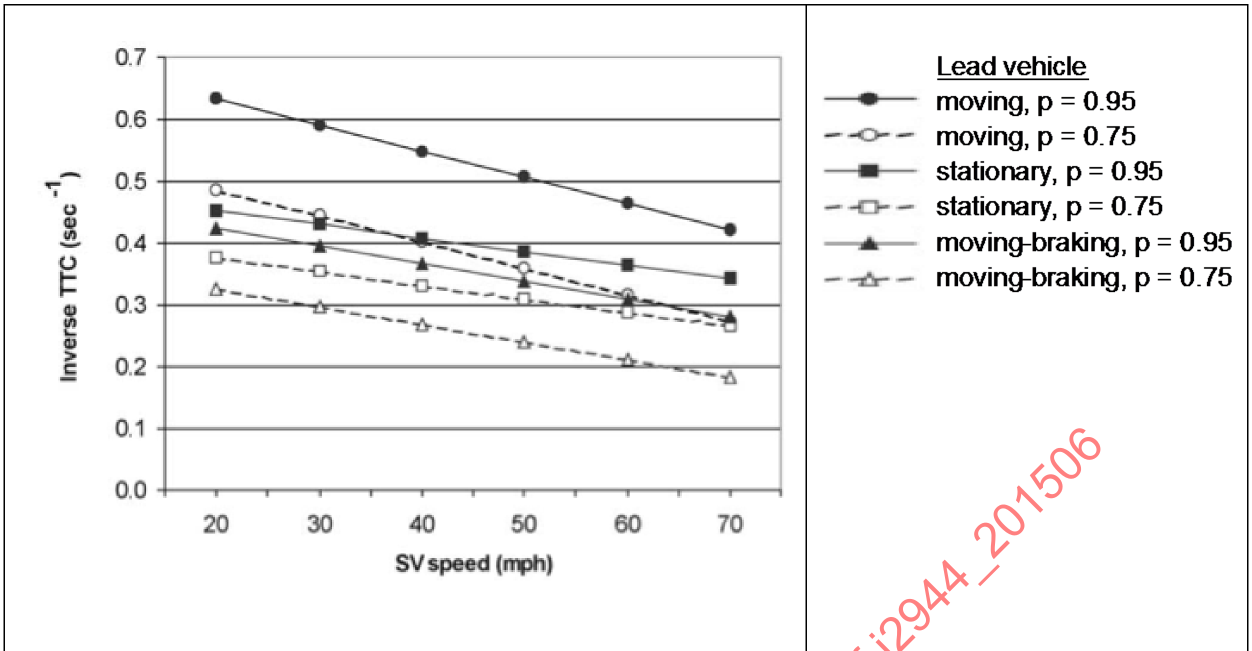

Figure 26 - Inverse TTC versus speed of subject vehicle in hard braking scenario
Source: Kiefer, LeBlanc, and Flannagan (2005), p. 301

8.2.7 Required deceleration

Amount of constant deceleration, usually measured in g's (or m/s^2, ft/s^2), required of the subject vehicle to avoid a crash, if that vehicle instantaneously decelerated (Figure 27).

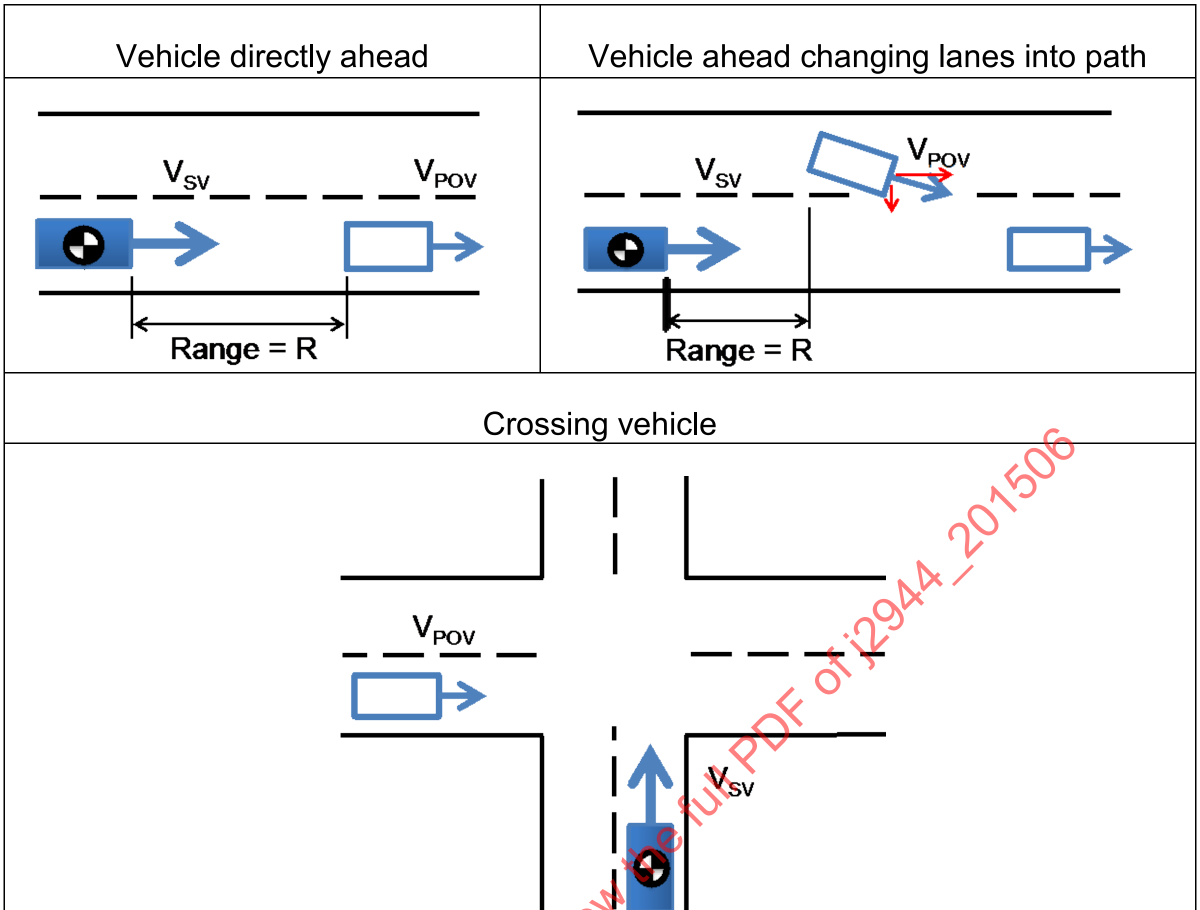

Figure 27 - Three cases of required deceleration

NOTE 1: Although required deceleration is normally applied with respect to a lead vehicle at the time when a vehicle brakes, the term could apply at any time to any vehicle on any intersecting path (such as a vehicle changing lanes or crossing at an intersection) or to a fixed object. This broader definition makes the term *required deceleration* consistent with the use of the term *time to collision*. Table 3 gives the equations for the directly ahead case and Figure 26 shows examples of the directly ahead, lane change, and crossing vehicle cases. The vehicle applying the brakes is assumed to be traveling in a straight line along the path of the lane. The calculation is only valid at the point where the principle other vehicle (POV) enters the path of the subject vehicle. The original variable names are used in Table 3 to be consistent with the research on which they are based. See Table 4 for definitions.

Table 3 - Quantities related to required deceleration

Modified from: Kiefer, Flannagan, LeBlanc, Palmer, Deering, and Shulman (2003), p. 42

Quantity	Variable	Time derivative, i.e., $\frac{d}{dt}$(Variable)
Range	R	$-\Delta V = V_{POV} - V_{SV}$
Closing speed	$\Delta V = V_{SV} - V_{POV}$	$\Delta a = a_{SV} - a_{POV}$
Time-To-Collision or TTC (assuming both vehicles maintain current speed)	$TTC = \frac{R}{\Delta V}$	$-1 - TTC \cdot \frac{\Delta a}{\Delta V}$
Required deceleration to avoid impact, assuming constant accelerations of both vehicles	$a_r = a_{POV} + \frac{\Delta V^2}{-2R}$, when $R \le \frac{\Delta V \cdot V_{POV}}{-2a_{POV}}$	$\frac{d}{dt}(a_r) = \frac{-\Delta V}{R}\left(\Delta a + \frac{\Delta V^2}{2R}\right) = \frac{1}{TTC} \cdot (a_r - a_{SV})$
Required deceleration to avoid impact, assuming constant acceleration of both vehicles	$a_r = \frac{-V_{SV}^2}{2\left(R + \frac{V_{POV}^2}{-2a_{POV}}\right)}$, when $R > \frac{\Delta V \cdot V_{POV}}{-2a_{POV}}$	$\frac{d}{dt}(a_r) = \frac{2}{V_{SV}} \cdot a_r(a_{SV} - a_r)$

Table 4 - Variable definitions for required deceleration

Type	Abbreviation	Name
primary	a	acceleration
	R	range between 2 vehicles
	TTC	time to collision
	V	velocity
subscript	SV	subject vehicle
	POV	principal (primary) other vehicle (usually lead vehicle)
	r	required
	t	time

NOTE 2: Kiefer, Cassar, Flannagan, LeBlanc, Palmer, Deering, Shulman (2003, p. 11) define *required deceleration* as “the constant deceleration level required for the driver to avoid the crash at braking onset. This measure was calculated by using the current speeds of the driver’s vehicle and the lead vehicle, and assuming the lead vehicle continued to slow at the prevailing deceleration value.” Similarly, Kiefer, Flannagan, LeBlanc, Palmer, Deering, and Shulman (2003, p. 14) refer to the “constant deceleration level (in g’s) required for the driver to avoid colliding with the lead vehicle at the point of braking or steering onset” and Kiefer, LeBlanc, and Flannagan (2005 p. 298) refer to “the constant deceleration level (in *g*) required for the driver to avoid colliding with the lead vehicle at maneuver onset.” The definitions are essentially the same, just expressed differently.

GUIDANCE for Required Deceleration: Kiefer, Cassar, Flannagan, LeBlanc, Palmer, Deering, Shulman (2003), reporting research from the CAMP (Collision Avoidance Metrics Partnership) project, found that when both vehicles were moving at the same speed, that mean required deceleration values ranged from 0.15 - 0.3 g, and for hard braking of the lead vehicle the values were 0.3 - 0.4 g. The required deceleration value depended upon whether the lead vehicle was stopped or moving and whether the driver braked normally or hard (waiting until the last possible moment to brake to avoid a collision) (Figure 28). They also found that across a wide range of vehicle-to-vehicle kinematic conditions, the 95th percentile required deceleration values under "normal" last-second braking instructions corresponded very closely to the 50th percentile (and the mean) required deceleration values under "hard" last-second braking instructions. They concluded, "These results provide strong evidence against a FCW timing approach that assumes a fixed driver deceleration value across kinematic conditions. Such a fixed deceleration approach (or for that matter, a fixed TTC approach) is likely to result in predictions of the driver deceleration parameter that are perceived by the driver as inappropriate under a wide range of vehicle-to-vehicle kinematic conditions." (p. 299).

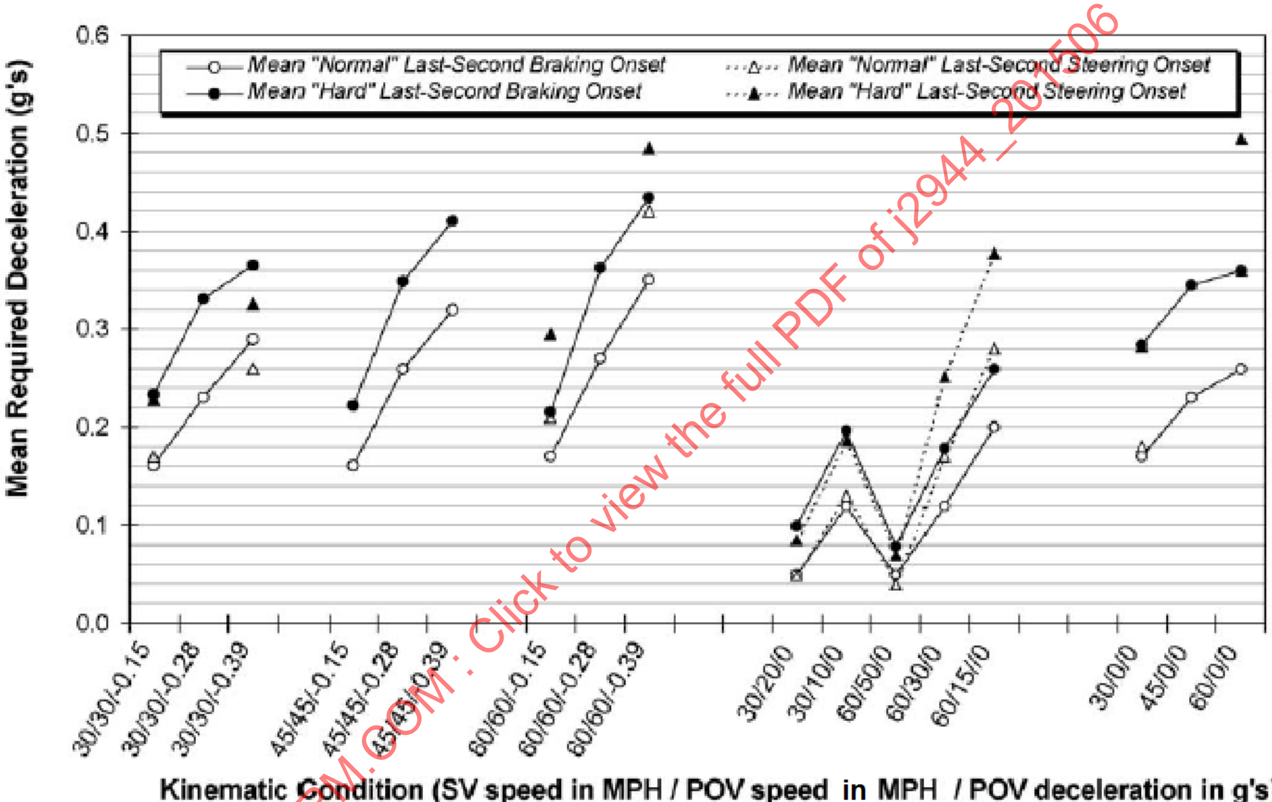

Figure 28 - Last-second braking data from CAMP
Source: Modified from Kiefer, LeBlanc, and Flannagan (2005), p. 300

The 1999 (Kiefer, LeBlanc, Palmer, Salinger, Deering, and Shulman, 1999) and 2003 (Kiefer, Cassar, Flannagan, LeBlanc, Palmer, Deering, Shulman, 2003) studies led to two equations which differ very slightly in their predictions of required deceleration for hard braking. The coefficients of the 2003 equation are as follows.

Required deceleration (g) = -0.164 + 0.668(lead deceleration in g's) - 0.00368(closing speed in mi/hr) + 0.078(indicator variable, =1 if lead moving)

(Source: Kiefer, Cassar, Flannagan, LeBlanc, Palmer, Deering, and Shulman, 2003, p. 30)

Required decelerations for lane changes in Beijing are provided in Zhang and Wang (2006) and Li, Men, Zhang, and Wang (2008).

8.3 Vehicle Following Measures

The measures in this section are derived from a vehicle following task, typically referred to as a “car following” task. In that task one vehicle is following immediately behind another trying to maintain a constant following distance while matching the speed variations of the lead vehicle. This task can be performed both on open roadways (in naturalistic studies and staged experiments) and in driving simulators. Normally the lead vehicle speeds are close to a posted speed limit and traffic volume is light enough to not force the test vehicles to slow down (Level of Service A or B). Numerous models of driver longitudinal control have been developed from data collected in this task (e.g., Gazis, Herman, and Potts, 1959; Gipps, 1980; Brackstone and MacDonald, 1999; Rakha and Crowther, 2002).

8.3.1 Coherence ($\gamma^2(f)$)

Dimensionless measure of the squared correlation between the speed signals from the lead vehicle and the following vehicle that indicates the quality of following in a vehicle-following task.

$$\gamma^2(f) = \frac{|G_{xy}(f)|^2}{G_x(f) * G_y(f)} \leq 1$$

where:

$G_{xy}(f)$ is the cross-spectral density function between the lead vehicle speed (input, $x(t)$) and the following vehicle speed (output, $y(t)$), respectively.

$|G_{xy}(f)|$ is the magnitude of $G_{xy}(f)$. $G_{xy}(f)$ is also the Fourier transform of the cross-correlation function of these two speed signals (Bendat and Piersol, 2010).

$G_x(f)$ is the power spectral density of the lead vehicle speed.

$G_y(f)$ *is* the power spectral density of the following vehicle speed.

f is frequency in Hz.

NOTE 1: For a valid result, the coherence function requires a mean of two or more time segments of the input and output signals. These segments should be long enough to contain the lowest frequency of interest in the analysis. For only one time segment, the coherence function registers unity at all frequencies and is not meaningful.

NOTE 2: The spectral analyses are often done using the MATLAB spectral analysis toolbox. See also Chapter 11 in Bendat and Piersol (2010).

NOTE 3: Coherence measures how well the following vehicle driver is able to match the speed variations of the lead vehicle in a vehicle-following task. Coherence therefore provides an indication of the quality of the following driver’s responses. When drivers are performing other tasks in addition to vehicle following, coherence values provide a useful way to evaluate the effect of the additional tasks on vehicle-following performance.

A sample input signal $x(t)$, the speed of the target vehicle, and output signal $y(t)$, the speed of the subject’s vehicle, for a vehicle-following task are shown in Figure 29 for one driver.

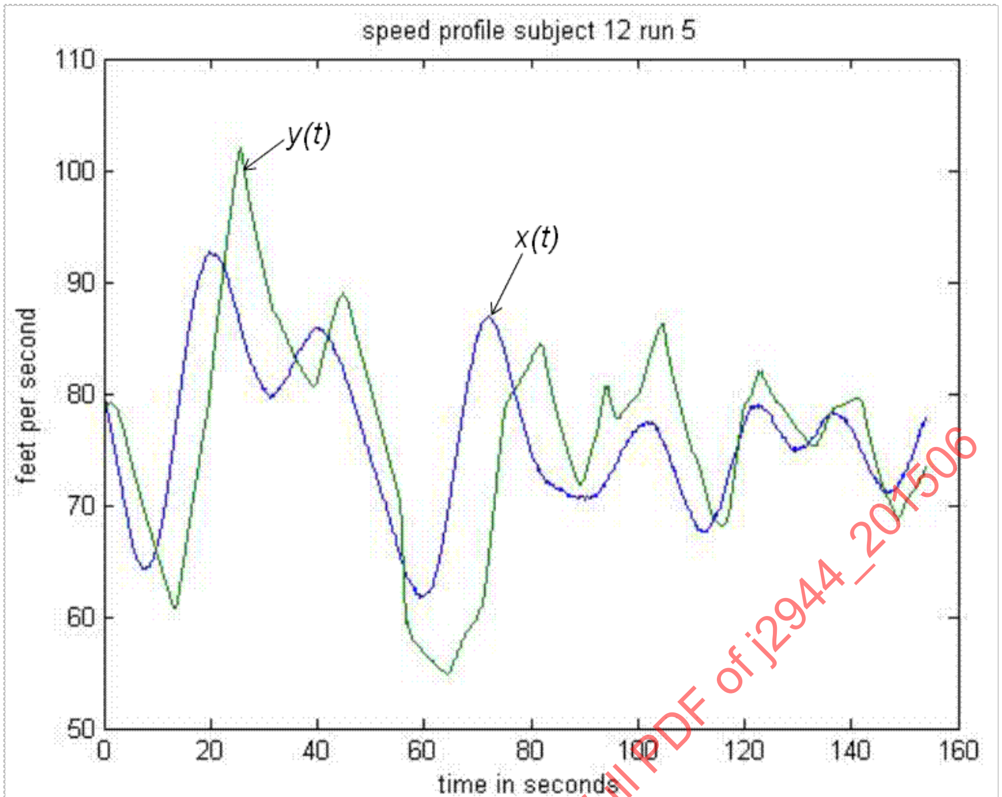

Figure 29 - Sample speed trace of subject vehicle, y(t), following the lead vehicle, x(t)

Source: modified from Ranney, Baldwin, Parmer, Domeyer, Martin, and Mazzae (2011), p. 64

NOTE 4: Coherence has a range of 0 - 1. When $\gamma^2(f)$ = 0 at a particular frequency, the two speed signals *x(t) and y(t)* are incoherent (uncorrelated) at that frequency. If $\gamma^2(f)$ = 1 at a given frequency the speed signals are coherent (perfectly correlated) at that frequency.

GUIDANCE for Coherence:

Test Site: Coherence data are most often collected in driving simulators to provide the desired control over speed though they have been conducted on closed courses and public roads. On public roads, other traffic may affect the speed of the lead and following vehicle.

Input Signal: To compute coherence, the input speed signal needs to have sufficient power at frequencies that drivers are capable of generating. Experimenters need to understand the range of speed signal input frequencies that will be part of the analysis. When developing an artificial speed signal, it is important to ensure that the input frequencies are consistent with naturalistic driver behavior. To ensure that a driver and a driven vehicle can produce the speed signal without excessive of acceleration or deceleration, have a few drivers pilot test drive the input speed signal to verity that the signal to be followed is reasonable.

The lead vehicle speed is typically generated by a combination of sine waves. In general, the sum of three or more non-harmonic sinusoids provides the desired degree of unpredictability. Ranney, Mazzae, Baldwin, and Salaani (2007) used two different input speed functions. One pattern was a single trigonometric sine function with frequency of 0.03 Hz and extreme speed values of 50 and 65 mph. The associated acceleration and deceleration were well within limits associated with normal driving (i.e., < 0.4 g). The second speed pattern was more complex (band-filtered white noise) and intended to be less predictable, but had levels of deceleration and acceleration that were less severe than the simple sine wave.

Analysis: In addition to the traditional method of computing coherence in the frequency domain, Ranney et al. (2011) explored an alternate computation approach based on cross-correlation of speed signals in the time domain. Accordingly, this provided an additional coherence-like measure, which he called Cohere (CC). Cohere (CC) is designated as ρ_{xy} in this document and is defined in 8.3.5.

Typical Values: Ranney et al. (2011) argue that coherence $\geq$ 0.8 is necessary to indicate that the subject was truly following the lead vehicle, so that the measures of gain and time delay (described in 8.3.2 and 8.3.4) are meaningful. Ward et al. (2003) were considerably more generous in deciding the quality of the following vehicle speed data, suggesting that a coherence value $\geq$ 0.3 is sufficient for measures of gain and time delay to be meaningful. Coherence values of 0.8 represent very good vehicle following behavior whereas 0.3 is fairly poor vehicle following. In practice, the criterion selected to represent adequate vehicle following likely will differ depending on characteristics of the lead vehicle speed signal. A higher level of coherence may be warranted for a simpler signal in an constrained task while a lower level may be warranted in a more naturalistic setting in which the lead vehicle speed signal is more complex and may not contain sufficient power at the frequencies of interest. Ranney (personal communication, 2014) believes that there have not been a wide enough variety of car following situations nor enough different lead vehicle speed signals tested to date and therefore the coherence criterion should be established empirically from a careful consideration of the data. Examination of the lead and following vehicle speed signals as well as the computed time delay value(s) is necessary to determine the level of coherence at which vehicle following deteriorates past a point that the computed time delay values make sense or can be interpreted.

Coherence, along with gain and time delay, is a measure of vehicle-following performance used to determine driver performance in the U.S. DOT Driver Following and Detection (DFD) protocol in the *Visual-Manual NHTSA Driver Distraction Guidelines* (U.S. Department of Transportation, 2013f). In that protocol, subjects follow a lead vehicle at approximately 120 feet (36.6 m), trying to stay within plus or minus 60 feet (18.3 m). If they drive outside that range, a tone sounds once every five seconds until they are within range.

8.3.2 Gain

Measure representing the amplification of the following driver's speed signal in response to the lead vehicle speed variation in a vehicle-following task.

Gain can be determined as a function of frequency from the magnitude of the cross spectral density function, $|G_{xy}(f)|$, between the lead vehicle (input) and the following vehicle (output) speeds, respectively. Gain is the mean value of the cross spectrum magnitude over the frequencies present in the input signal and is typically expressed in decibels.

$$\text{Gain} = \text{Mean } |G_{xy}(f)| \text{ over input frequencies}$$

NOTE 1: When the lead vehicle speed signal is a sum of sinusoids, gain can also be reported separately for each input frequency. Many authors only report the gain value for the input frequency having the greatest magnitude.

NOTE 2: Gain is sometimes referred to as “modulus” as it is the magnitude (absolute value) of the cross-spectral density function in complex polar notation.

GUIDANCE for Gain: Gain has a range of zero (no output) to infinity. Gain values near 1.0 indicate that the following driver is closely matching the speed values of the lead vehicle. Gain values significantly greater than 1.0 indicate potentially aggressive overcorrection (amplification) and values smaller than 1.0 indicate undercorrection. Values at either extreme reflect increased potential for safety problems resulting from inadequate following distances (Ranney et al., 2007).

Ranney, Mazzae, Baldwin, and Salaani (2007), using trials for which coherence was greater than 0.8, report mean gain values of approximately 0.95 - 1.15 for baseline driving as well as when using voice information systems in vehicle following situations on a test track. They also report significant age differences with gain values of approximately 1.1 for subjects age 18 - 25, 1.08 for subjects age 30 - 45, and 0.9 for subjects age 50 - 60.

For driving in simulated fog of varying densities, Kang, Ni, and Anderson (2008) report gains of 1.0 - 1.25.

The ability to decompose the gain by frequency provides an opportunity to examine how drivers following a vehicle respond to different frequencies of the lead vehicle speed signal. For example, one could hypothesize that younger drivers would be more likely to respond to the higher frequency changes in lead vehicle speed, which would be revealed as higher levels of gain in the high frequency component of the signal. In contrast, older drivers may be less attuned to higher frequency changes and would respond primarily to the lower frequency changes in the lead vehicle speed signal. To date, authors have not reported if such differences occur or are contributors to vehicle following behavior. In most cases, authors are interested in determining a single value for the gain measure.

8.3.3 Phase angle

Measure representing the amount in radians by which each sinusoidal frequency present in the input signal (lead vehicle speed) is shifted (angularly displaced) in the output signal (following vehicle speed).

NOTE 1: This measure is sometimes called phase, phase shift, or phase lag. Phase angle is typically plotted as a function of frequency for the cross-spectral density function $G_{xy}(f)$ between the lead vehicle (input) and the following vehicle (output) speeds in a vehicle-following task. The phase angle of the cross spectrum between the two speed signals represents the phase shift of the following vehicle speed at frequency *f*.

NOTE 2: The time delay of the following driver's response to the speed variations initiated by the lead vehicle can be directly computed from the phase angle (see 8.3.4.1).

8.3.4 Time delay

Measure representing the time lag between the lead and following vehicle speeds in a vehicle following task.

NOTE: The information contained in this measure and in the phase angle measure is identical. Transformation to a time-based measure allows interpreting the time delay measure as a generalized indication of response time.

8.3.4.1 Calculation via cross spectrum

The time delay at a given frequency, *f*, can be determined from the phase angle as follows:

$$\text{Time delay} = \tau_d = \frac{Phase\ Angle[G_{xy}(f)]}{2\pi f}$$

If the input signal contains a range of frequencies, time delay is calculated as the slope of the phase angle across the frequencies present in the input signal,

$$\text{Time delay} = \tau_d(f) = \text{Slope [Phase } G_{xy}(f)] / 2\pi$$

where the slope is calculated over the input frequencies via linear regression.

NOTE 1: Interpretation of the time delay measure is similar to that of discrete response time measures (section 7) in that longer time delay values reflect poorer performance than shorter values.

NOTE 2: Time delay can also be determined in the time domain using the cross-correlation function, $R_{xy}(\tau)$. See 8.3.4.2. The cross spectrum method allows time delays to be determined as a function of frequency, which is not directly available from the cross-correlation function method. Time delays that vary with input frequency are interesting from an engineering viewpoint, but less so from a behavioral one. Behaviorally, they are more difficult to interpret as there is no theory that relates a driver's following behavior to different frequency components of the lead vehicle speed. Typically, the analyst desires a single measure of response delay and therefore chooses a single input frequency at which to calculate the time delay. The frequency chosen is usually an input frequency having significant power in the mid-range of the input frequencies.

An alternate method to compute a single value for time delay when the input speed signal x(t) consists of a sum of sinusoids is to weight the value of time delay at each input frequency by the input power at that frequency, as follows

$$\text{Time delay (weighted)} = \tau_{dw} = \frac{\sum_i G_{xx}(f)*\tau_{d_i}}{\sum_i G_{xx}(f)}$$

where:

$G_{xx}(f)$ is the auto power spectral density of the input signal at frequency f_i, and

τ_d is the time delay at frequency f_i

This method was used by Ranney, et al (2007, personal communication).

NOTE 3: When coherence is relatively high (e.g., ≥ 0.80), the driver is adequately following the lead vehicle's speed changes, which implies that the time delay measure is meaningful. When coherence values are low, the estimates of time delay are considered suspect.

8.3.4.2 Calculation via cross-correlation of speed profiles

NOTE: This section is mostly derived from Ranney, Baldwin, Parmer, Domeyer, Martin, and Mazzae (2011), p. 64-67.

For the vehicle following task, the input signal, *x(t)*, is the speed of the target vehicle, and the output signal, *y(t)*, is the speed of the following vehicle (Figure 30, top). The time delay between *x(t)* and *y(t)* can be found from the cross-correlation function, $R_{xy}(\tau)$, shown in, Figure 30 (bottom), where in continuous time

$$R_{xy}(\tau) = \int_0^\infty x(t)\, y(t+\tau)\, dt$$

and when sampled $R_{xy}(r) = \frac{1}{N}\sum_{n=1}^{N-r+1} x(n)y(n+r-1)$

where:

N = number of equally spaced samples in the sampled records of *x(t) and y(t)*

r = 1,2,3,..N+1 is the sample (or lag) number

sample time lag $\tau = rh$.

h = spacing between samples (or sampling period)

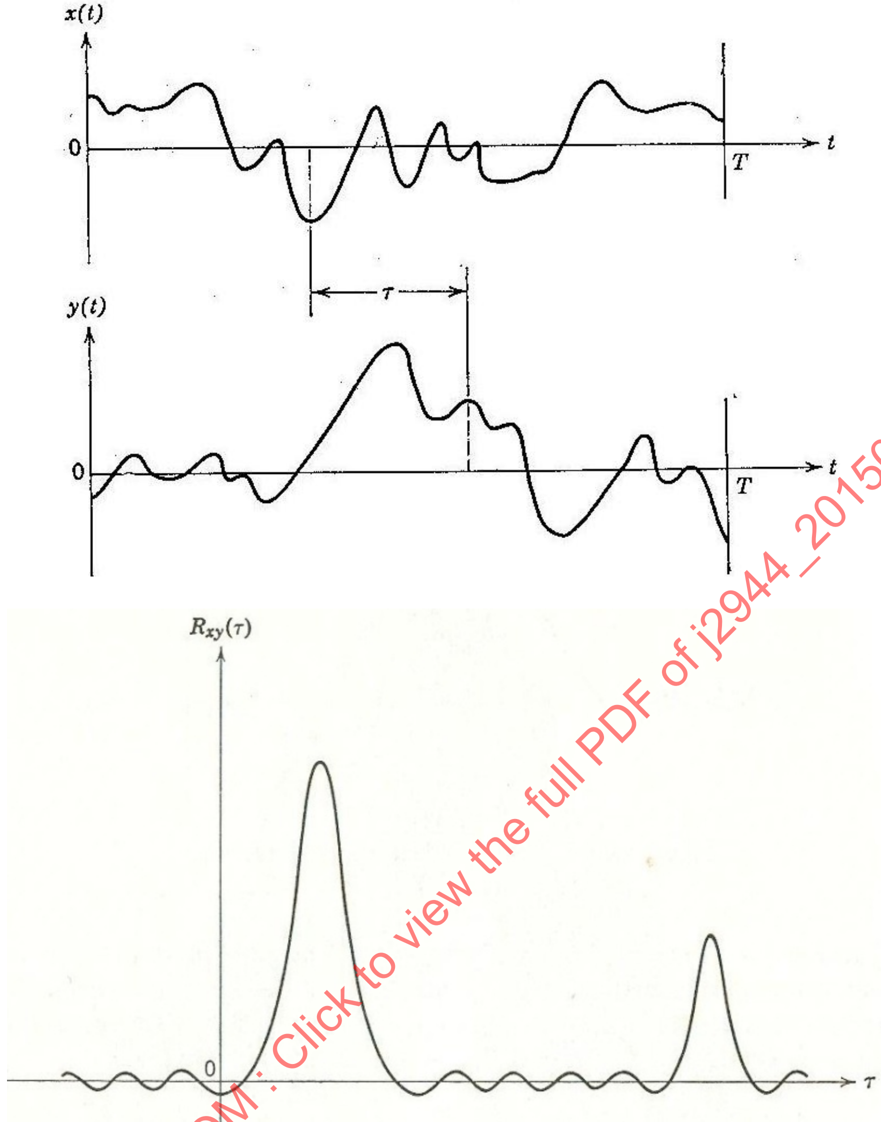

Figure 30 - Illustration of cross-correlation measurement (top) and sample plot (bottom)
Source: Bendat and Piersol (1971), p. 29

For a linear system, when the output signal is delayed from the input, the cross-correlation function will peak at the time delay in following driver's speed response (Figure 29). Therefore, the driver time delay can be determined from the observed peak (maximum) in the cross-correlation function between a zero mean *x(t)* and *y(t)*.

$$\text{Time delay, } \tau_d = \text{Arg max}[R_{xy}(\tau)]$$

where:

Arg max = argument (value of τ) at the maximum of R_{xy}.

To find the cross-correlation between the speed functions *x(t)* and *y(t)*, subtract the means from each function and use the MATLAB function "xcorr" to obtain the plot shown in Figure 31.

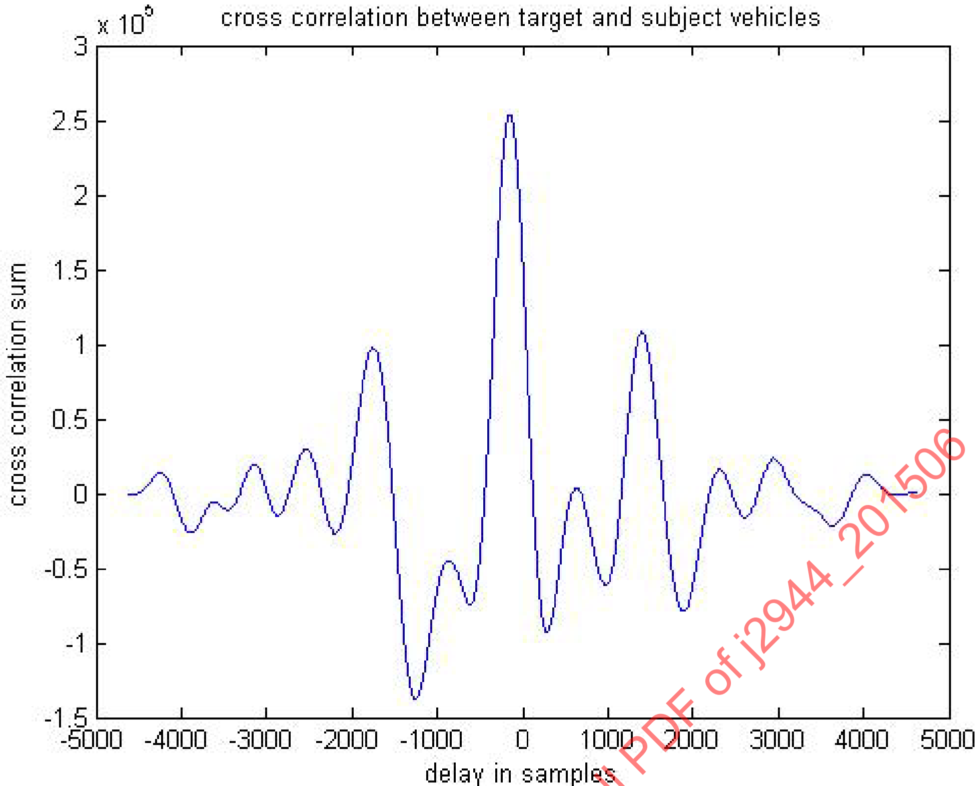

Figure 31 - Cross-correlation between subject and lead vehicles
Source: Ranney, Baldwin, Parmer, Domeyer, Martin, and Mazzae (2011), p. 65

The peak of the cross-correlation function in Figure 31 occurs at an offset of -149 samples. At 30 samples per second, this is a delay of -149/30 = -4.97 seconds. As the input functions are periodic, there are several smaller peaks corresponding to "matches" which are integral numbers of period offsets from the maximum offset. As a check, the output speed is plotted in Figure 32 with a -149-sample delay.

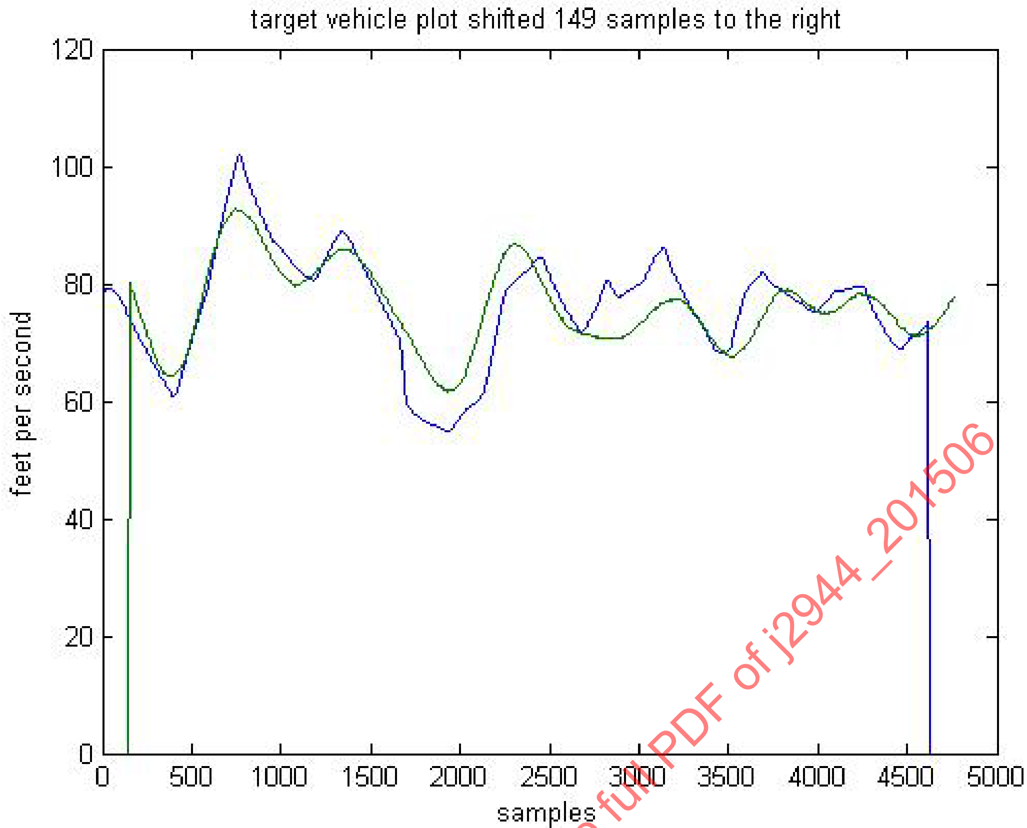

Figure 32 - Peak of cross-correlation function (offset of -149 samples)
Source: Ranney, Baldwin, Parmer, Domeyer, Martin, and Mazzae (2011), p. 66

This figure shows reasonable agreement between the two functions after shifting the input function 149 samples (4.97 s) to the right. The nearly vertical lines on the right and left sides of the plot are artifacts of padding the plots with zeroes.

If the cross-correlation does not have a distinct peak, the cross spectrum method can be used to determine the time delay.

GUIDANCE for Time Delay: Typically, the analyst desires a single measure of response delay and therefore chooses a single input frequency at which to calculate the time delay. The frequency chosen is usually an input frequency having significant power in the mid-range of the input frequencies. Behaviorally, time delays that vary with input frequency have rarely been investigated, in part because they are more difficult to interpret. There is no theory that relates a driver's following behavior to different frequency components of the lead vehicle speed.

Ranney, Mazzae, Baldwin, and Salaani (2007) report mean time delay values of approximately 4.0 - 5.5 s for baseline driving as well as when using voice information systems in vehicle following situations on a test track. They also report significant age differences with time delay values of approximately 3.8 s for subjects age 18 - 25, 4.6 s for subjects age 30 - 45, and 6.0 s for subjects age 50 - 60.

8.3.5 Quality of vehicle following, correlation coefficient based on cross-correlation

Once the input has been time shifted by the amount of the time delay, the magnitude of the maximum cross-correlation can be used to calculate a sample correlation coefficient. The cross-correlation is normalized to have values less than or equal to one by dividing by the product of the mean square values of *x(t)* and *y(t)*. The resulting correlation coefficient, ρ_{xy}, is as follows:

$$\rho_{xy} = \frac{R_{xy}(\tau=\tau_d)}{\sqrt{R_{xx}(0)\,R_{yy}(0)}} \leq 1$$

where:

$R_{xx}(0) = \frac{1}{N}\sum_{n=1}^{N} x(n)\,x(n) = E\{|x(n)|^2\} = \overline{x^2}$, is the autocorrelation of *x(t)* at zero lag, which gives the mean square value of *x(t)*. Similarly, $R_{yy}(0)$, the autocorrelation of *y(t)* at zero lag, gives the mean square value of *y(t)*.

When this normalization is applied to real discrete signals, a correlation coefficient greater than about 0.7 or 0.8 indicates a pretty good match between *x(t)* and *y(t)*. This correlation coefficient provides a similar measure to coherence for evaluating the quality of the following driver's speed response to the lead vehicle speed signal. See Ranney et al. (2011).

NOTE: This correlation coefficient is measure of the quality of vehicle following, analogous to the coherence defined in 8.2.1.

8.3.6 Guidance for vehicle following measures

Rather than transforming *x(t)* and *y(t)* into the frequency domain and comparing the resulting spectra $G_X(f)$ and $G_Y(f)$, the cross-correlation technique allows an analyst to compare the input signal directly with the output signal without using the frequency domain as an intermediate step. Also, the cross-correlation method does not have the frequency domain's windowing issues (Ranney et al., 2011).

Unlike the frequency analysis approach, which requires that the lead-vehicle signal can be decomposed into a range of frequencies and that the signal be long enough to produce multiple periods of the lowest frequency, the cross-correlation approach does not require a range of input frequencies and can be used to analyze shorter segments of driving behavior. In essence, this approach finds the point in time at which the following speed signal best matches the input speed signal. The approach can produce spurious results. The analyst should determine a reasonable range of values for gain and time delay and carefully examine all trials that produce results indicating the best fit values were outside of this range. Constraining the search to a given range will generally produce a reasonable outcome (Ranney, personal communication, 2014).

Ranney et al. (2007 p. 46) state, *"Based on the experience of Brookhuis (Brookhuis et al., 1994), we expected that drivers would generally be able to follow the lead vehicle adequately while performing a secondary task and that distraction effects would be revealed as increased values of delay (phase shift), reflecting slower responses to lead vehicle speed changes while engaged in secondary tasks. Our results were not entirely consistent with this model in that reduced coherence and increased delay occurred together in many of our comparisons. Results of an earlier study may help explain the nature of these effects. In that study, the pattern of coherence and delay effects differed for different groups of drivers (Ranney, et. al, 2004a). Specifically, among high-performing drivers, coherence remained consistent across secondary task conditions while delay increased as secondary task demands increased. However, low performing drivers increased their following distances while performing secondary tasks, which reduced coherence to the point that delay was not interpretable. A similar pattern was observed in the present study among older drivers, who exhibited increased following distances and reduced coherence values, although not to the point that delay was uninterpretable.*

These patterns suggest a two-level model of performance impairment. In the first level, which represents relatively minor degradation, drivers are generally able to follow lead-vehicle speed changes accurately and there is no significant drop in coherence. At this level, performance impairment is revealed as increased delay, reflecting slower responses to lead vehicle speed changes. However, as impairment becomes more severe, drivers become less able to maintain their car following and as a result the coherence drops. The drop in coherence is due in part to increased headways, which drivers may exhibit while performing secondary tasks. Thus, according to this model, significant decreases in coherence reflect more severe performance impairment than increased delay. In the present study, the consistently higher coherence *values observed during the simulated phone trials provided the strongest evidence that the 511 tasks were more disruptive than the simulated phone task.*"

To aid reader understanding of the computation of these measures, Table 5 shows example data for one subject (Dastrup et al., 2009). Each row represents data for a particular frequency. The bold text corresponds to the peak spectral densities. The values for coherence, gain (calculated from ratio of the spectral densities), and delay (calculated from phase) for only the row with the text shown in bold was used in the authors' analysis. For example, this subject had a coherence of 0.78, a gain of 2.15 (gain = 325.5543 / 151.7221), and a delay of 2.79 s (delay = 0.610183 / (0.003641*60)).

Table 5 - Example spectral analysis output from data of one subject
Source: Adapted from: Dastrup, Lees, Dawson, Lee, and Rizzo (2009)

Frequency from 0 to PI	PERIOD	Coherence of LV Velocity and Subject Velocity	Spectral Density of LV Velocity	Spectral Density of Subject Velocity	GAIN	Phase of LV Velocity and Subject Velocity	Time Delay
0		0.849	9.15	28.4		0	
0.0036	**1725.6**	**0.782**	**151.72**	**325.55**	**2.15**	**0.610**	**2.79**
0.0088	710.5	0.862	24.55	21.72	0.88	1.722	3.25
0.0125	503.3	0.236	10.28	10.17	0.99	2.237	2.99
3.1413	2.0	0.353	1.73E-08	4.35E-07		−0.816	

The parameters in coherence calculations depend on the dynamics of the vehicles involved, with more responsive vehicles (greater horsepower-to-weight ratios) being more capable of shorter time delays. Furthermore, the velocity profile of the lead vehicle depends on how quickly it can accelerate, the importance of fuel economy to the driver of the lead vehicle, and other factors. For information related to trucks, see Agharayk, Sarvi and Young (2012).

Although this section offers specific guidance for the gain and time delay measures in vehicle following studies, the recommended values for these measures also depend on what is being assessed – such as impairment (driver fatigue, effects of drugs, alcohol, etc.) and driver characteristics (age, experience, etc.). The effects of impairment and driver characteristics on driving performance can be predicted by determining how these factors affect the gains, time delays, and other parameters of the underlying control theoretic driver models (Allen, Jex, McRuer, and DiMarco, 1975; McLean and Hoffman, 1975; McRuer, Allen, Weir, and Klein, 1977; Allen, Marcotte, Rosenthal, and Aponso, 2005; and Karjewski, Sommer, Trutschel, Edwards, and Golz, 2009), providing more compelling results.

For analogous fundamental work on driver lateral control, see McRuer, Allen, Weir, and Klein (1977) and Jagacinski and Flach (2011).

REQUIREMENTS: The first instance the terms *gain, time delay or phase, or quality of vehicle following (coherence or cross correlation coefficient)* are used in a document, the coherence value below which *gain and time delay* are not meaningful to compute shall be reported. The spectral characteristics of the lead vehicle speed signal, as well the range and maximum of its deceleration, shall be reported. The procedure for calculating *gain* and *time delay* for each trial, whether across a frequency band or at a single frequency, shall be reported.

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 33).

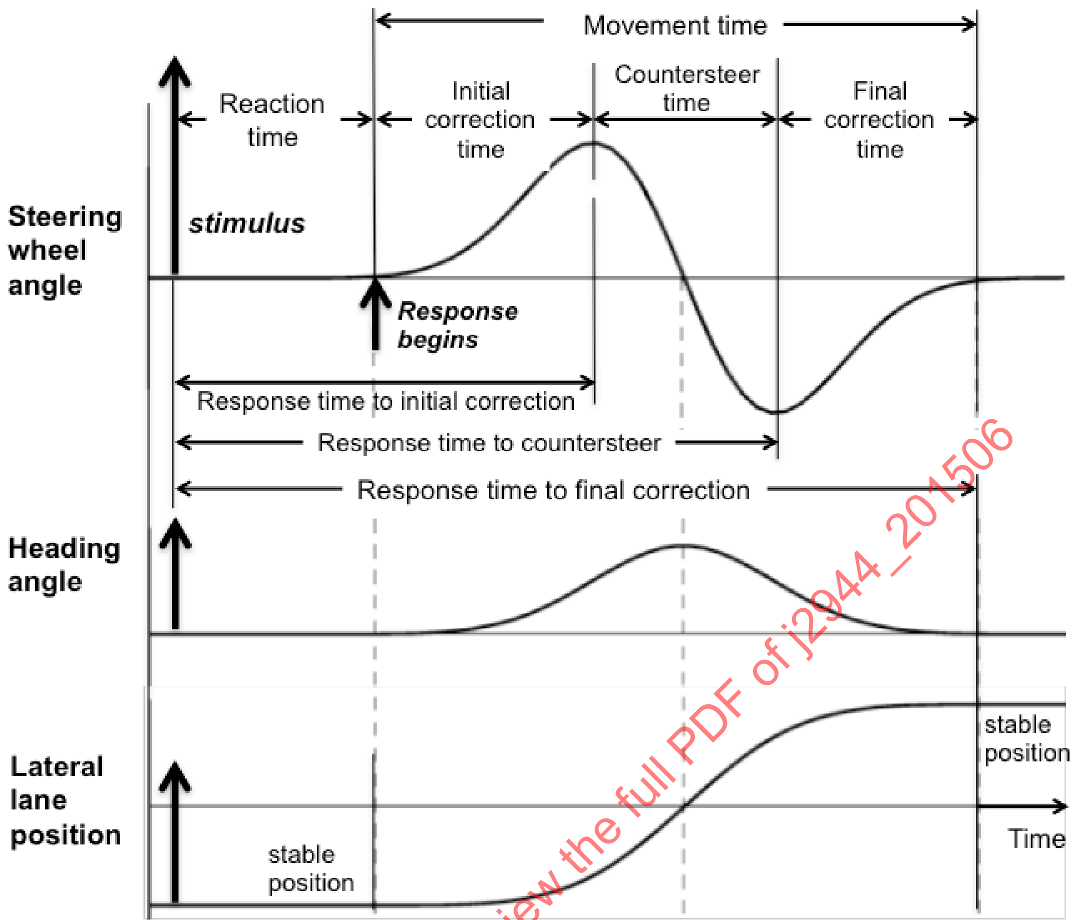

Figure 33 - Steering reaction, movement, and response times

NOTE: Figure 33 shows the conceptual relationship between steering wheel angle, heading angle, lateral lane position, and time. The actual values on all scales will depend upon the speed of travel, the lane width, how quickly the lane change occurs, the road surface condition, and the vehicle type (e.g., sports car versus truck). Between vehicle types, the steering gain (the relationship between steering wheel angle and front wheel angle) varies.

GUIDANCE for Steering Reaction Time: For mean reaction times to a haptic warning signal involving vibration of the steering wheel, Deroo, Hoc, and Mars (2012) reported values of 473 ms on straight roads and 492 ms on curves.

What minimal steering motion is needed to determine that a response has begun? McGehee, Lee, Rizzo, Dawson, and Bateman (2004) had subjects drive “rural, two-lane roadways” that began with the subject merging into a lane. Details such as whether curves were present and their radii, lane widths, etc. were not provided. Except for three events involving maneuver of other vehicles, their task was to drive the DriveSafety simulator normally. Results indicated there were few instances where steering wheel angles larger than +/- 6 degrees occurred after 5 minutes of driving, suggesting use of a 6 degree threshold for a steering reversal.

A more detailed analysis comes from examining the variability in typical steering data. Table 6 shows the standard deviation of steering wheel angle for baseline driving on different types of public roadways based on the Advanced Collision Avoidance System (ACAS) naturalistic driving data set (Green, Wada, Oberholtzer, Green, Schweitzer, and Eoh, 2007). Interestingly, the data are better fit by a double exponential distribution than a normal distribution, suggesting a steering response threshold of 8 degrees for limited access roadways, 10 degrees for major roadways, and 20 degrees for minor roadways. These values seem excessively large. Surprisingly, differences were not found distinguishing between steering data on straight and curved segments.

Table 6 - Standard deviation of steering wheel angle (deg)
Source: Green, Wada, Oberholtzer, Green, Schweitzer, and Eoh (2007), p. 25

Age Group	Limited Access Roadway	Major Roadway (Arterial, Minor Arterial)	Minor Roadway (Collector, Local)
21 - 30	4	6	19
41 - 50	5	7	17
61 - 70	4	8	19

What are typical steering reaction times? - Dozza (2013), from an analysis of evasive maneuvers in the 100-car and 8-truck naturalistic driving data reported reaction times for evasive maneuvers of 1.31 ± 0.95 s for braking only, 1.31 ± 1.15 s from steering and braking, and 1.65 ± 1.22 s for steering alone. However, Dozza's reaction time distributions are not quite symmetrical, so the plus/minus error value presented in Dozza may be misleading.

Currently, the preferred method to determine that a steering response has begun is to determine the local maximum steering wheel angle immediately after the triggering event for each subject for each trial or segment, either manually or using software, and use the time at which that maximum occurred as the end point of the reaction time and start of the response movement.

REQUIREMENTS: 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 shall 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, or part of, the steering wheel movements made to bring the vehicle to the desired path of travel (Figure 32).

NOTE: 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 32, 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.

REQUIREMENTS: 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, or part of, the 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 time and movement time.

NOTE 2: If desired, steering response times can be computed for various segments of the movement, as illustrated in Figure 32. In most applications, steering response time includes all steering movements to achieve the desired vehicle path.

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.

REQUIREMENTS: The first instance the term *steering response time* is used in a document, (1) the initiating event and time of event onset (2) the angular change required to identify movement start and end points, and (3) the associated time window within which the movement can 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 being reported more often as research on lane departure warning and lane keeping assistance systems advance.

GUIDANCE for Steering Response Times: Figures 34 (for a driving simulator) and 35 (for a real roadway) 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 warning (the event onset), and that lateral position changes in response to the steering movements continue as long as an additional 2.5 s, with the vehicle response nearly 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 reported so it can be replicated.

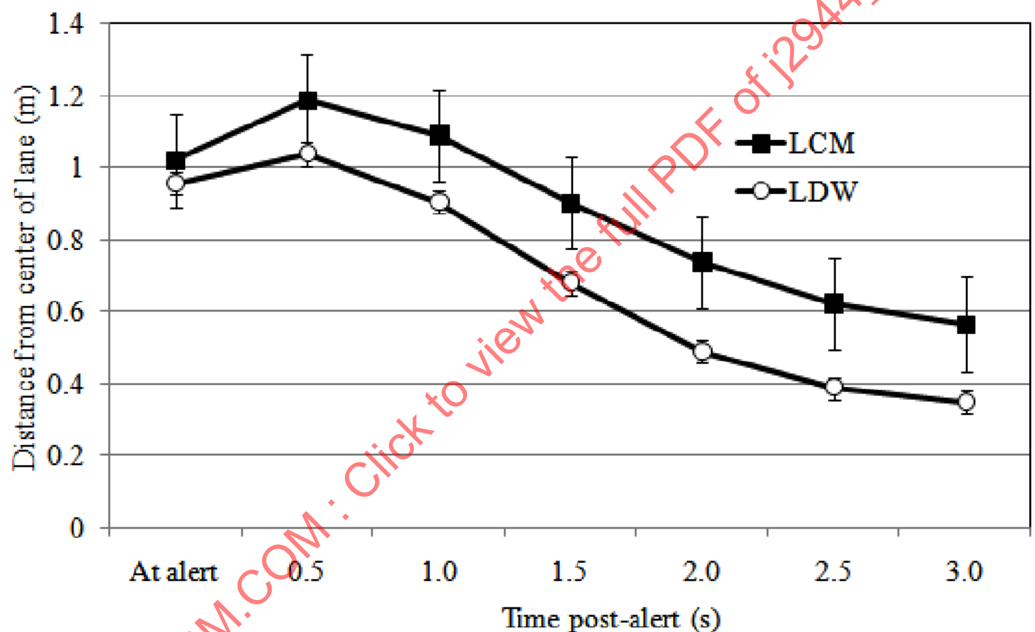

Figure 34 - Driver response to lane departure (LDW) and lane change merge (LCM) warnings
Source: Green, Sullivan, Tsimhoni, Oberholtzer, Buonarosa, Devonshire, Schweitzer, Baragar, and Sayer (2008), p. 61

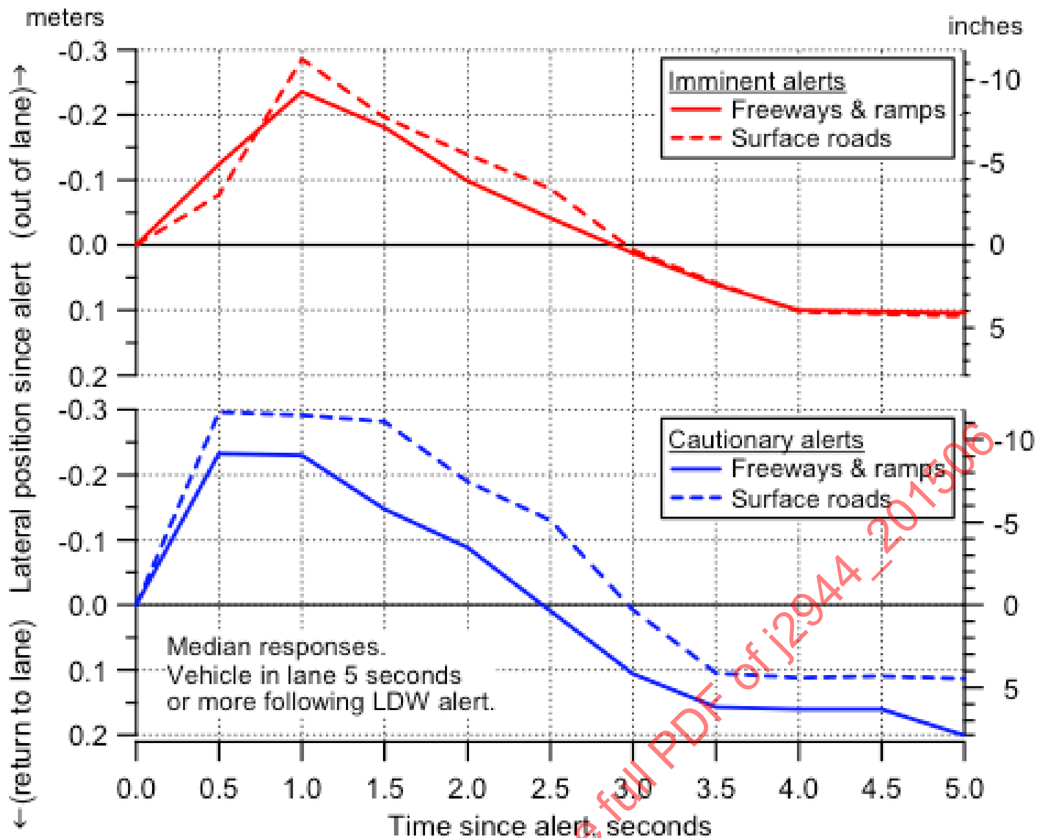

Figure 35 – Median lateral position following LDW alerts from the RDCW field test
Source: LeBlanc, Sayer, Winkler, Ervin, Bogard, Devonshire, Mefford, Hagan, Bareket, Goodsell, and Gordon (2006), p. 8-4

9.2 Steering Performance Statistics

9.2.1 Steering reversal (SR)

Change in the movement direction of a steering device, usually after a prior movement in the opposite direction exceeded a minimum threshold amplitude, and usually determined from a steering device signal that has been filtered.

NOTE 1: There are two different methods to determine when a steering reversal has occurred, (1) the amplitude threshold method (option A, 9.2.1.1) and (2) the amplitude and velocity thresholds method (option B, 9.2.1.2).

NOTE 2: Steering wheel reversals do not include steering movements associated with an intentional vehicle turning maneuver such as curve negotiation or lane change. Reversals represent steering wheel movements associated with maintaining the path within the current lane of travel.

NOTE 3: The most common steering device is a steering wheel, so the movements are steering wheel rotations. However, the steering control device does not have to be a wheel. Accordingly, the definition herein refers to device movement, not just wheel rotation, though new movement criteria may be needed for non-wheel devices.

NOTE 4: The reasoning behind steering wheel reversals as a performance measure is that as drivers become less attentive (due to distraction, fatigue, etc.), they usually make fewer small steering corrections and more larger 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).

9.2.1.1 Steering reversal - amplitude method (Option A)

A steering reversal occurs at the point when the steering device amplitude changes direction after a movement in the opposite direction by an amount exceeding a minimum amplitude threshold

NOTE 1: This method uses either the local maxima or minima of the steering device amplitude (typically steering wheel angle) signal or the zero crossings of the steering wheel velocity signal to identify a reversal. A minimum amplitude threshold for identifying a reversal is included to avoid treating minor oscillations as reversals (Figure 36). Option B additionally applies a threshold (dead zone) around the zero crossings of the steering wheel velocity signal to identify a reversal.

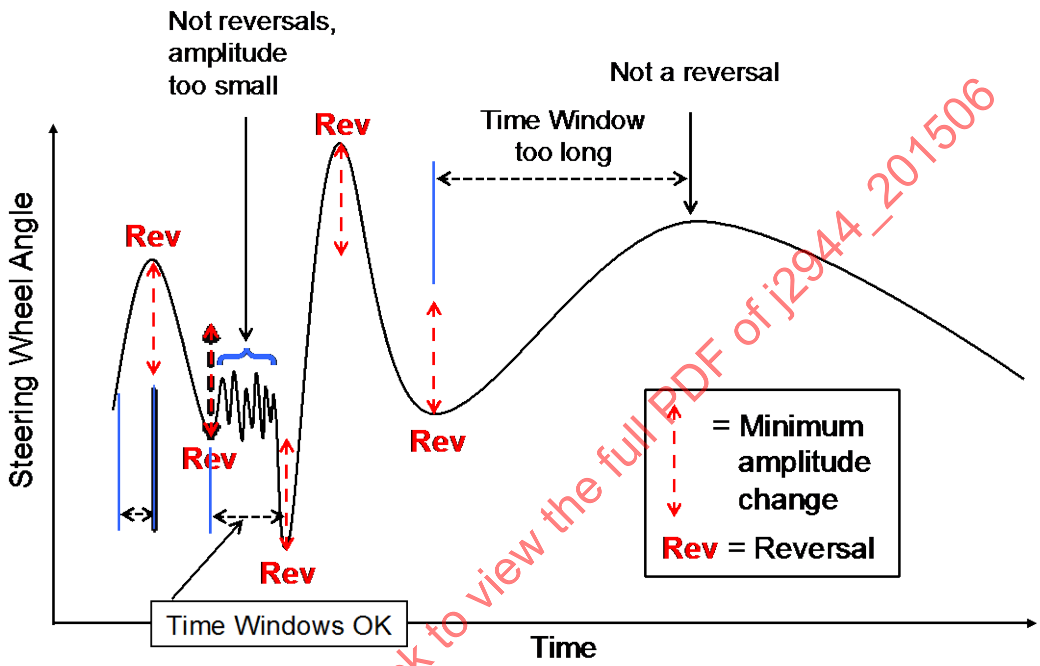

Figure 36 - Illustration of steering reversals

NOTE 2: Reducing the threshold will increase the number of reversals.

NOTE 3: The computational method used by Markkula and Engstrom (2006) is given in Appendix F. In this method, steering wheel angles over successive equal time periods are compared to determine the change in angular position, which is also an indication of steering wheel velocity. A change in sign is a reversal.

NOTE 4: To avoid treating slow drifts as reversals, sometimes a moving time window is applied to the steering angle amplitude signal to identify slow drifts prior to a reversal. A steering reversal that exceeds the amplitude threshold has to occur within the duration of the time window. An alternative way to remove slow drifts is to apply a high-pass filter to the steering angle signal.

NOTE 5: The first device to collect steering wheel reversals, the Greenshields and Platt “Drivometer,” was developed in 1961/1962 (Platt, 1966; Greenshields, 1967).

9.2.1.2 Steering reversal - amplitude and velocity thresholds method (Option B)

A steering reversal occurs when the steering device velocity changes sign and the steering amplitude and / or velocity exceed pre-defined minimum thresholds.

NOTE 1: The computational method used by Ranney, Mazzae, and Baldwin (2007) is described in Appendix F.

NOTE 2: A velocity threshold is sometimes used to remove noise from a velocity signal that was derived by differentiating the steering wheel angle signal. It can also be used to remove slow drifts in steering angle.

NOTE 3: The velocity threshold is normally a dead band around the zero velocity. In describing this method, sometimes reference is made to "zero velocity crossings," meaning the zero velocity dead band (threshold) has been crossed.

NOTE 4: There are also studies where a velocity dead band was used without an accompanying amplitude threshold being identified (Verway and Veltman, 1996). In this case whenever the steering velocity exceeds the velocity dead zone threshold a steering reversal will be counted no matter the steering angle amplitude, which can result in a greater number of reversals than when an amplitude threshold is also employed.

REQUIREMENTS: The first instance the *term steering reversal* is used in a document, the computational method used (option A or B), the values of the minimum amplitude and velocity thresholds, and if the thresholds in each movement direction are equal shall be reported. If the amplitude or velocity signal is filtered, the filter type and cutoff shall be reported.

GUIDANCE for Steering Reversals: Specifying recommended values for parameters relevant to determining steering reversal is difficult because the number of steering reversals depends on many factors, such as vehicle type, steering system characteristics, speed, lane width, traffic (MacDonald and Hoffman, 1980), and other factors. Class 8 commercial trucks typically have larger steering wheel angles when lane keeping on straight roadways (Figure 37). Higher speeds lead to fewer reversals, especially smaller ones (McLean and Hoffman, 1975). Wider lanes lead to more reversals than narrower lanes (McLean and Hoffman, 1975).

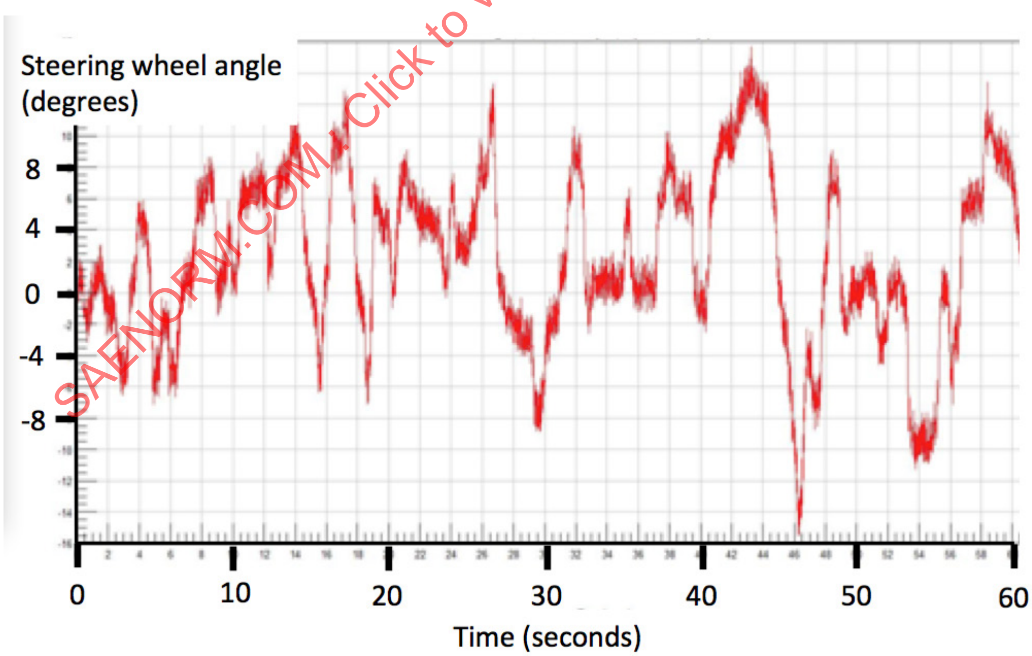

Figure 37 - Steering pattern for a large truck for straight-line driving
Source: Jahns (2013), personal communication

Which method is recommended, option A (amplitude) or B (velocity)? Both methods can be used. Option A does not require recording the steering wheel velocity signal. The two methods should produce a similar number of steering reversals, but we have not found a study to verify this assertion.

If angular movement is required, how large should the amplitude be? Steering systems typically have a small dead band (free play) about zero steering wheel angle as a way of desensitizing the steering a bit so the vehicle will continue on a straight path in spite of very small steering wheel movements. Older hydraulic steering systems, especially those of the 1970s and 1980s, had significant dead bands compared to today's vehicles. One degree is a fairly typical value for a dead band, but the size of the dead band depends upon the design of the steering system. Currently, hydraulic power steering systems typically have larger dead bands than electric steering systems. Further, large trucks tend to have larger dead bands than traditional American full-size passenger cars, which in turn have larger dead bands than sports cars. An amplitude threshold effectively accounts for this dead space as well as small variations around the current steering angle.

The patents for the Greenshields and Platt "Drivometer" describe how the device worked but do not indicate the angular change required for a reversal nor the amount of dead space. However, Platt (1962) notes that the equipment could measure steering wheel reversals of three degrees but that the system did not pick up reversals at vehicle speeds over 50 mi/hr. Greenshields and Platt (1967) refer to micro reversals of 2.5 degrees and macro reversals of 8.5 degrees. Platt, Gram, and Hobday (1969) refer to reversals of two degrees for fine steering and 12 degrees for coarse steering (to count lane changes and turns). King and Plummer (1973) divided the steering wheel reversals into two groups - 2.5 degrees (micro) and 8.5 degrees (macro). Platt (1964) and Platt and Feddersen (1964) show sample reversal plots.

McLean and Hoffman (1975) examined how reliable repeated measures of the number of steering reversals were for several different steering wheel amplitude thresholds in two experiments, one in which subjects' sight distance was limited, a second in which lane width was limited. The maximum reliability of the number of steering wheel reversals occurred for amplitude thresholds (gaps) of 0.5 - 0.7 degrees, a narrow range, although amplitudes from 0.3 - 3.0 degrees were almost as reliable (Figure 38).

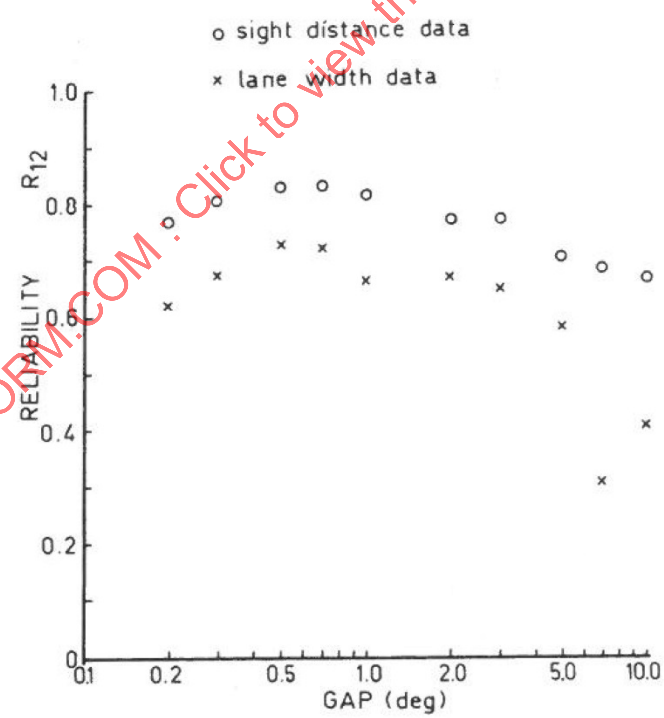

Figure 38 - Effect of the reversal threshold on task reliability (correlation of two successive test runs)
Source: McLean and Hoffman (1975), p. 251

Wierwille and Gutmann (1978) and Hicks and Wierwille (1979) both used two-degrees for the steering amplitude threshold. In contrast, McGehee, Lee, Dawson, and Rizzo (2004) required a change of six degrees before counting a reversal, primarily to avoid counting noise and driver dither as a steering reversal.

Reed and Green (1999, p. 1025) determined that an amplitude threshold was met by examining "a series of first-order steering-wheel-angle differences that do not change sign for more than 0.33 s (ten samples at 30 Hz) and that represent a net monotonic change in steering-wheel position of more than one degree." Thus, their criterion included both a minimum angular threshold of 1 degree and a minimum time period of 0.33 s during which the steering wheel angle must be monotonic (either increasing or decreasing).

Should multiple amplitude thresholds be used? The change being studied, at least in terms of distraction, is a reduction in the number of small corrections and possibly an increase in the number of large corrections. This suggests the possibility of using multiple amplitude thresholds. In an on-road experiment to examine fatigue, Sherman, Elling, and Brekke (1996) used thresholds of one and five degrees. However, their data were highly filtered. To avoid spurious responses, if two thresholds are desired to differentiate smaller from larger changes for passenger cars, the thresholds should be 2 - 6 degrees, and more than 6 degrees. To avoid spurious classification, Tijerina, Kiger, Rockwell, Wierwille (1995) recommended three categories – less than 2 degrees, 2 - 6 degrees, and greater than 6 degrees.

The recommendations for minimum amplitude thresholds depend on if and how the data are filtered, with false positives (non-reversals identified as reversals) due to noise being much more likely for unfiltered signals for thresholds of one degree, unlikely for thresholds of five degrees, and very unlikely at thresholds of six degrees or greater. Given this, and the research described in this section, recommended amplitude thresholds for passenger cars on reasonably straight roads at highway speeds are two degrees for filtered signals and five degrees for unfiltered signals.

A recent and thorough examination of filter characteristics and reversal amplitude appears in the AIDE methods and measures report (Ostlund, Peters, Thorslund, Engstrom, Markkla, Keinath, Horst, Juch, Mattes, and Foehl, 2005) and in Markkula and Engstrom (2006). *"The two free parameters of the (steering reversal) metric having major effects on metric sensitivity, gap size and low pass filter cut-off frequency, were varied through all combinations of:*

- Gap-size (degrees): {0.1, 0.5, 1, 2, 3, 4, 5, 10}
- Low pass filter (LPF) cut-off frequency f_{LP} (Hz): {0.6, 2, 5, 10}

The analysis was mainly done by means of visual inspection of surface plots where effect size was plotted as a function of gap size and LPF cut-off frequency. The following were the main findings from this analysis:

- For the visual task in straight driving conditions, the optimal gap size could be found in the range of 2 - 4 degrees and the LPF cut-off frequency did not have a major influence.
- For the visual task in curves, the LPF frequency cut-off had a strong influence, where the highest sensitivity was achieved for the lowest cut-off value tested (0.6 Hz). Moreover, the optimum for the gap-size was increased to 5 degrees or even higher, depending on the LPF cut-off setting.
- For the cognitive task, the optimal gap size is much smaller than for the visual task. In fact, the sensitivity was largest for the smallest of the gap sizes investigated (0.1 and 0.5 degrees). It should be noted that smaller gap sizes could not be detected as the angular resolution of the steering wheel angle sensor was limited to 0.1 degrees. The cut-off frequency parameter had some influence, mainly in the moving base and field conditions, where the effect was reduced somewhat for the lowest value (0.6 Hz). This could be expected as much of the variance related to the cognitive secondary task lies in the higher frequencies…" (Markkula and Engstrom, 2006, p. 8)

Figure 39 *"illustrates effect size as a function of gap size for both the visual and the cognitive tasks in all conditions. In this plot, the cut-off frequency was held constant at 2 Hz. The Figure clearly shows that the largest sensitivity for cognitive load was obtained for the smallest or second smallest gap size in all conditions. By contrast, for the visual task, the optimum gap size varied between 2 and 10 degrees, with the largest optimal gap sizes in curves. The gap size optima were also generally larger in the moving base simulator than in the fixed base simulator and the field. These consistent differences in optimal gap sizes clearly indicate the very different effects of visual and cognitive load on steering and the need for different parameter settings in order to obtain optimal sensitivity of the steering wheel reversal rate metric to visual and purely cognitively demanding tasks respectively"* (Markkula and Engstrom, 2006, p. 9).

"Given the results obtained in the present study, the best choice of parameters for measuring the visual load component using the proposed steering wheel reversal rate metric seems to be f_{LP} = 0.6 Hz and a gap size of 3 degrees. It should however be noted that the optimal gap size may vary between 2 - 5 degrees depending on the experimental conditions (in particular the steering dynamics of the experimental vehicle/simulator). Thus, it could be useful to calculate a range of gap sizes and only use the most sensitive one. When choosing the gap size for measuring visual load, it should be considered that larger reversals occur more rarely than smaller ones, which means that choosing too large gap sizes may be problematic when evaluating tasks that are short in duration. The best parameterisation for measuring the cognitive load component seems to be f_{LP} = 2 Hz and a gap size of 0.1 degrees.

As an alternative to using one "visual component" parameterisation and one "cognitive component" parameterisation, a general approach of always measuring a full range of gap sizes, from the smallest possible to about ten degrees could also prove useful, at least as a tool for qualitative analysis. Regarding the f_{LP} parameter, it would clearly be preferable to find a single value somewhere between 0.6 and 2 Hz that is acceptable for both visual and cognitive load. This is an issue for further investigation" (Markkula and Engstrom, 2006, p. 10-11).

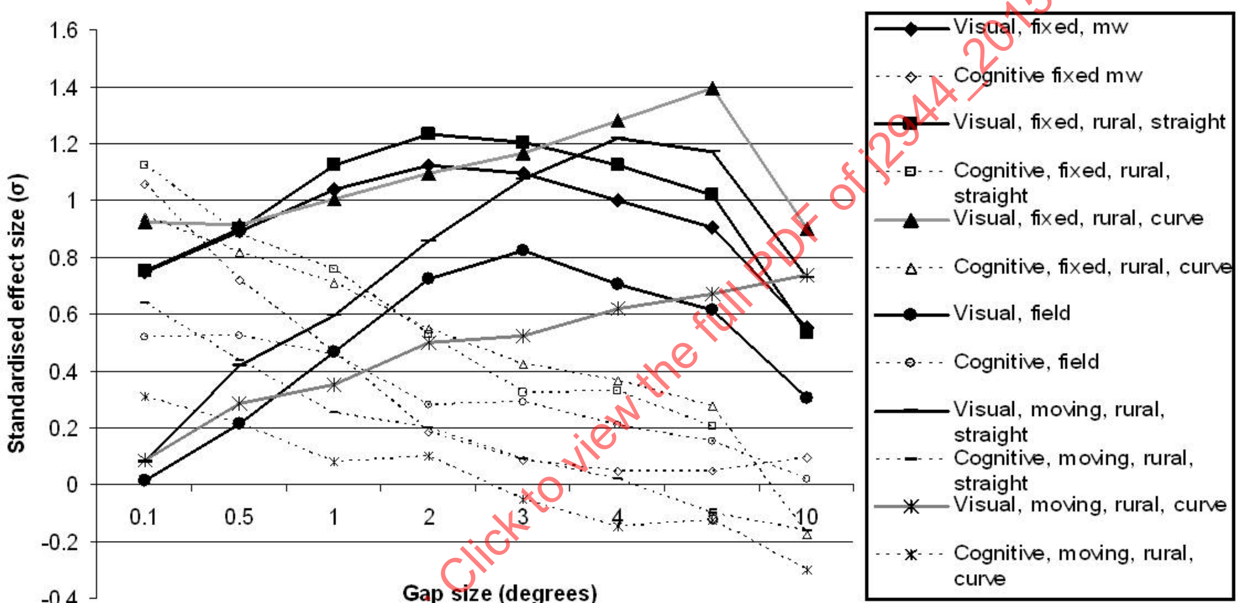

Figure 39 – Performance effect size as a function of steering wheel gap (amplitude) size using a 2 Hz filter cutoff frequency
Source: Markkula and Engstrom (2006), p. 10

Given all these considerations, for visual tasks in cars, a low-pass Butterworth filter with a 0.6 Hz cutoff frequency and an amplitude threshold of 3 degrees are recommended. For cognitive tasks in cars, a low-pass Butterworth filter with a 2.0 Hz cutoff and an amplitude threshold of 0.1 degrees are recommended. Details are in Appendix F.

If a moving time window is used, how large should it be? The steering corrections of interest are often the small, discrete corrections, not drifts. Drifts are removed by either limiting the time period over which a reversal can be counted, by using a high-pass filter on steering angle, or possibly by a steering velocity dead band (which considers both amplitude and time). Lee, Moeckli, Brown, Roberts, Schwarz, Yekhshatyan, Nadler, Liang, Victor, Marshall, and Davis (2013) utilized a six-second time window for their examination for steering reversals and that window is recommended. Alternatively, a high-pass filter with a cutoff frequency of approximately 0.05 – 0.1 Hz can also be used to remove slow drifts in the steering wheel angle signal. Tijerina et al (1995) used a high-pass filter with a cutoff frequency of 0.047 Hz and a 20 db/decade rolloff to remove slow steering trends due to traveled way curvature.

If an amplitude dead band is used, how large should it be? A dead band in steering wheel angle (Figure 40) occurs when there is free play in the steering system so that a small movement of the steering wheel from the straight-ahead or current position causes no change in front wheel angle. Sizeable dead bands were in cars with hydraulic steering systems, up to the 1980s. Currently, hydraulic power steering systems typically have larger dead bands than electric steering systems. Further, heavy trucks tend to have larger dead bands than traditional American full-size passenger cars, which in turn have larger dead bands than sports cars. Thus, if dead bands are applied to the steering wheel angle signal, the dead band size should be tailored for the vehicle being tested, with one degree being a fairly typical value for a dead band.

However, an amplitude dead zone is not typically used when determining steering wheel reversals. Reversals are an indicator of steering activity of drivers. As such, it is not necessary that steering wheel motions (such as reversals) actually lead to changes or reversals in front wheel steer angle, and consequently a change in vehicle lateral motion. For example, the change in steering activity induced by driver distraction is not entirely related to maintaining lateral directional control, as is evident from the amplitude thresholds recommended for visual and especially cognitive secondary tasks.

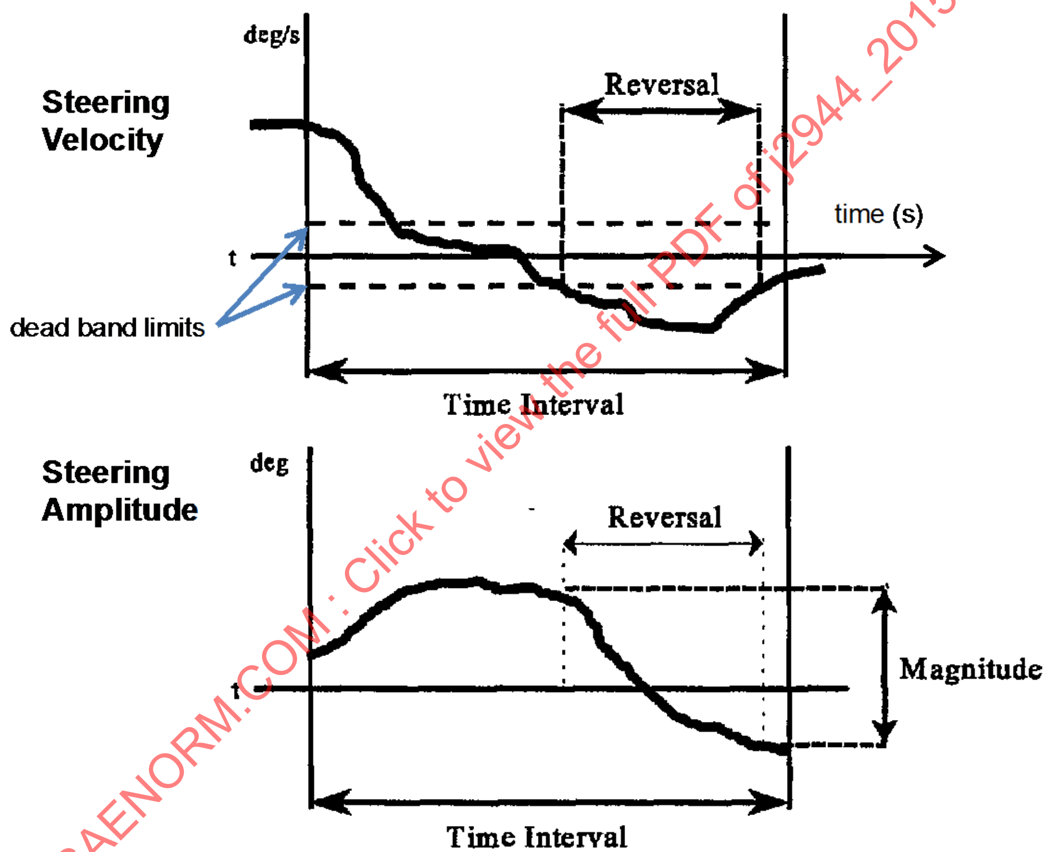

Figure 40 – Finding a steering reversal using a velocity dead band
Top – Steering Velocity with Dead Band, Bottom – Magnitude of Steering Reversal
Source: modified from Tijerina, Kiger, Rockwell, and Wierwille (1995), p. B-9 and B-13

What should the steering velocity dead band threshold be? Skipper and Wierwille (1986) make reference to the use of a velocity threshold, but do not provide a value. Vervey and Veltman (1996) indicate the velocity threshold should exceed 1.0 deg/s. Theeuwes, Alferdinck and Perel (2002) used 3.0 deg/s. DeGroot, de Winter, Garcia, Mulder, and Wieringa (2011) also used 3.0 deg/s, citing Theeuwes, et al.

Ranney, Harbluk, Smith, Huener, Parmer, and Barickman, (2003) considering both velocity and amplitude, defined a reversal as when the steering rate (velocity) passed through a dead band of ±1 deg/s and the steering angle changed by more than 2 degrees. Ranney, Mazzae, Baldwin, and Salaani (2007) defined a reversal as when the steering wheel velocity exceeded ±1.5 deg/s and the steering wheel angle changed by greater than ±1.0 deg. In addition, the raw steering wheel angle and velocity data were first filtered using a 4-pole Butterworth low-pass phaseless digital filter with a cutoff frequency of 3.6 Hz.

9.2.2 Number of steering reversals

Number of times that the steering device changes direction (above a threshold value) accumulated over some time span spent driving (e.g., per minute) or distance travelled (e.g., per mile, kilometer or roadway segment).

GUIDANCE: This measure has been used as an indicator of driver distraction and for other purposes (Lee, Moeckli, Brown, Roberts, Schwarz, Yekhshatyan, Nadler, Liang, Victor, Marshall, and Davis, 2013.). When distracted, drivers attend less to steering, making fewer small steering corrections but more large corrections that are classified as reversals. More often, the statistic based on this, *steering reversal rate*, is reported.

REQUIREMENTS: The first time the term *number of steering reversals* is used in a document, the option used to define a reversal (A or B), the filter characteristics, and the amplitude threshold (if used), shall be reported. If option B is used, the velocity threshold shall be reported. If multiple thresholds are used, the then thresholds for each shall be reported.

9.2.3 Steering reversal rate (SRR)

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

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

REQUIREMENTS: The first time the term *steering reversal rate* is used in a document, the option used to determine a *steering reversal* (A or B) as well as other parameters required by each option shall be reported.

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 using a 1-degree threshold and 18 - 25 per minute using a 3-degree threshold for rural roadway 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 using a 6-degree threshold to be 14, 4, and 2 per minute for older subjects and 16, 3, and 1 per minute for younger subjects driving for the first, second, and third minutes of a drive on a straight rural roadway 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.

9.2.4 Steering entropy (H_P)

Statistic indicating the amount unpredictability/randomness of the steering wheel movements computed based on the frequency distribution of predicted errors in steering wheel angle for each driver in a given test condition.

NOTE 1: Two methods are provided for calculating Steering Entropy, (1) the 1999 Boer method and (2) the 2005 Boer method. See Appendix G for the calculations. The MATLAB code is on the UMTRI Driver Interface web site.

NOTE 2: Steering entropy values are between 0 and 1 where 1 is maximum randomness. Steering entropy is dimensionless.

NOTE 3: One steering entropy value is calculated per trial during a particular test condition.

NOTE 4: Steering entropy has been used as a statistic to indicate driver workload, though it can be used to indicate any instance of inattention (due to fatigue, drugs, etc.). The less the driver is attending to steering, presumably because the driver is paying attention to something else or unable to attend, the less consistent (more irregular and unpredictable) is the steering wheel angle. In other words, the steering behavior indicates a lower level of order, or more randomness, i.e., a state of higher entropy.

NOTE 5: Steering entropy analyses are determined relative to a baseline condition involving normal driving with no secondary task or debilitating condition.

RECOMMENDATIONS AND REQUIREMENTS: The first instance the term *steering entropy* is used in a document, the calculation method (1999 or 2005) shall be reported. If other computation methods are used, a link to the source code should be provided.

GUIDANCE for Steering Entropy: Nakayama, Futami, Nakamura, and Boer (1999) provide a method to compute steering entropy and used it to quantify workload. See also Boer (2000) and Boer (2001) for additional explanations. Later a revised computation was presented in Boer, Rakauskas, Ward, and Goodrich (2005). The 2005 version is preferred. Steering entropy is generally computed using MATLAB or Excel.

Examples of studies using steering entropy include Rakauskas, Ward, Bernat, Cadwallader, Patrick, and de Waard (2005), Ranney, Mazzae, Baldwin, and Salaani (2007), Dawson, Cosman, Lei, Dastrup, Sparks, and Rizzo (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 7 provides baseline and task-related steering entropy data.

Table 7 – Steering entropy for various tasks for 4 subjects
Source: Nakayama, Futami, Nakamura, and Boer (1999), p.6

	Subject				
Task	**1**	**2**	**3**	**4**	**Mean**
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

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 boundary, measured perpendicular to the traveled way.

NOTE 1: There are three ways to compute lateral lane position: (1) with regard to the lane center (option A, 10.1.1.1), (2) with regard to the mean path driven within the lane (normalized, option B, 10.1.1.2), and (3) with regard to the lane edge towards the roadway center (option C, 10.1.1.3).

NOTE 2: Lateral position can be measured relative to different four locations on a vehicle, (1 - the lateral midpoint of front bumper, 2 - the center of the vehicle front axle, 3 - the center of gravity, or 4 - the spatial center), either at the current vehicle position or at a predicted vehicle position a short time into the future.

NOTE 3: In driving simulators, the lateral lane position is usually determined with regard to one of the four locations on the vehicle described in note 2, most often the center of gravity.

NOTE 4: For a vehicle on a test track or road (and specifically for options A (10.1.1.1) and B (10.1.1.2), lateral lane position is determined by means of a camera or cameras 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 accuracy of the lateral lane position measurement. Generally, the lateral position can be determined with regard to any of the four locations in note 2. The front axle location is often used for real vehicles, though if part of a lane departure system, the vehicle position may be some distance or time in front of the current vehicle position. If a real vehicle has multiple front axles, the most forward axle serves as the reference.

10.1.1.1 Lateral position relative to lane center (Option A)

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

NOTE: Using a right-handed coordinate system, distance to the right of the lane centerline is positive and to the left is negative. This is consistent with the Z down reference system in SAE J670 (forward, right, and down are positive).

10.1.1.2 Lateral position relative to mean 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 1: 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 41). 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.

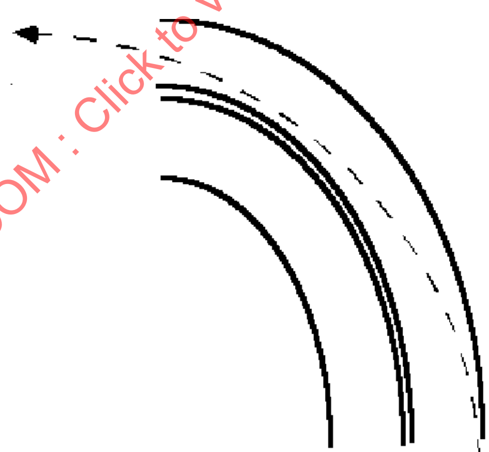

Figure 41 - Example of lane position showing curve cutting
Source: U.S. Department of Transportation (1997)

NOTE 2: Using a right-handed coordinate system, distance to the right of the lane centerline is positive and to the left is negative. This is consistent with the Z down reference system in SAE J670 (forward, right, and down are positive).

10.1.1.3 Lateral position relative to lane edge (Option C)

Lateral distance, usually measured in inches, feet, centimeters, or meters, from a reference point on the vehicle to the inside edge of the lane boundary perpendicular to the lane centerline (Figure 42).

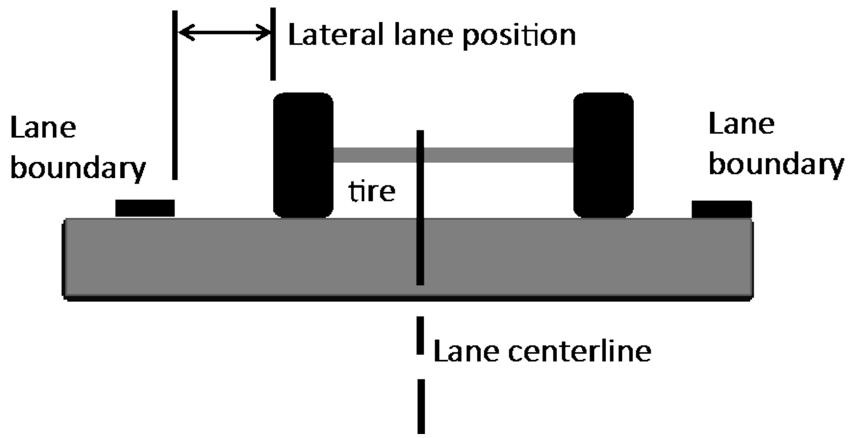

Figure 42 - Example of lateral position relative to lane edge (option c) relative to the front axle (option 2)

NOTE 1: 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 2: There may be situations where two cameras are used. They are usually attached to the exterior mirrors and often aimed directly downward or angled towards a front tire.

REQUIREMENTS: 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 (1-front bumper, 2-front axle, 3-spatial center, 4-center of gravity) and the vehicle position at which the measurement is made (current or predicted).

If option C (10.1.1.3) is used, the relevant lane edge (left or right) shall be reported. If the reference location is in front of the vehicle, the distance from the front bumper shall be reported. If the predicted vehicle location varies with the vehicle speed, the equation describing that relationship shall be provided. The values for straight and curved roadway sections shall be reported separately.

For driving simulator studies, the method for determining lateral position on curved traveled ways shall be reported, and if the computation was chord-based, the maximum error of the computation shall be reported.

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

Quality checks should be made on lateral lane position data obtained from a camera system. 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 being completed in 0.5 s. Quality is often indicated by a confidence measure. Confidence measures, typically ranging from 0 (no confidence) to 1 (complete confidence), indicate the certainty that the lateral position data is correct. How confidence measures are computed is rarely specified or reported.

For most evaluations, option A is recommended, though there may be situations where option B is more appropriate. 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. Option C is generally not recommended because lanes vary slightly in width. Traveled ways 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 43). In those cases, the lateral lane position is the distance from the centerline of the chord, not the curve. To provide a numeric example, consider a 200 m (650 ft) radius curve. Suppose, that curve was approximated by 20 chords. The angle of each chord would then 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 (6 in), a considerable amount considering that the standard deviation of lane position is on the order of 0.2 m (8 in).

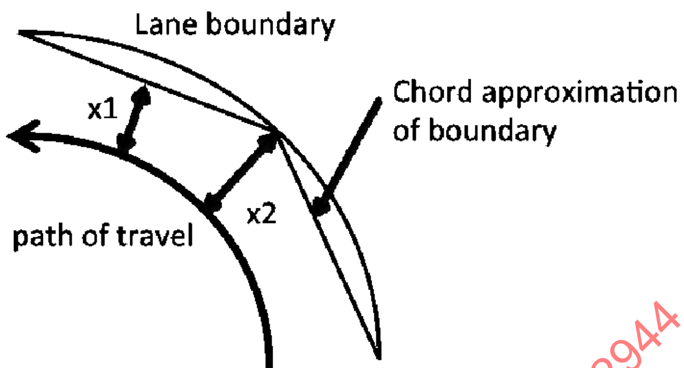

Figure 43 - Chord lane boundary problem

Some simulators get around this problem 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 44, the spline approximation is indistinguishable from the original data. The National Advanced Driving Simulator provides output measures for both splined and non-splined lane boundaries (Schwarz, 2012, personal communication).

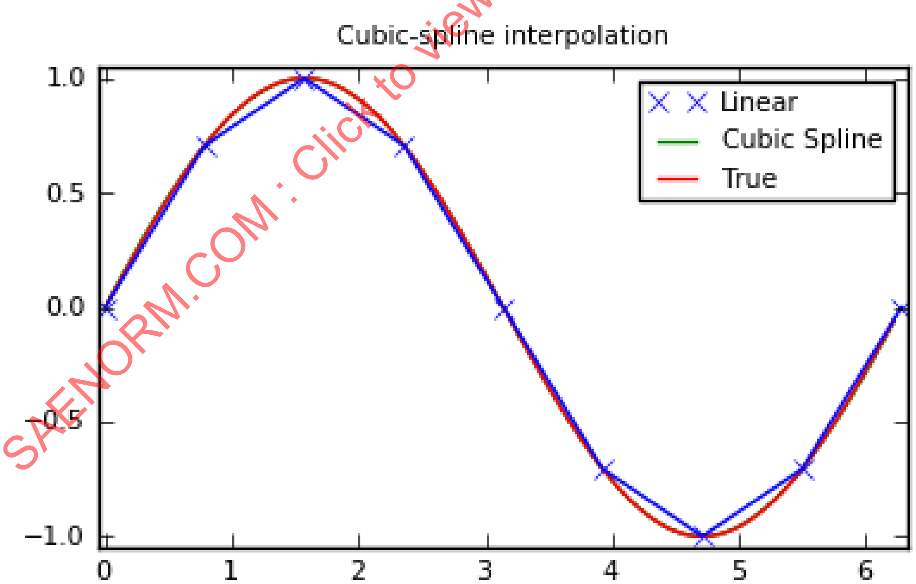

Figure 44 - Cubic spline approximation of a sine wave
Source: http://library.isr.ist.utl.pt/docs/scipy/tutorial/interpolate.html

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

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 longitudinal location in the lane, or along a specified longitudinal distance in the lane, determined by adding up the lateral position data points (one per vehicle/driver at any given point on the lane centerline) and dividing by the number of data points.

NOTE 1: Depending upon the situation, the mean could be computed for (1) a single subject along a lane segment, (2) multiple subjects along a lane segment or (3) multiple subjects at a single point on the lane longitudinal centerline. The context will make it apparent which is being computed.

NOTE 2: Sometimes this term has been referred to as lane offset (Figure 33).

NOTE 3: See Mas, Merienne, and Kemeny (2011) for a description of line integral of the lateral position, an alternative statistic for the *mean lateral lane position*.

REQUIREMENTS: If the term *lateral lane position* is not defined in a document before the first instance the term *mean lateral lane position* is used in a document, the method used to calculate lane position (option A, B, or C) and the reference point on the vehicle (1 - lateral midpoint of front bumper, 2 - center of the vehicle front axle, 3 - center of gravity, or 4 - spatial center) shall be reported.

GUIDANCE for Mean Lateral Lane Position: Figure 45 shows the distribution of lateral lane positions (labeled as lane offset) for all drivers for all driving conditions examined in the IVBSS project (Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blanespoor, and Winkler, 2011). The mean lateral position varies with the time of day and vehicle speed, with the mean position being to the left of lane center (Option A) by 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.

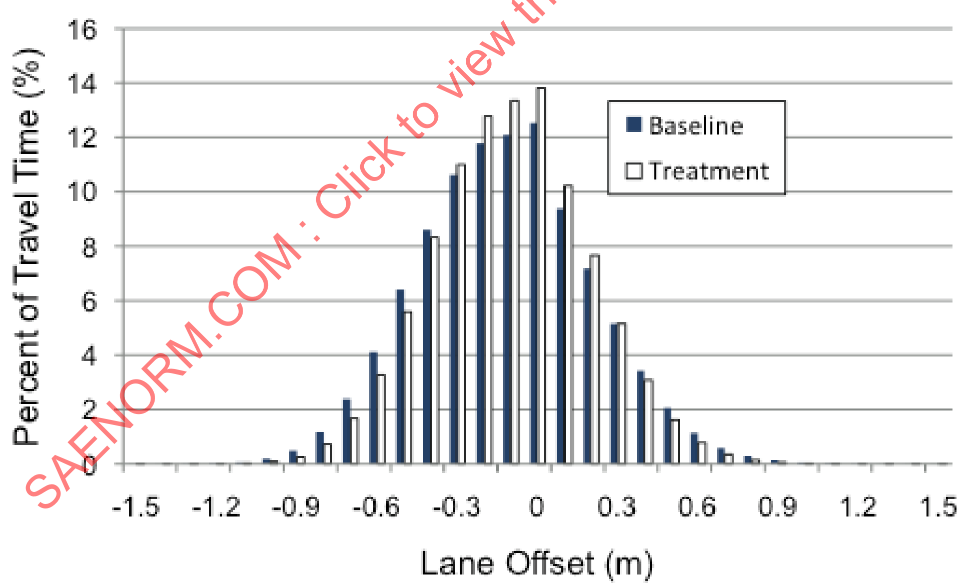

Figure 45 - Distribution of lateral positions from the IVBSS project for all driving conditions
(Treatment refers to the IVBSS warning suite being on.) Source: Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blanespoor, and Winkler (2011), p. 50

Tarko (2012) reports that the distribution of lateral lane positions that nearly (but do not) result in a lane 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).

10.1.3 Standard deviation of lane position (SDLP)

Statistic describing the dispersion/variability 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 lateral lane position
$\overline{x}$ = mean lateral 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: SDLP is the most frequently reported lateral lane position statistic.

REQUIREMENTS: The first instance that *standard deviation of lane position* is used in a document, the denominator term (N or N-1), the option used to compute the mean (option A, B, or C), the reference point on the vehicle used to determine lateral lane position (1 - lateral midpoint of front bumper, 2 - center of the vehicle front axle, 3 - center of gravity, 4 - spatial center), the time or distance in front of the vehicle bumper (if vehicle position is predicted), and the test condition(s) and/or independent variables over which the mean was determined (e.g., conditions, subjects, etc.) shall be reported.

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

Kircher, Uddman, and Sandin (2002) report 0.2 m is 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.

10.2 Lane Departure Measures and Statistics

10.2.1 Lane Departure

Interval when some part of the vehicle is no longer in the travel lane, until the entire vehicle has returned to the original lane of travel or the vehicle comes to a stop before returning to the lane, excluding lane changes and turning maneuvers.

NOTE 1: When a lane departure occurs, a vehicle could strike another vehicle or pedestrian in an adjacent lane or on a shoulder or contact a roadside appurtenance such as a sign, lamp post, mailbox, lane barrier, curb, or retaining wall.

NOTE 2: There are four parts of a vehicle typically used to determine the start of a lane departure: (1) the front tire contact patch, (2) the widest part of vehicle, (3) a rear tire contact patch, and (4) the front or rear overhang (including the corners), if the vehicle is spinning. They are used in combination with the inside edge, middle, or outer edge of a lane boundary marking.

NOTE 3: There may be instances where some amount of departure beyond the lane boundaries is accepted practice, primarily for large trucks and buses traveling in narrow lane widths. In these cases and the lane boundaries may be expanded. See 6.3.3.

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

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. Similarly, a passing maneuver is not a lane departure.

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

NOTE 8: SAE J2808: 2007, section 3.6 defines a *lane departure* as "the point of departure across the lane boundary," which is insufficiently specific because the term lane boundary is not defined.

NOTE 9: ISO 17361:2007 defines a *departure* as a "situation in which the outside of one of the front wheels of a vehicle or of the leading part of an articulated vehicle - or, in the case of a three-wheeled vehicle, the outside of one of the wheels on the axle with the widest track - is crossing a specified line" and defines a lane departure as the "point of departure across the lane boundary." Unfortunately, "crossing" is not defined.

NOTE 10: *Lane departure* is sometimes called *lane exceedence* or *lane boundary excursion* (LANEX). See ISO 17287.

10.2.1.1 Summary of options

There are 11 ways that a lane departure can begin and end. The 11 options (A - K) 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 8). 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. Options H, I, J, and K are used in driving simulators. See 10.2.1.2 - 10.2.1.12.

Table 8 - 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 Edge 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 Edge of Lane Boundary	
F – Any Tire, Outside Edge of Lane Boundary	
G – Any Tire, Tire Beyond Outside Edge of Lane Boundary	
H – Bounding Box of Body, Inside Edge of Lane Boundary	Body bounding box of vehicle or vehicle-trailer combination is inside lane of travel, or vehicle comes to a stop before returning to the lane of travel
I – Bounding Box of Body with Mirror, Inside Edge of Lane Boundary	
J – Bounding Box of Body, Outside Edge of Lane Boundary	
K– Bounding Box of Body with Mirror, Outside Edge of Lane Boundary	

NOTE: There may be instances where other criteria for a departure are appropriate, especially for wide vehicles driven in narrow lanes or for vehicles towing trailers, because lane departures may occur so often or last so long that one is not able to discriminate among test conditions. This occurred for Boer and Ward (2003) in their study of lateral position support systems for 8.5-ft wide buses driven in 9-ft lanes. In their research they added an extra half bus width to the lane boundary before considering that a departure had occurred. See 6.3.3 for a discussion of lane expansion.

10.2.1.2 Widest part of the vehicle, middle of the lane boundary

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 marking. See Figure 46.

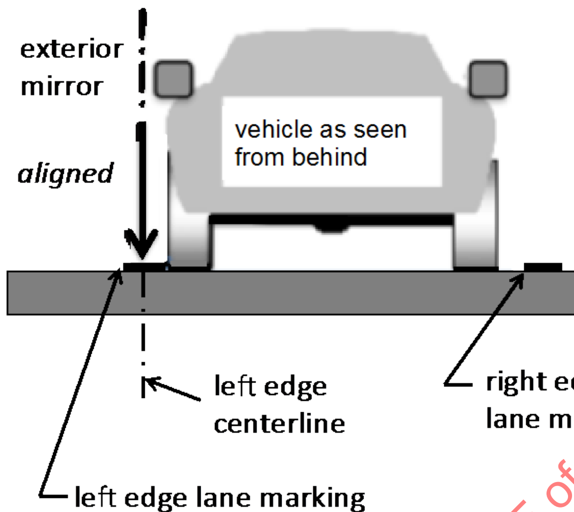

Figure 46 - Lane departure, option A: Widest part of vehicle crosses lane marking centerline

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 laterally moveable and a wide trailer is towed, they would be deployed to the outermost setting.)

NOTE 3: For sports cars the widest point may be 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 roadside structures serve as the lane boundary.

10.2.1.3 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 47.

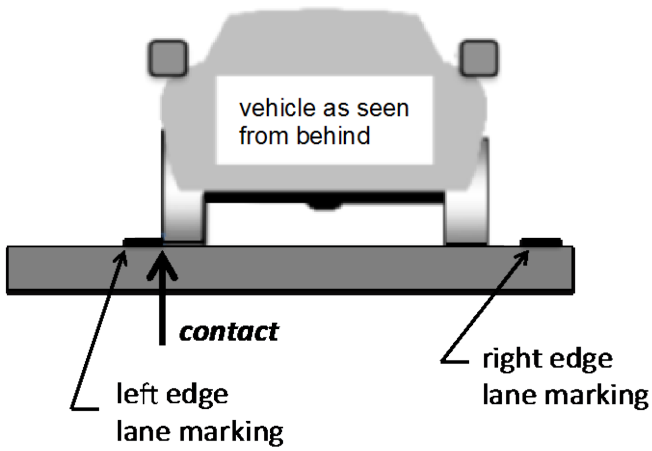

Figure 47 - Lane departure, option B: Front tire touches inside of lane marking

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

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.

10.2.1.4 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 48).

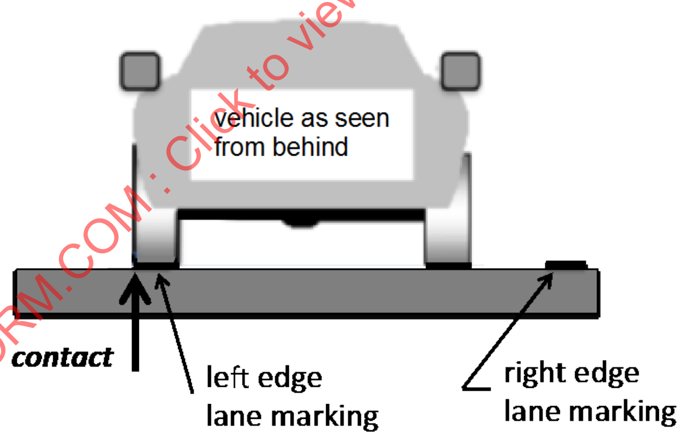

Figure 48 - Lane departure, option C: Front tire touches outside of lane marking

NOTE 1: The difference between Options B and C is the width of a lane marking, typically 4 in (10 cm), but sometimes 6 in (15 cm).

NOTE 2: Ranney, Baldwin, Parmer, Martin, and Mazzae (2012) used this option.

10.2.1.5 Beyond outside of lane marking, front tire (Option D)

A departure begins when either front tire contact patch is completely beyond the outside edge of the closest lane marking (Figure 49).

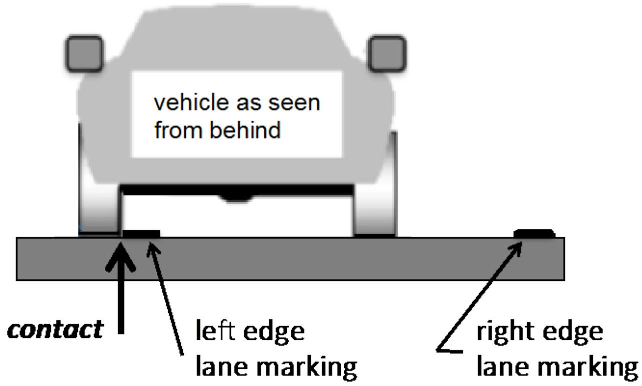

Figure 49 - Lane departure, option D: Front tire outside of lane marking

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 (7 in) whereas tire width for a 2012 Cadillac Escalade EXT is 285 mm (11 in). For heavy trucks, 284 mm (11 in) is fairly typical.

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

10.2.1.6 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 (Figure 50).

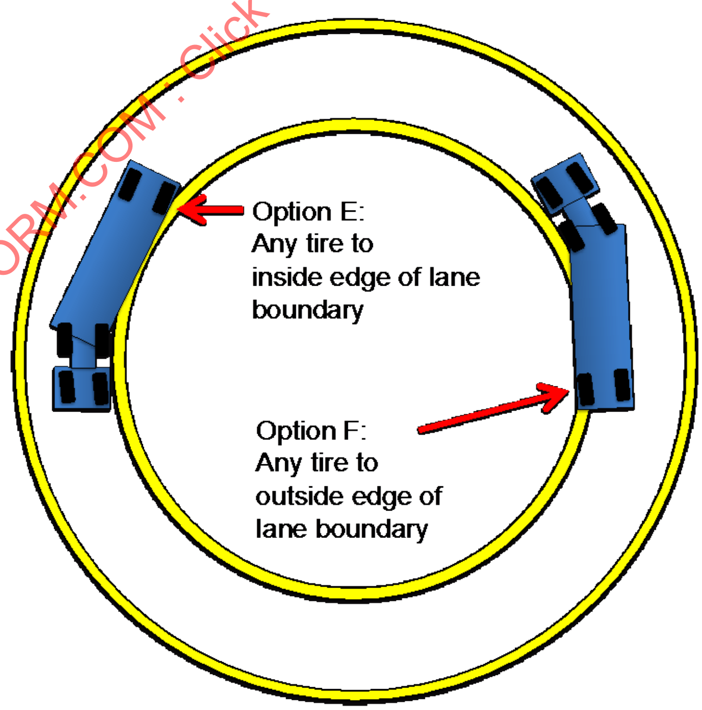

Figure 50 - Lane departure, options E and F:
Any tire touches inside/outside of lane marking

NOTE 1: This definition is identical to option B except that it refers to any tire. Although Figure 50 depicts a tractor-trailer, the vehicle could be any vehicle with a trailer, any articulated vehicle, or any vehicle in a spin.

NOTE 2: There may be situations, such as when a tractor-trailer is driven 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 through a curve 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 determining that a tractor-trailer lane departure ended, keep in mind that for a tractor-trailer, even though the cab may return to the lane before the trailer, all tractor and trailer tire contact patches have to be inside the original lane of travel.

10.2.1.7 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.

10.2.1.8 Tire fully outside of lane marking, any tire (Option G)

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

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

10.2.1.9 Bounding box of the vehicle body touches the inside of the lane marking (Option H)

A departure begins when a bounding box that is equal to the vehicle body width and length touches the inside edge of the closest lane marking.

NOTE: The NHTSA NCAP procedure defines a lane departure as "a lane departure is said to occur when any part of the two-dimensional polygon used to represent the test vehicle breaches the inboard lane line edge. In the case of tests performed in this procedure, the outside front corner of the polygon will cross the line edge first. In other words, if the vehicle departs its lane to the left, the left front corner of the polygon would first breach the lane line edge." A footnote states, "The inboard side of the line is defined as that which is closest to the vehicle before the departure occurs" (U.S. Department of Transportation, 2010b, p. 17-18). It is unknown if the width is for the body only (this option) or includes the exterior mirrors (option I).

10.2.1.10 Bounding box of the vehicle body with the exterior mirror touches the inside of the lane marking (Option I)

A departure begins when a bounding box that is equal to the vehicle body length and width including the exterior mirror touches the inside edge of the closest lane marking.

NOTE: This definition is identical to option H except that it includes the exterior mirror.

10.2.1.11 Bounding box of the vehicle body touches the outside of the lane marking (Option J)

A departure begins when a bounding box that is equal to the vehicle body width and length touches the outside edge of the closest lane marking.

NOTE: This definition is identical to option H except that contact is with the outside edge of the lane marking.

10.2.1.12 Bounding box of the vehicle body with the exterior mirror touches the outside of the lane marking (Option K)

A departure begins when a bounding box that is equal to the vehicle body width and length including the exterior mirror touches the outside edge of the closest lane marking.

NOTE: This definition is identical to option I except that contact is with the outside edge of the lane marking.

Guidance for Lane Departure: The preferred option for the start of a lane departure will depend on the intended use of the data, the requirements of other standards, and possibly other reasons. Lane departure 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 documents, such as the NCAP Forward Crash and Lane Departure Warning System 2010 Test Procedures (U.S. Department of Transportation, 2010a, b) and the Alliance Driver Focus Guidelines (Alliance of Automobile Manufacturers, 2006), may use different definitions.

In some countries, lane markings are viewed as a suggestion, in which case lane departures may not be a major societal concern. In highly developed countries lane maintenance is widely observed and lane departures, even brief ones are considered unacceptable, though some tolerance is given when the traveled way has very narrow lanes.

The focus of the literature has been on the lane departures of cars. However, lane departures of trailers or tractor-trailers in North America, especially on traveled ways with 9-ft or narrower lane widths can be common. Cars and pickup trucks towing trailers with 5 x 8-ft beds may also be more likely to depart the lane on these lane widths.

The popping sound of driving over Botts dots (raised non-reflective pavement markers) or raised reflective pavement markers often indicates an option C lane departure is about to occur or has just occurred.

RECOMMENDATIONS AND REQUIREMENTS: The first instance the term *lane departure* is used in a document, the start option (A – K) and the value of lane expansion, if used, shall be reported. The option used for when a vehicle is skidding shall be reported. Separate records should be reported for lane departures that do and do not return to the lane of travel, and for departures from straight and curved roads, provided that roadway curvature data are available. Should intentional and unintentional departures be identified, the criteria for the distinction shall be reported.

10.2.2 Number of lane departures

Count of the number of times usually reported for a particular distance, often per 100 mi or 100 km, when some part of the vehicle is no longer in the travel lane.

NOTE 1: The number of lane departures depends on how a lane departure is determined. There are 11 options (A – K). See Table 8 and 10.2.1 - 10.2.12.

NOTE 2: If a vehicle crashes and does not re-enter the lane, the lane departure has ended.

NOTE 3: Lane changes, passing, and turning maneuvers are not lane departures because they are intentional.

NOTE 4: For departures not ending in a crash, the departure is deemed to end if all tire contact patches or the entire vehicle has returned to the lane of travel, or the vehicle stops outside the lane of travel.

NOTE 5: There are often instances in which a vehicle returns to a lane after departing and then immediately leaves the lane again, in which case a second lane departure is recorded. In this case the first departure ends when all tires have crossed the lane boundary they originally departed.

RECOMMENDATIONS AND REQUIREMENTS: The first instance the term *number of lane departures* is used in a document, the start option (A - K), the end of the departure (all tires in the lane of travel, crash, or stopped vehicle), and any lane expansion shall be reported. Separate records should be reported for lane departures that do and 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 alert 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 (or 4.4, 5.2, 5.7, and 3.7 per 100 km). When a warning system was provided, the number of warnings was 15.9, 13.7, 16.4 and 11.0 per 100 miles (or 9.9, 12.8, 10.2, or 6.8 per 100 km). 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 were about 20 departures/100 miles (12 per 100 km) for pickup and delivery routes over limited access and surface roads and 16 - 21 departures/100 miles (10 - 13 per 100 km) for line haul routes. Installing lane departure warning systems reduced those rates slightly (Sayer, Bogard, Funkhouser, LeBlanc, Bao, Blankespoor, Buonarosa, and Winkler, 2010).

10.2.3 Lane departure duration

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

RECOMMENDATIONS AND REQUIREMENTS: The first instance the term *lane departure duration* is used in a document, the start option (A – K, Table 8, 10.2.1–10.2.12) and any lane expansion shall be reported. Separate records should be reported for lane departures that do and do not return to the lane of travel.

GUIDANCE for Lane Departure Duration: As shown in Figure 51, lane departure durations are exponentially distributed and most are less than 2 s (Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler, 2011).

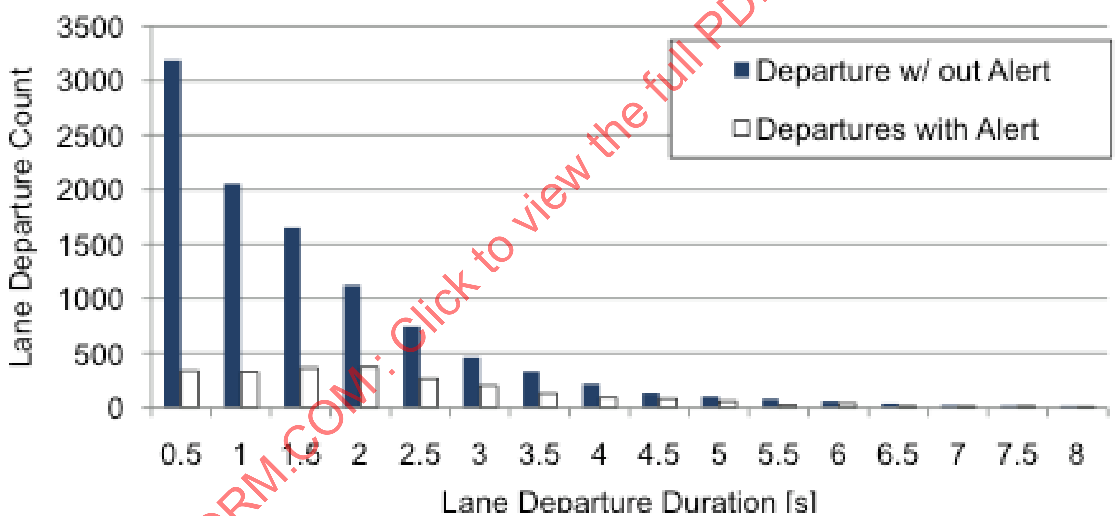

Figure 51 - Distribution of lane departure durations

Source: Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler (2011), p. 56

10.2.4 Lane departure magnitude

Perpendicular distance from the edge of the lane boundary that was departed to the center of the first tire contact patch to depart, usually measured in inches or centimeters.

RECOMMENDATIONS AND REQUIREMENTS: The first instance the term *lane departure magnitude* is used in a document, the start option (A – K) used to determine a departure shall be reported. Separate records should be reported for lane departures that do and do not return to the lane of travel.

GUIDANCE for Magnitude of Lane Departures: Figure 52 shows a distribution of lane departure magnitudes from the IVBSS report. A value of 6 cm (3 in) was most common; departure magnitudes larger than 18 cm (7 in) were quite rare. The statistic of interest most often is the maximum lane departure magnitude, the largest departure distance from the start to the end of the lane departure.

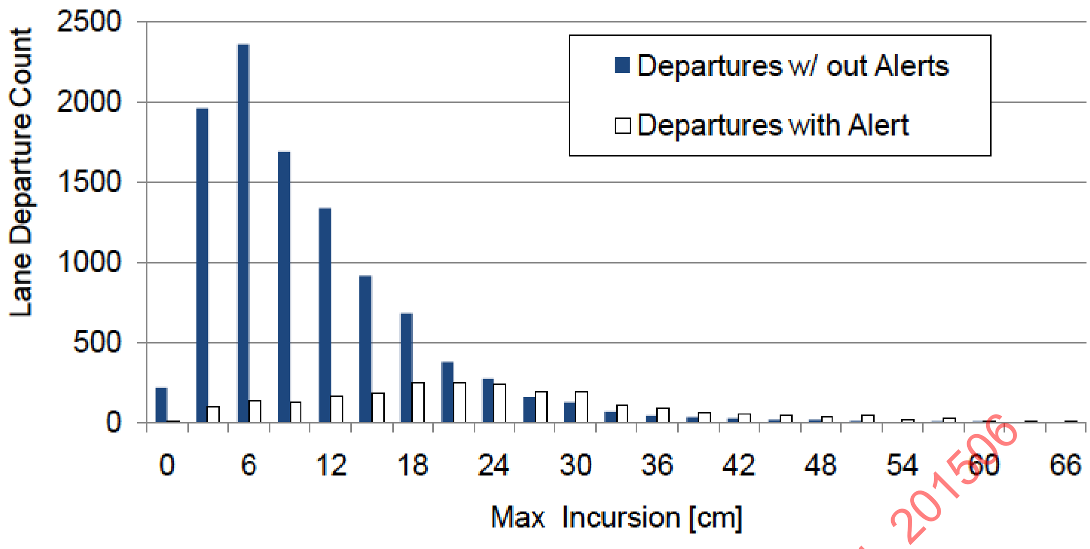

Figure 52 - Maximum lane departure magnitude (incursion)
Source: Sayer, Buonarosa, Bao, Bogard, LeBlanc, Blankespoor, Funkhouser, and Winkler (2011), p. 78

10.3 Lateral Position Exposure Statistics

10.3.1 Time-integrated lane departure magnitude

Integral, usually measured in meter-seconds or feet-seconds, of the lane departure magnitude (as a function of time) times dt, the incremental time, integrated over the time interval from start to end of the departure (Figure 53).

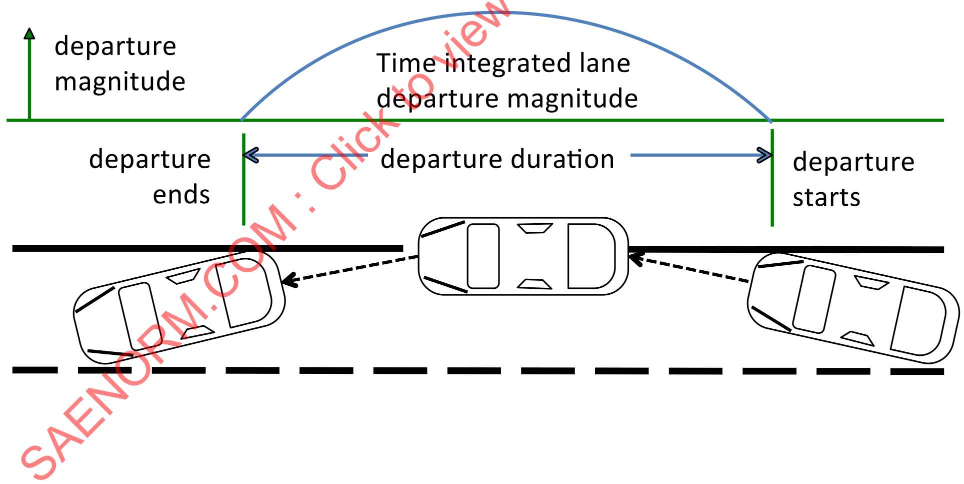

Figure 53 - Time-integrated lane departure magnitude

NOTE 1: This statistic can only be computed for lane departures where the vehicle returns to the lane. The start and end times of the lane departure define the limits of the integral.

NOTE 2: This statistic indicates the risk (exposure time and magnitude) of striking or being struck by another vehicle or hazard during the lane departure and is useful in comparing short high magnitude departures with longer low magnitude departures.

NOTE 3: Hollopeter (2011) refers to a similar exposure measure "Lane Exceedence Exposure (Area)" (p. 30). The measure, having units of meters^2, is computed as the integral of the lane departure magnitude times dx, the incremental distance along the lane edge from the start to the end locations of the departure. See also Hollopeter, Brown, and Thomas (2012) for additional data.

REQUIREMENTS: The first instance the term *time-integrated lane departure magnitude* is used in a document, the start option (A – K) for a lane departure shall be reported.

GUIDANCE for Time-Integrated Lane Departure Magnitude: This statistic can be estimated by multiplying the mean magnitude of lane departure by the mean departure duration**.** As this statistic is quite new, data are not available.

10.3.2 Time to line crossing (TLC)

Time, usually in seconds, required for some part of a vehicle to reach a lane boundary assuming the steering wheel angle and speed (or acceleration) are kept constant so the vehicle continues on the current path at the current speed (or acceleration).

NOTE 1: That part could be a front tire, a rear tire, or the widest part of the vehicle. Most often, the part is the front tire.

NOTE 2: Consistent with the definition of a lane departure, there are 11 ways in which line crossing can be determined (options A - K). See 10.2.1.2 - 10.2.1.12 for these options and Table 8 for a summary.

NOTE 3: There are three ways time to line crossing can be computed (1) option A, acceleration method, (2) option B, first derivative method, and (3) option C, trigonometrically. See 10.3.2.2.

NOTE 4: The trigonometric computational method for TLC reported in Van Winsum, Brookhuis, and de Waard (2000) is provided in Appendix H. See Lin and Ulsoy (1995), Mammar, Glaser, and Netto (2006), and Mammar, Glaser, and Sebsadji (2007) for additional computational details.

NOTE 5: TLC was first described in Godthelp and Konings (1981) with additional details provided in Godthelp (1984), Godthelp, Milgram, and Blaauw (1984), and Godthelp (1988).

NOTE 6: TLC measures are only defined if the vehicle is within a lane having well-defined lane boundaries and lane markings. TLC is not a suitable measure for urban driving including roadway junctions and parking lots.

NOTE 7: TLC measures are often reported for driving simulator studies, for which the center of each edge marking and mirror-to-mirror vehicle width (or some other measure of vehicle width) may be readily available. However, readers should be aware that the logical and visual databases might not be perfectly aligned. Exactly how various simulators compute TLC is usually not reported.

10.3.2.1 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 in 10.2.1.3.

10.3.2.2 Acceleration method (Option A)

Time, usually in seconds, required for some part of a vehicle to reach a lane boundary if the vehicle continues on its current path at the current acceleration, calculated using the instantaneous lateral distance, velocity, and acceleration as follows.

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

where:

y = lateral distance from either front wheel perpendicular to the closest lane boundary

y' = lateral velocity after 1 s

y'' = lateral acceleration

NOTE: This method is described in more detail in Appendix I and in van Winsum and Godthelp (1996).

10.3.2.3 TLC Velocity Method (Option B)

Time, usually in seconds, required for some part of a vehicle to reach a lane boundary if the vehicle continues on its current path at the current speed, calculated using the instantaneous lateral distance and velocity as follows.

$$TLC = y/y'$$

where:

y = lateral distance between the front wheel and the closest lane boundary

y' = lateral velocity, sometimes call the rate of departure

NOTE: ISO 17361:1997, definition 3.9 (page 2) defines *time to line crossing* (which it abbreviates as TTLC) as "calculated time to lane departure," which is computationally identical to TLC, option B, but uses different nomenclature. Specifically, "The simplest method of calculating TTLC is to divide the lateral distance, D, between the predetermined part of the vehicle and the lane boundary by the rate of departure, V (defined as "the approach velocity at right angle to the lane boundary"), of the vehicle relative to the lane."

GUIDANCE for TLC Option B: This computation may be easier to do in a simulator than on a real roadway 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.

10.3.2.4 TLC trigonometric computation, TLC_tri (Option C)

Time, usually in seconds, required for some part of a vehicle to reach a lane boundary if the vehicle continues on the current path at the current speed, based on an exact trigonometric calculation.

NOTE 1: In computing TLC, roadway curvature, curvature of the vehicle path, vehicle distance to the lane line edge, vehicle speed, and location of the center of a curved roadway are all considered, as described by Winsum, Brookhius, and de Waard (2000). For additional computational information on computing TLC for straight and curved paths, see Mammar, Glaser, and Netto (2006).

NOTE 2: Although this may appear to be the exact computational solution, it often is not because curves on real roadways are often not of constant radius (blended curves).

REQUIREMENTS: The first instance the term *time to line crossing* is used in a document, the option used to determine a departure (A - K) and the computational method (A – C) shall be reported. Authors shall also report: (1) the maximum value of TLC in excess of which values are ignored, (2) the minimum and maximum sample durations for TLC waveforms, and (3) if the data are filtered, the filter used and its parameters.

GUIDANCE for Time to Line Crossing: The time to line crossing is determined most often with regard to the front tire touching the inside of the lane boundary line (lane departure option B). Östlund et.al (2005) recommended two TLC measures, mean TLC (10.3.4) and number of lane departures (line crossings), for assessing drivers' ability to stay on the traveled way.

Should the data be filtered? Some filtering and data quality checks to avoid amplifying noise should be considered when TLC collected in field experiments is analyzed. (See 5.1.4.) 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). For additional information on real-time signal filtering, see Cario, Casavola, Franze, Lupia, and Brasilli (2009).

What minimum and maximum TLC thresholds are recommended? Sometimes TLC waveforms can result in brief peaks, so Ostlund, Nilsson, Tornros, and Forsman (2006) recommend ignoring TLC waveforms of less than 1 s.

If drivers do not consider the lane markings as delineating a safe travel path, then how they drive the traveled way (e.g., straddling the line and crossing it often) can result in TLC values that are very small or very large. Meaningfully shorter TLC values represent poorer lateral control. When drivers disregard the lane markings, the TLC values are not meaningful (Östlund et.al, 2005). For wide vehicles travelling in narrow lane widths, the concept of lane expansion (6.3.3) could be investigated.

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 gives a misleading impression of driving safety. Ostlund, Nilsson, Tornros, and Forsman (2006) showed that TLC values greater than 20 s should also be ignored when computing mean TLC because they are irrelevant from a safety point of view.

What is the recommended minimum data duration? TLC durations need to be long enough to avoid statistical artifacts. As was noted elsewhere in an AIDE project (Ostlund, Peters, Thorslund, Engstrom, Markkula, 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 unfeasible for data less than several minutes long.

For which conditions is each of the TLC computational methods used? The first step is to determine what data are available. Option C, the exact trigonometric method is the most accurate, but it 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 vehicle yaw angle relative to the roadway, and the difference in location between the center of the curve radius and the center of the vehicle's turning radius. GPS data is now readily available for real roadways, so a vehicle's location relative to the roadway geometry can be determined. Further, for real roadways, curve radii are shown on as-built plans, which can be obtained, albeit with some effort. However, the calculations assume that real roadways 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. Thus, as a practical matter, the data needed is usually only available for driving simulators.

Some driving simulators have built in functions for TLC, though the calculation method may not be identified. Do not expect the simulator provided value to be accurate. Consequently, always check the simulator-provided TLC data using the x, y coordinate data for vehicle position, data on lane position and yaw angle, and data on vehicle length, width and front axle location, all of which are accurate. Depending on the simulator, the x, y position coordinates could be the spatial center or the geometric center.

To select a computation method, one needs to know when the differences between methods matter. Van Winsum, Brookhuis, and de Waard (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 exact trigonometric solution (option A). They conducted three 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.

In the second experiment involving normal lane changes, the method with acceleration (option C) gave better estimates of TLC_tri when the vehicle was 0.6 s or less from the lane boundary. However, when the vehicle was 0.8 - 1.0 s from the lane boundary, option B predictions more closely approximated the exact value of TLC.

In a third experiment concerning drowsiness, estimated lane departures were examined. The findings were similar to the lane change experiment. For true TLC values 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. Van Winsum, Brookhuis, and de Waard (2000, p. 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 … 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 (option B here) 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 (option C*) or the second approximation* (option A) *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."*

What are some typical TLC values? Wiethoff (2003), based on the data of Godthelp (1988) and Brookhuis, de Waard, and Fairclough (2003), reported the TLC values shown in Table 9 as being representative of impaired driving due to inattention, fatigue, alcohol, or for other reasons.

Table 9 - TLC values for impaired driving

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 - 6.9 s for a simulated rural roadway, 7.2 - 8.1 s for a simulated motorway, 4.9 - 5.6 s for a real motorway. For additional information on TLC values and their distribution, see Lin and Ulsoy (1995). See also Glaser, Mammar, Neto, and Lusetti (2005) for experimental issues, and Gordon, Kostyniuk, Green, Barnes, Blower, Bogard, Blankespoor, Leblanc, Cannon, and McLaughlin (2010) and Gordon, Kostyniuk, Green, Barnes, Blower, Blankespoor, and Bogard (2011) for the application of TLC.

10.3.3 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 if the vehicle continues on the current path.

NOTE 1: TLC data typically have waveforms with multiple local minima. Certain rules of thumb are used to identify TLC minima. See the AIDE report (Ostlund, Peters, Thorslund, Engstrom, Markkula, Keinath, Horst, Juch, Mattes, and Foehl, 2005) for more details.

NOTE 2: The local minima are used to calculate several TLC measures. These include the mean, median and 15th percentile of TLC minima (Östlund et.al, 2005). For short data durations, few or no minima will be found, making the 15th percentile unfeasible to compute.

NOTE 3: The TLC versus sample number plot in Figure 54 reveals a series of TLC epochs, between 1 and 27 s, in which the driver is approaching either the left or right lane boundary, often in an alternating pattern. TLC values greater than 27 s were truncated. TLC minima represent the local TLC minimum within each epoch, which sometimes is to the left lane line and sometimes to the right lane line.

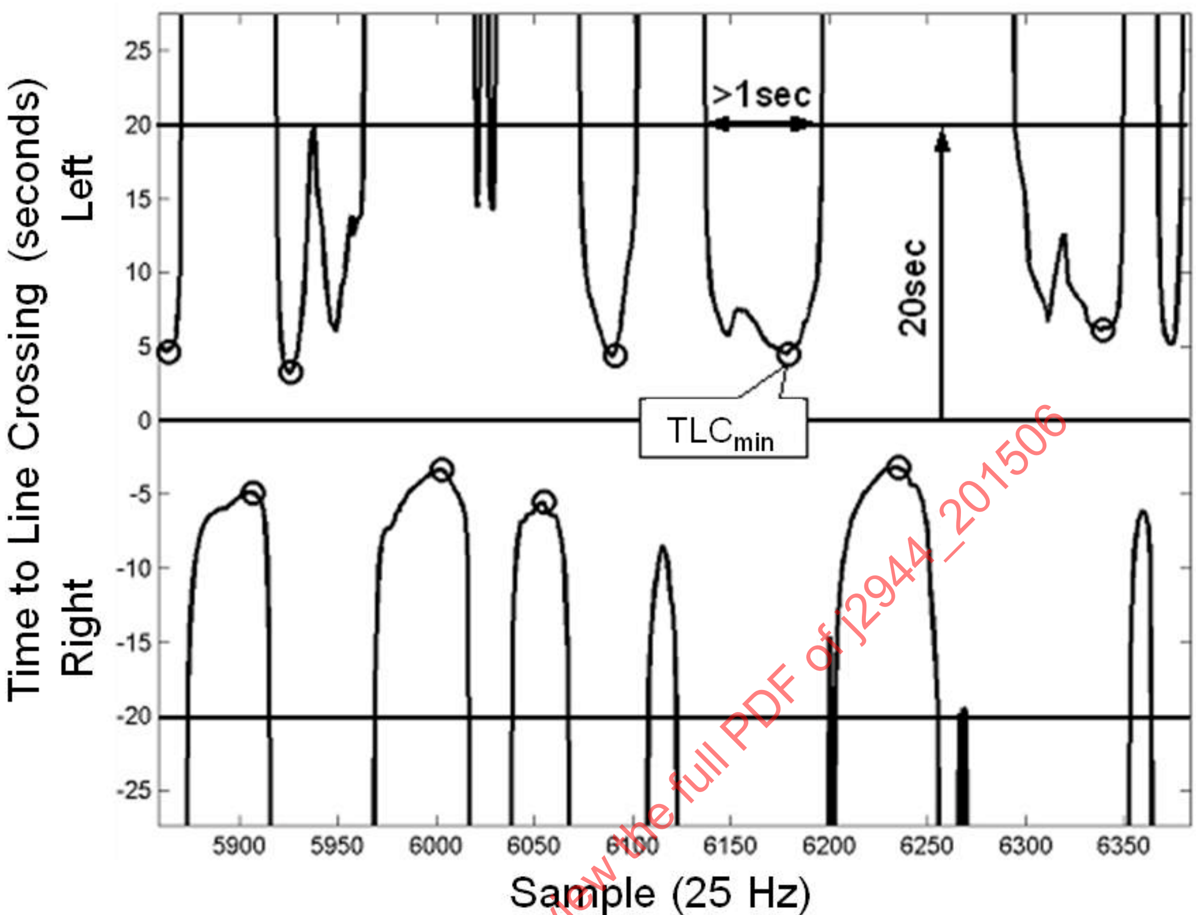

Figure 54 – TLC versus time left and right lane boundary line
Source: Östlund et al, (2004), p. 279

NOTE 4: Negative values in Figure 54 do not indicate TLC was actually negative but rather serve to differentiate between vehicles approaching the left (positive) and right (negative) lane boundaries.

NOTE 5: Additional details on minimum TLC calculations appear in Appendix I. Readers interested in the calculation of TLC minima should also see van Winsum and Godthelp (1996), Kircher, Uddman, and Sandin (2002), or Östlund, Peters, Thorslund, Engstrom, Markkula, Keinath, Horst, Juch, Mattes, and Foehl (2005).

REQUIREMENTS: The first instance the term *minimum time to line crossing* is used in a document, the option used to determine a departure (A – K) and the TLC computation method (A – C) shall be reported. Authors shall also report: (1) the maximum value of TLC in excess of which values are ignored, (2) the minimum and maximum sample durations for TLC waveforms, and (3) if the data are filtered, the filter used and its parameters.

GUIDANCE for Minimum Time-to-Line Crossing: For lane changes on a two-lane, straight roadway with 3.1 and 3.5 m wide lanes in a driving simulator, van Winsum, de Waard, and Brookhuis (1999) report minimum mean TLC values of 1.36 s to the left and 1.70 s to the right, with greater speeds leading to smaller minimum TLC values (50 km/h: 1.74 s; 80 km/h: 1.48 s; 120 km/h: 1.36 s).

10.3.4 Mean time-to-line crossing (Mean TLC_{min})

Mean of local minima in time to line crossing, measured in seconds.

NOTE: This value is not the mean value of the TLC waveform but the mean of the local TLC minima.

REQUIREMENTS: The first instance the term *mean time to line crossing* is used in a document, the option used to determine a departure (A – K) and the TLC computation option (A – C) shall be reported. Authors shall also report: (1) the maximum value of TLC in excess of which values are ignored and (2) the minimum and maximum sample durations for TLC waveforms, and (3) if the data are filtered, the filter used and its parameters.

GUIDANCE for Mean Time to Line Crossing: In the HASTE project (Östlund et.al, 2005), task lengths of approximately 5 - 50 s were used. Significant effects of visual or cognitive distraction were found on mean TLC for task lengths longer than approximately 10 seconds. For very short tasks, no effects may be found because there are too few TLC minima (often 0 - 2) on which to base statistics. Measures such as 15th percentile are unfeasible for durations of less than several minutes. The 15th percentile value is an estimate accurate to the nearest 5 percent provided at least 20 minima are used in the computation. For tasks shorter than a few minutes but having more than two TLC minima, the mean of the TLC minima is recommended.

10.3.5 Inverse time to line crossing

Reciprocal of time to line crossing, usually measured in inverse seconds.

REQUIREMENTS: The first instance the term *inverse time to line crossing* is used in a document, the option used to determine a departure (A – K) and the TLC computation option (A – C) shall be reported. Authors shall also report: (1) the maximum value of TLC in excess of which values are ignored and (2) the minimum and maximum sample durations for TLC waveforms, and (3) if the data are filtered, the filter used and its parameters.

GUIDANCE for Inverse Time to Line Crossing: Boer and Ward (2003) argue for looking at the 75th percentile value of inverse TLC because "strong events are expected to correlate higher with subjective metrics than minor ones" (p. 121). Their median value for inverse TLC is approximately 0.09 s^{-1}.

10.4 Lane Change Measures and Statistics

10.4.1 Lane change

Lateral movement of a vehicle from (1) a merge lane into a lane of a traveled way, (2) one lane of a traveled way to another lane on the same traveled way with continuing travel in the same direction in the new lane, or (3) a lane on a traveled way to an exit lane departing that traveled way.

NOTE 1: In the literature, the term lane change has been used both in a limited way (option 2) where the origin and destination are in the same direction, and in a broader way (options 1 and 3) where merges and exits are included.

NOTE 2: Lane changes are either mandatory or 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 to 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. The geometry of the traveled way usually makes the need for a lane change apparent to all drivers, which influences their driving behavior (e.g., by opening gaps so other drivers can merge). 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) for models of lane change decisions.

NOTE 3: Lane changes can be intended (sometimes signaled) or unintended (windblown or other loss of control such as when skidding). Unintended lane changes are lane departures. Intentional lane changes that are aborted before completion are considered to be a lane departure, not a lane change.

NOTE 4: Lane changes are (1) most often 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 18). 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 ending two or three lanes away from the original vehicle lane is called a two-lane change or a three-lane change.

NOTE 5: Both FARS (Fatality Analysis Reporting System) and GES (General Estimates System) include variables relating to changing lanes. Variable PC17 Pre-Event Movement Prior To Recognition of Critical Event) has “changing lanes” (code 15) as one of the 19 options. Page 586 of the FARS GES analysis and coding manual (U.S. Department of Transportation, 2013a) states, “15 (Changing Lanes) is used when this vehicle was traveling straight ahead and changed travel lanes to the right or left while on the same roadway.“ Interestingly, the next code (16, p. 587) is for merging, which it distinguishes from changing lanes - “16 (Merging) is used when this vehicle was moving forward and merging from the left or right into a traffic lane (e.g., roadway narrows, exit/entrance ramps).“ For related material on lane-change crashes, see Wang and Knipling (1994), Fitch, Lee, Klauer, Hankey, Sudweeks, and Dingus (2009), and Fitch and Hankey (2012).

NOTE 6: Variable PC23 (Crash Type) for Category II: Same Trafficway, Same Direction, Configuration F: Sideswipe/Angle includes codes 46 (Changing Lanes to the Right) and 47 (Changing Lanes to the Left). However the FARS and GES analysis and coding manual does not provide additional details to specify when a lane change is considered to begin or end.

NOTE 7: There are five ways a lane change could be identified as beginning (1) when the driver begins to look towards an adjacent lane with the intent to change lanes (option A), (2) when the turn signal control is first moved to signal a lane change is imminent, realizing that drivers do not always signal (option B), (3) when the vehicle begins to move laterally towards the adjacent lane (option C), (4) when a tire or some surface on the vehicle crosses the lane boundary (option D), and (5) based on some integrated analysis of multiple signals (option E, 10.4.1.5).

NOTE 8: Similarly, lane changes could be identified as ending when (1) looking to settle in the lane ends (option A), (2) the turn signal is turned off, either by the driver or automatically (option B), (3) the vehicle is stably positioned in the lane to which it moved (option C), (4) a rear tire or trailing surface of the vehicle crosses the lane boundary (option D), or (5) some other action occurs as identified by other signals. The options identifying when a lane change begins and when it ends may be different.

10.4.1.1 Looking towards adjacent lane (Option A)

A lane change begins when the driver glance times to the destination lane and driven lane are equal, and ends when driver glance times to the mirrors, the new driven lane, and the original lane are stable.

GUIDANCE for Option A: Salvucci and Liu (2002) classified glances as being to three areas, (1) the currently driven or start lane, (2) the destination or end lane, and (3) the mirrors. When deciding to change lanes drivers may look to the side and ahead of their vehicle, as well as look to the exterior and interior rear-view mirrors or to blind spot detection indicators to search for vehicles in that lane. Salvucci and Liu (2002) suggest using the gaze dwell ratio, the fraction of total glance time spent allocated to each of the three areas as a way to determine the start and end of a lane change, with the term “glance” as defined in SAE J2396.

Figure 15 shows the glance data from a lane change on a highway in a driving simulator, showing the fraction of glances to the origin lane, the destination lane, and the mirrors. The point when the gaze ratios (fraction of total glance times) for the driven and destination lanes are equal indicates the start of the lane change (the beginning of phase LC1 in Figure 55). The lane change ends when the gaze ratios to the start and end lanes, and particularly to the mirror, are stable (the end of LC2 in the figure). Typically, the gaze ratio to the mirrors is the last to stabilize as drivers check that they are not cutting too abruptly in front of the following vehicle. See Salvucci, Liu, and Boer (2001) for additional details on gaze behavior associated with lane changes.

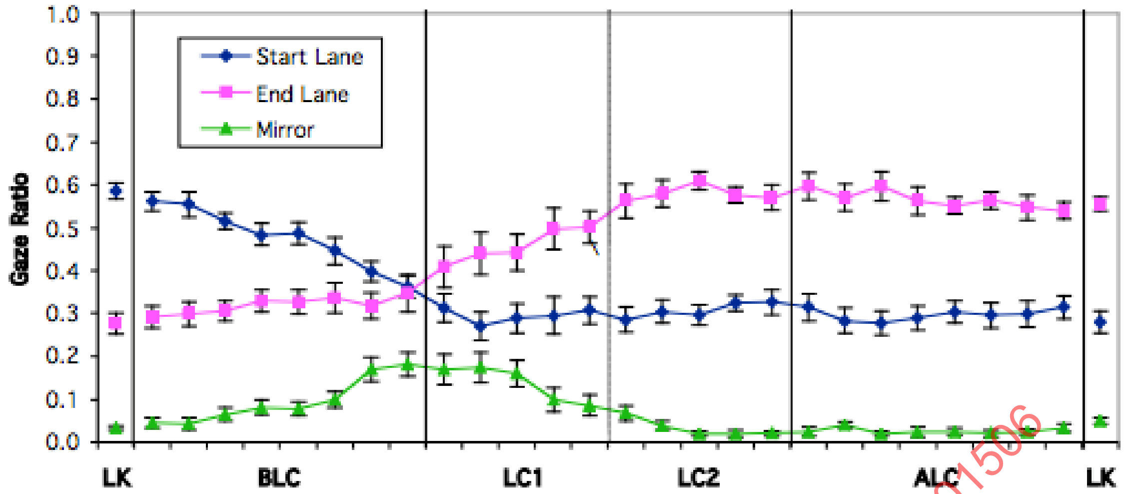

Figure 55 - Gaze time course during a lane change averaged across subjects
(Each tick mark on the x-axis is approximately 0.5 s.)
LK = lane keeping, BLC = before lane change, LC1 = lane change, vehicle in start lane,
LC2 = lane change, vehicle in destination lane, ALC = after lane change
Source: Salvucci, Liu, and Boer (2001), p. 209

In addition, total glance time can be decomposed into the number of glances and the mean duration of each glance (Figure 56). Gaze durations are longer to the lane where lateral control is required (initially, the lane in which they are driving) and shorter to the lane in which they intend to enter or are departing. During the lane change, the driven and non-driven lanes reverse, and the gaze durations change accordingly.

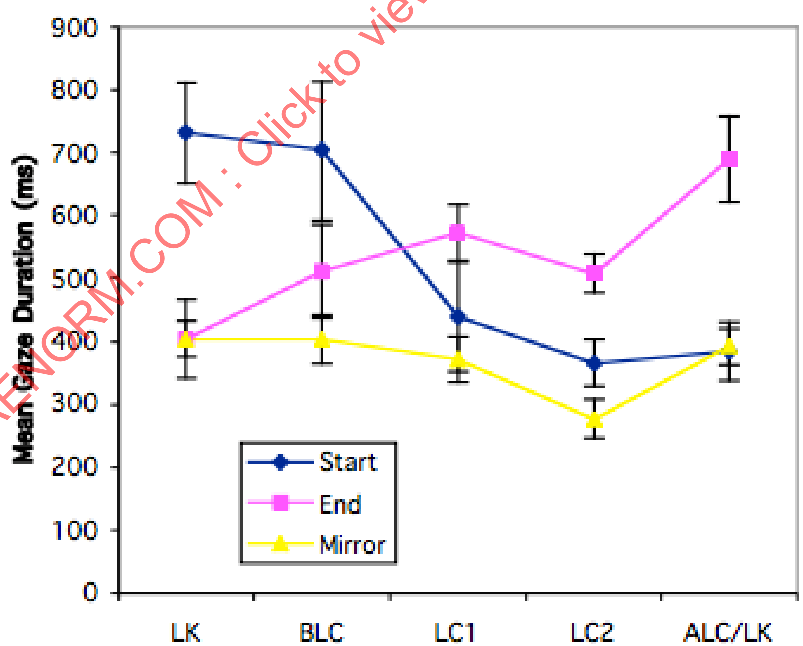

Figure 56 - Mean gaze durations associated with lane changes
Source: Salvucci, Liu, and Boer (2001), p. 210

For information on predicting head and eye motions during lane changes, see Doshi and Trivedi (2008). For other data on eye fixations and lane changes, see Finnegan and Green (1990) and Tijerina, Garrott, Gleckler, Stoltzfus, and Palmer (1997).

10.4.1.2 Turn signal use (Option B)

Turn signal activation may indicate the intent to change lanes or the execution of a lane change is in progress (Salvucci, and Liu (2002).

GUIDANCE for Option B: The point at which a lane change begins could be when the driver first actuates the turn signal control (usually a lever), or when the turn signal lamp is first visible to other drivers. This action could either indicate intent to change lanes or the execution of a lane change. As shown in the driving simulator data in panel 4 of Figure 57, some drivers actuate their turn signal about 1.5 s before the vehicle begins to move laterally for a lane change (Salvucci and Liu, 2002). However, in this study, the turn signal lamp was on only 43 % of the time at the beginning of the lane changes, but was on at some point in 90 % of the lane changes. The evidence to indicate the start of a lane change may be limited, e.g., minor changes in lane position, throttle position, and steering wheel angle.

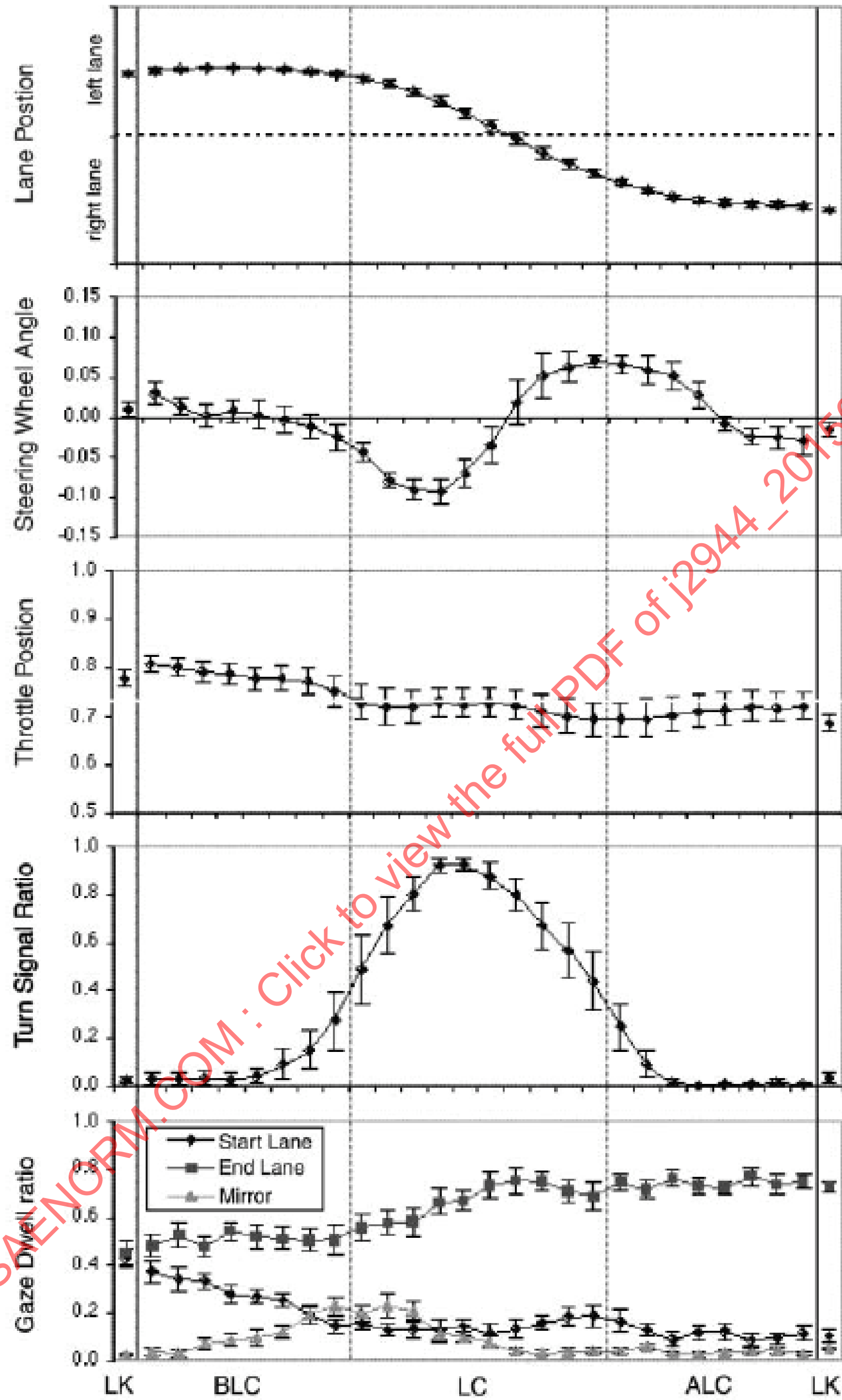

Figure 57 - Mean time histories of various lane change measures and statistics

(Each tick mark on the x-axis is approximately 0.5 s.)

Source: Salvucci and Liu (2002), p. 127

Donmez, Reimer, Mehler, Lavalliere, and Coughlin (2011) report similar values for turn signal use for on-road driving, with maximum use reaching approximately 77 - 96 % of all lane changes, depending on the cognitive demand when the lane change was made. Between 10 and 20 % drivers never used their turn signal, depending on the test conditions.

A lane change can end when the turn signal is turned off, either manually by the driver or automatically by the vehicle. That point could be determined either when the driver actuates the control, or when the next flash of the turn signal lamp has occurred. As Salvucci and Liu (2002) reported, some drivers turned off their turn signal well before the lane change was completed.

10.4.1.3 Vehicle lateral movement (Option C)

This option, if used to define both the beginning and end of a lane change, considers a lane change to occur when a vehicle moves from a stable position in one lane to a stable position in another lane.

GUIDANCE for Option C: For this option, what constitutes “beginning to move” and “stably positioned and driving in the new lane” need to be defined. Salvucci, Mandalia, Kuge, and Yamamura (2007, p. 537), defined a *lane change* as a *“segment in which the vehicle starts moving toward another lane and continues, without reversal, through to that lane. We also used a minimum threshold on lateral velocity to eliminate slow, possibly unintended drifts from our analysis to focus on typical intended lane-change maneuvers. The value of this threshold was set at 0.35 m/s, which represents a conservative threshold considering that, assuming a 3.5-m lane width, a lane change below this threshold would require at least 10 s, whereas average lane-change durations fall in the range of 3 to 7 s … According to this definition, then, the onset of the lane change … corresponds to the point at which the vehicle achieves the minimum lateral velocity and proceeds, without a lateral reversal, through the lane boundary into the destination lane*.”

10.4.1.4 Cross lane boundary (Option D)

Crossing the lane boundary is defined in a manner consistent with that for a lane departure, for which there are 11 options (A – K, Table 8, 10.2.1).

10.4.1.5 Combinations of driver and vehicle measures (Option E)

A lane change begins and ends when so indicated by a combination of driver- and vehicle-related variables over a moving time window of fixed duration, distinct from options A – D.

NOTE: Those variables could include lateral velocity and acceleration, steering wheel angle, lead vehicle velocity, driver gaze direction, head orientation, and other measures, and were combined in a manner that varied from study to study.

GUIDANCE for Option E: This option represents the current research direction (Mandalia and Salvucci, 2005; McCall, Wipf, Trivedi, and Rao, 2007). In brief, the most reliable predictions of when drivers intend to change lanes involve processing multiple signals over various time windows, which may or may not overlap. For example, Mandalia and Salvucci (2005) examined measures including subject vehicle longitudinal and lateral acceleration, lane position at the front bumper and 10, 20, and 30 m ahead of the vehicle, heading angle and distance gap to a lead car. In their work, the lane position measures provided the best predictions. McCall, Wipf, Trivedi, and Rao (2007) also examined various vehicle and lane related measures (lane position, lane heading, lane curvature - and their derivatives, as well as other measures), but importantly found that head motion estimation substantially improved the prediction of lane change occurrence.

For option E, the probability of a lane change is computed using data from a moving time window over the prior 2 - 4 s (Mandalia and Salvucci, 2005; McCall, Wipf, Trivedi, and Rao, 2007).

10.4.1.6 Lane change overview

REQUIREMENTS: The first instance the term *lane change* is used in a document, the method used to determine the start and end of a lane change (option A - E) shall be reported. Passing maneuvers where the driver immediately returns to the original lane because of opposing traffic shall be reported separately from other lane change data. Discretionary and mandatory lane changes shall be reported separately, as well.

If Option B is used and an automatic function to deactivate the turn signal is provided, the rules of operation of the deactivation function (e.g., the time period after which it turns the signal off) shall be reported.

If Option D is used, then the *lane departure* option used to define when the vehicle begins to depart the lane and reenter the adjacent lane shall be reported. See 10.2.

If Option E (integrated signal processing) is selected, then (1) the specific signals (variables) being combined, (2) how they were filtered (if at all), (3) the statistic selected (e.g., mean, percentile), (4) how the values are to be combined (regression coefficients, category thresholds, etc.), and (5) the time window shall be reported.

GUIDANCE for Lane Changes: Identifying a clear beginning and end point for a lane change is difficult, as can be seen from the five options presented in this document. Of them, option B is not recommended because the turn signal is not always used, and the point at which it is actuated and deactivated during lane changes is inconsistent between drivers.

The topic of when a driver intends to change lanes has been examined in several studies, in part because knowing such information before significant lateral vehicle movement occurs would allow the driver changing lanes and other drivers in that driver's path to be warned of a potential crash (Hetrick, 1997; Chovan, Tijerina, Alexander, and Hendricks, 1994; Van Winsum, de Waard, and Brookhius, 1999; and Fitch, Lee, Klauer, Hankey, Sudweeks, and Dingus, 2009).

The preferred option to define a lane change depends upon the purpose for which the lane change data are to be used and the other data that are available. If the purpose is to predict intent to change lanes, and vehicle data are available, then some variation of option E is preferred, though there is no consensus as to which combination of measures and statistics provides the best prediction. As a fallback, consider option C. If the goal is to infer intent, and eye glance data are available, then option A is preferred. If the goal is to simply determine a lane change has occurred, then option D is preferred. Option D the most widely used option to define a lane change.

It is important to not only describe driver performance, but also to be able to predict performance, so developing performance models is extremely useful. For models of lane changes, see Godthelp (1985), Toledo, Kourtsopoulos, and Ben-Akiva (2003), Choudhury (2005), Hwang and Park (2005), Lee (2006), Pei and Xu (2006), Sun (2009), Lee, Kim, Yi, and Jeong (2011), Moridpour, Sarvi, Rose, and Mazloumi (2012), Rahman, Chowdhury, Xie, Hill (2012), Sun and Elefteriadou (2012), and He (2013). Most of these documents also contain empirical data and statistical distributions that users of this document may find useful.

10.4.2 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.

REQUIREMENTS: The first instance the term *number of lane changes* is used in a document, the method used (options A – E, 10.4.1.1 – 10.4.1.5) to determine the start and end points of the *lane change* shall be reported, as well as any details required by that option.

GUIDANCE for Number of Lane Changes: Lee, Olsen, and Wierwille (2004) provide an extensive review of prior studies on lane changes including data on the number of lane changes per unit time reported by each study. Those values vary considerably, in part because what constitute the beginning and end points of a lane change varies between studies, or these points are not reported. Furthermore, the number of lane changes per unit distance varies considerably, due traffic density and speeds driven. For extensive lane change data prior to 1970, see Worrall and Bullen (1970). For more recent data, see Knoop, Hoogendoorn, Shiomi, and Busson (2012).

Figure 58 shows data from the IVBSS project on the number of lane changes per 100 miles for various situations. Approximately 20 - 25 lane changes per 100 miles (12 - 16 per 100 km) are typical when averaged across all roadway types.

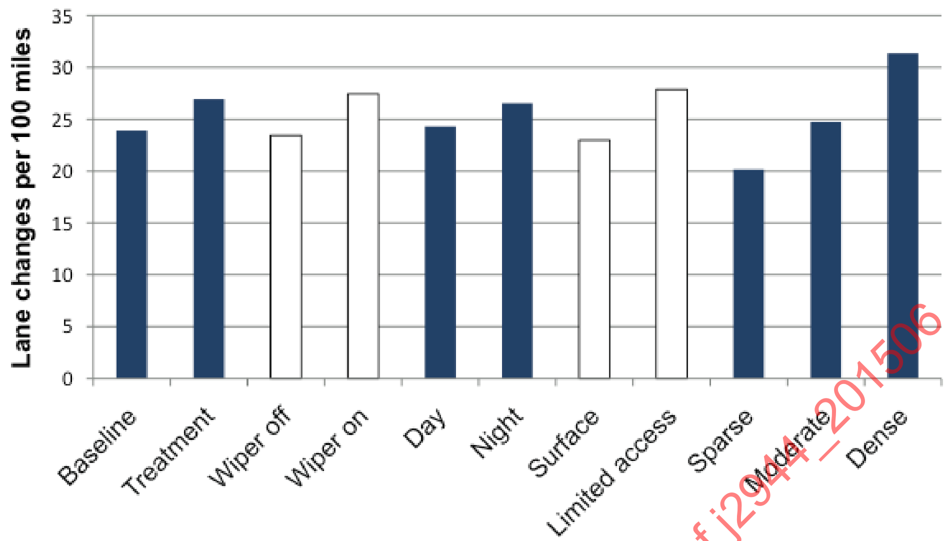

Figure 58 - Number of lanes changes per 100 miles
Source: Sayer, Bogard, Buonarosa, LeBlanc, Funkhouser, Bao, Blankespoor, and Winkler (2011), p. 70

10.4.3 Lane change duration

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

REQUIREMENTS: The first instance the term *lane change duration* is used in a document, the method used (options A – E, 10.4.1.1 – 10.4.1.5) to determine the start and end points of the lane change shall be reported, as well as any details required by that option.

GUIDANCE for Lane Change Duration: The distribution of lane change times is log normal (Figure 59) as was shown by Hetrick (1997), and Toledo and Zohar (2007). Most studies report lane change times on the order of 2.5 - 8.0 s (Table 10; see also Olsen, Lee, Wierwille, and Goodman, 2002; Lee, Olsen, and Wierwille, 2004). The range of times can vary considerably between studies, depending upon the direction of the lane change, the vehicle type (car vs. truck), and the traffic volume (Toledo, Koutsopoulos, and Ben-Akiva, 2003), gaps in the traffic stream (Gurupackiam and Jones, 2012) and differences in the speed of vehicles in the traffic stream (the speed ratio). However, lane change durations vary between studies primarily because the beginning and end points of a lane change differ between studies, if those points are reported at all.

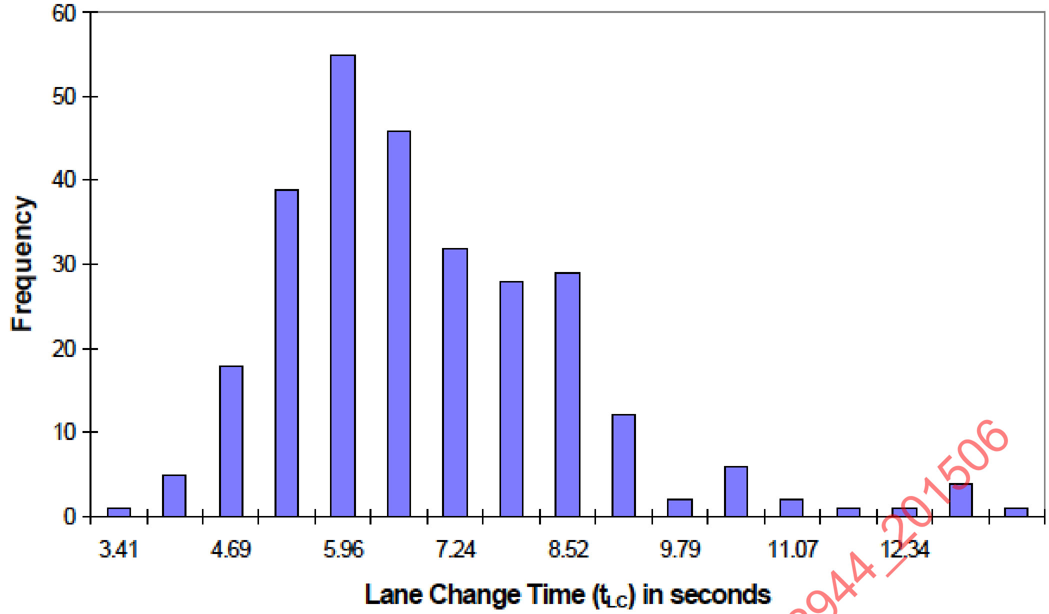

Figure 59 - Distribution of lane change durations
Source: Hetrick (1997), p. 35

Table 10 - Lane change statistics reported in the literature
Source: Lee, Olsen, and Wierwille (2004), p. 9

Source	Range (s)	Average (s)	Notes
Worrall & Bullen (1970)	2.3 - 4.1	Median = 3.2	underestimated due to resolution
Finnegan & Green (1990)	4.9 - 7.6	Median = 6.3	including visual search time
Chovan et al. (1994)	2.0 - 16.0	NA	initial range for Collision Avoidance System
Tijerina et al. (1997)	3.5 - 6.5	Mean = 5.0	city streets
Tijerina et al. (1997)	3.5 - 8.0	Mean = 5.8	highway
Hetrick (1997)	3.4 - 13.6	Mean = 6.0	city and highway segments
Hanowski et al. (2000a)	1.1 - 16.5	Mean = 4.8	local short-haul truck drivers, speeds < 45 mph; does not include headway

Lane change durations are longer for heavy trucks than those for passenger cars with means of approximately 8.1 - 9.4 s (Table 11).

Table 11 - Lane changes times for heavy trucks
Source: Fitch, Blanco, Camden, Olson, McClafferty, Morgan, Wharton, Howard, Trimble, and Hanowski (2012), p. 220

Direction	Cameras	Condition	Mean (s)	SE (s)	N	Min (s)	Max (s)
left	fender + rear + night vision	baseline	8.6	0.3	56	5.0	16.0
		test	8.3	0.2	142	4.1	16.5
	fenders	baseline	9.4	0.4	73	4.1	20.8
		test	8.6	0.2	212	3.9	20.0
right	fender + rear + night vision	baseline	8.4	0.2	208	4.0	18.6
		test	8.1	0.1	550	3.6	18.3
	fenders	baseline	9.1	0.2	191	3.9	19.4
		test	8.4	0.1	580	3.9	22.8

10.4.4 Lane change severity

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

GUIDANCE: 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 12. 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). For their mixture of limited access roadways and highways, they found 95 % of the 8667 lane changes they examined had a severity rating of 1, 1 % had a severity rating of 2 or 3, and 4 % had a severity of 5. All others were 0.2 % or less.

Table 12 - 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, $T_r < 1.0$ s
3	in the fast approach zone with time to reach closest end of zone in the range $1.0 < T_r < 3.0$ s
2	in the fast approach zone with time to reach closest end of zone in the range $3.0 < T_r < 5.0$ s
1	in the fast approach zone with time to reach closest end of zone, $T_r \geq 5.0$ s, including the case where there is no vehicle in the adjacent lane

REQUIREMENTS: The first instance the term *lane change severity* is used in a document, the method used (options A – E, 10.4.1.1 – 10.4.1.5) to determine the start and end points of the lane change shall be reported, as well as any details required by that option.

10.4.5 Lane change urgency

Subjective, four-level rating of how soon the lane change was needed based on TTC with the closest vehicle ahead in the current travel lane (or behind for accelerating vehicles such as tailgaters). See Table 13.

Table 13 - Lane change urgency rating scale
Modified from: Lee, Olsen, and Wierwille (2004), p. 33

Rating	Name	Description
4	critical incident/crash	collision occurs with a vehicle (or object) in (1) the 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

GUIDANCE: For a mixture of limited access roads and highways, Lee, Olsen, and Wierwille (2004) report that approximately 96 % of all lane changes had an urgency of 1, approximately 4 % had an urgency of 2 and 0.3 % an urgency of 3.

REQUIREMENTS: The first instance the term *lane change urgency* is used in a document, the method used (options A – E, 10.4.1.1 – 10.4.1.5) to determine the start and end points of the lane change shall be reported, as well as any details required by that option.

10.5 Roadway Departure Measures and Statistics

10.5.1 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 back on the roadway surface or the vehicle has stopped or crashed without returning to the roadway.

NOTE 1: As noted in 6.2.3, the term *roadway* is defined four ways, (1) including usable shoulders (option A - AASHTO), (2) including parking lanes but not bicycle lanes (option B - MUTCD/FARS/HCM), (3) excluding usable shoulders (option C - ANSI), and (4) excluding shoulders and opposing lanes (Option D - FHWA).

NOTE 2: A roadway departure cannot begin in an intersection.

NOTE 3: Striking or going over a curb, guardrail, Jersey barrier, or other fixed object that serves as a roadway boundary is a roadway departure.

NOTE 4: An intentional lane change or turn, for example, one that is indicated by turn signal operation or glances in the intended direction, is not a roadway departure.

NOTE 5: SAE J2808: 2007, clause 3.6 defines a road departure as, “the point of departure across the road boundary." Clause 3.5 of SAE J2808 defines a departure as, “from ISO 17316: situation in which the outside of one of the front wheels of a vehicle or of the leading part of an articulated vehicle is crossing a specified line. In the case of a 3-wheel, vehicle, it is the same except that the wheel is one of the wheels on the axle with the widest track.” This definition may be applied by those examining 3-wheel vehicles.

GUIDANCE: Roadway departures are important because when a vehicle departs from the road, the probability of a crash increases substantially. For information on the relationship between roadway geometric characteristics and roadway departure 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).

REQUIREMENTS: The first instance the term *roadway departure* is used in a document, the method used to define roadway (option A, B, or C) and the roadway boundaries shall be reported. Separate analyses and reports shall be made for roadway departures crossing the left and the right roadway boundaries, as well as into an opposing lane of traffic.

10.5.2 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: See 10.5.1, for the definition of the term *roadway departure* on which this statistic is based.

NOTE 2: For consistency, a roadway departure begins and ends when all vehicle tires are on the roadway, not when the vehicle is in the original or a new lane of travel. If a vehicle returns to a roadway and then departs the roadway again (on either side of the original lane), then a second roadway departure is recorded, even if the vehicle was not stable when it returned to the roadway after the first roadway departure.

REQUIREMENTS: The first instance the term *number of roadway departures* is used in a document, the method used to define a roadway (option A, B, or C, 6.2.3) and the roadway boundaries shall be reported.

10.5.3 Roadway departure duration

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

NOTE 1: See 10.5.1 for the definition of a roadway departure.

NOTE 2: This measure is much more likely to be collected in a driving simulator than in field studies.

REQUIREMENTS: The first instance the term *roadway departure duration* is used in a document, the method used to define a roadway (option A, B, or C, 6.2.3) and the roadway boundaries shall be reported.

10.5.4 Magnitude of roadway departure

Lateral distance, usually measured in centimeters, meters, inches, or feet, perpendicular from the roadway boundary (usually the center of the lane edge delineation line) to (1) the front bumper, (2) the center of the vehicle front axle, (3) the center of gravity, or (4) the spatial center after the vehicle has departed the roadway.

NOTE 1: The term roadway is defined three ways in 6.2.3.

NOTE 2: This measure is much more likely to be collected in a driving simulator than in field studies.

REQUIREMENTS: The first instance the term *magnitude of roadway departure* is used in a document, the method used to define a roadway (option A, B, or C), the roadway boundaries, and the location on the vehicle from which the magnitude is determined (front bumper, front axle, center of gravity, spatial center) shall be reported.

GUIDANCE for Number, Duration, and Magnitude of Roadway Departures: Report separate analyses for roadway departures from the left and from the right roadway boundaries. In addition, for the FHWA definition, provide a separate analysis and report of departures across a centerline or median into an opposing lane of traffic. Although there is considerable data on roadway departure crashes, a search of the literature was unable to locate data on any of these measures of roadway departures.

10.5.5 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 again on the paved roadway, or the vehicle has stopped or crashed without returning to the paved roadway.

NOTE 1: The statistics given in 10.2.1.1.1 – 10.2.1.1.3 also apply to roadway pavement departures.

NOTE 2: The start and end of a roadway pavement departure are easier to determine 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.

REQUIREMENTS: The first instance the term *roadway pavement departure* is used in a document, the method used to define a roadway (option A, B, or C) and the pavement boundaries shall be reported.

10.5.6 Time integrated roadway departure magnitude

Integral, usually measured in meter-seconds or feet-seconds, of the roadway departure magnitude (as a function of time) times dt, the incremental time, integrated over the time interval from start to end of the roadway departure.

NOTE 1: This statistic can also be computed by multiplying the mean magnitude of roadway departure by the mean roadway departure duration.

NOTE 2: This statistic can only be computed for roadway departures where the vehicle returns to the roadway.

NOTE 3: This statistic is analogous to *time integrated lane departure magnitude* (10.3.1) and to some extent, *time integrated time to collision* (8.2.5).

NOTE 4*:* This statistic indicates the risk (exposure time and magnitude) of striking or being struck by another vehicle or hazard off the roadway and is useful in comparing short high magnitude departures with longer low magnitude departures.

NOTE 5: In manner analogous to Hellopeter (2011) who examined the area of lane departures, one could compute the area of roadways departures, as the integral of the roadway departure magnitude times dx, the incremental distance along the roadway boundary line from the start to the end locations of the departure. The measure has units of $meters^2$.

REQUIREMENTS: The first instance the term *time integrated roadway pavement departure magnitude* is used in a document, the method used to define a roadway (option A, B, or C, 6.5.3) shall be reported.

GUIDANCE for Time Integrated Roadway Departure Magnitude: This is a relatively new measure and representative data are not available at this time.

11. NOTES

11.1 Marginal Indicia

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY THE DRIVER PERFORMANCE OPERATIONAL DEFINITIONS (DRIPOD) SUBCOMMITTEE OF THE SAE SAFETY AND HUMAN FACTORS STEERING COMMITTEE

APPENDIX A[2] - CALCULATION OF TIME TO COLLISION (TTC)

A.1 BACKGROUND

Time to Collision (TTC), as defined in 8.2.1, is the duration, usually measured in seconds, required for one vehicle to strike another object. There are two versions: Option A that considers acceleration and velocity and Option B that considers only velocity. In general, the larger the value of TTC, the safer the driver is. TTC can be applied to a single driver, a specified user class, or all vehicles that pass a given road segment during a time period.

A.2 COMPUTATIONAL METHOD

The method for calculating TTC is taken almost verbatim from van der Horst (1990), p. 167–170.

A.2.1 Procedure

Let the situation at a given time $t = T$ be given by Figure A1.

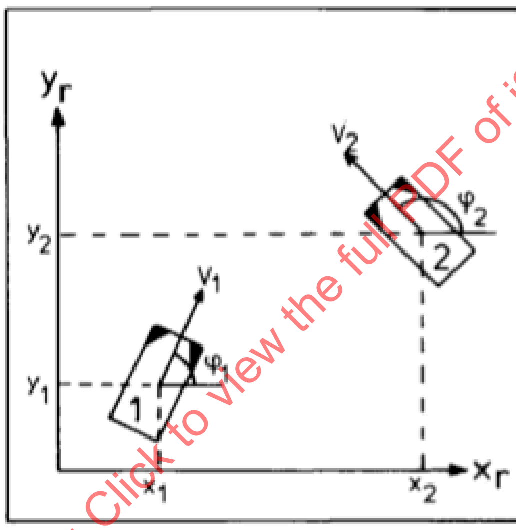

Figure A1 – TTC situation at t = T for two approaching vehicles

x_i = X-coordinate in the road plane, y_i = Y-coordinate, v_i = speed, a_i = acceleration and ϕ_i = heading angle of vehicle i, (i = 1, 2)

Regardless of which assumption is made for the continuation of movement from the moment *T* on, the TTC concept always requires two steps:

1. detect whether both vehicles have a mutual collision course, and if so,
2. calculate TTC at moment $t = T$.

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[2] All appendices contain excerpts of the original journal articles and proceedings papers on which definitions in this document are based. The excerpts are reproduced here with permission and are provided for the convenience of users of this practice. In a few instances, minor changes were made for improved clarity, including replacing the word average (which could be the mean, median, or mode) with the word mean where appropriate.

Symbols used in the original articles have been retained in these appendices to assure accurate reproduction of the equations. Many of the original articles and papers did not include lists of symbols so a list of symbols has been added at the end of each appendix, using the original notation. There may be instances where a particular variable is represented using different symbols in two appendices to maintain consistency with the original source material. As a result, variables used in each appendix are local to that appendix.

When two road users are approaching each other, in general, there will be an area of intersection S, defined by the dimensions of the vehicles (or the vehicle and the object). An example for the simple case of a perpendicular angle of intersection is given in Figure A2.

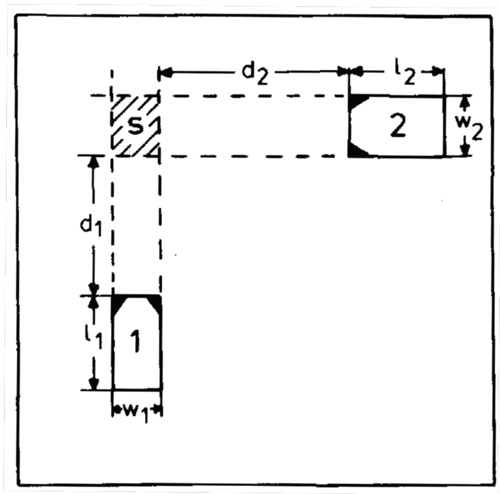

Figure A2 - TTC situation at t = T for a perpendicular approach
S, = area of intersection, l_i *= length,* w_i *= width of vehicle i (i = 1, 2) and* d_i *= distance from front of vehicle i to area S.*

A.2.2 Determination of Collision

A collision course will only occur if one of the following conditions is satisfied:

$$t_{f1} < t_{f2} < t_{r1} \quad \text{(A1)}$$

or

$$t_{f2} < t_{f1} < t_{r2} \quad \text{(A2)}$$

where:

t_{f1}, t_{f2} = the moment the fronts of vehicle 1 and vehicle 2, respectively, reach area *S*, and

t_{r1}, t_{r2} = the moment the rear of vehicle 1 and vehicle 2, respectively, leaves area *S*.

If neither Equation A1 nor Equation A2 is satisfied, there is no collision course, and consequently, TTC will be infinite.

If Equation A1 is true, the TTC value at time *t* = *T* is given by:

$$\text{TTC} = t_{f2} - T \quad \text{(A3)}$$

while if Equation A2 is true:

$$\text{TTC} = t_{f1} \quad \text{(A4)}$$

Of course, t_{f1} through t_{f2} will depend on the positions, the speeds, and the heading angles at *t* = *T*, as well as on the assumption of the continuation of movements from time *T* on.

TTC Based on Constant Speed and Heading Angle, Perpendicular Approach (Option B)

If the continuation or movement is defined by a constant remaining speed and heading angle, the time moments for the example of Figure A2 are given by:

$$t_{f1} = T + d_1/v_1 \tag{A5}$$

$$t_{r1} = T + (d_1 + l_1 + w_2)/v_1 \tag{A6}$$

$$t_{f2} = T + d_2/v_2 \tag{A7}$$

$$t_{r2} = T + (d_2 + l_2 + w_1)/v_2 \tag{A8}$$

If Equation A1 is satisfied, then substituting Equation A7 into Equation A3 gives:

$$\text{TTC} = d_2/v_2 \tag{A9}$$

And, if Equation A2 is satisfied, then substituting Equation A5 in Equation A4 gives:

$$\text{TTC} = d_1/v_1 \tag{A10}$$

A.2.3 Non-Perpendicular Approaches

A.2.3.1 General considerations

For non-perpendicular angles of intersection, all corner points of both vehicles have to be considered separately to determine whether a collision course is present or not. Also, more types or potential collisions have to be taken into account. For an acute angle, for example, six different collision types are possible (Figure A3) with separate conditions and equations for collision course and calculation of TTC.

In addition, both rear-end and head-on approaches require different computations.

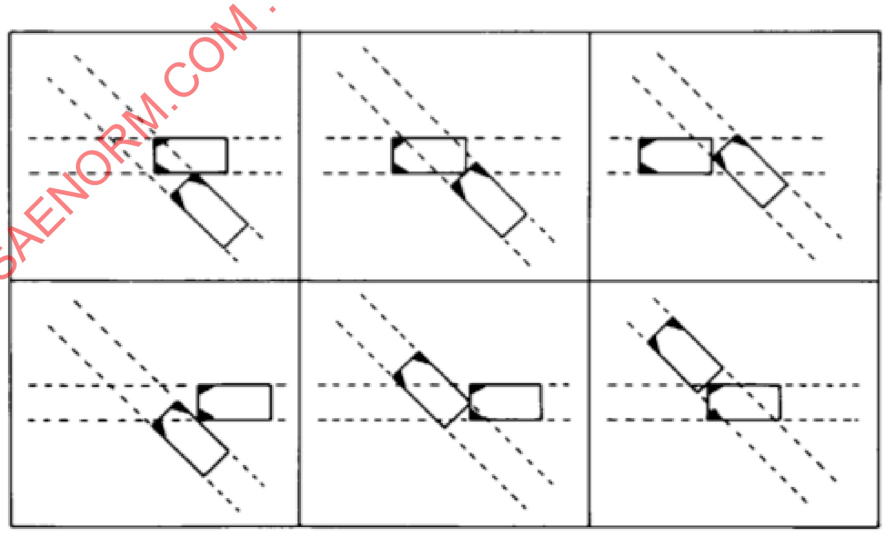

Figure A3 - Types of potential collisions for an acute angle of approach

A.2.3.2 TTCA - TTC Based On Constant Acceleration and Heading Angle (Option A)

When the continuation of movement is based on constant remaining accelerations (or decelerations), mathematical expressions for t_{f1} through t_{r2} can also be derived, with some restrictions dealing with potential stops before or after entering the area S. However, a more general computational approach can be followed by using numerical methods for solving a set of higher order equations, with both x and y from time T on given as an n^{th} order polynomial in t.

One example, called adjusted TTC in Appendix C, uses the mean accelerations of the lead and following vehicles from brake onset to collision to calculate the minimum TTC value.

A.3 LIST OF SYMBOLS

Symbol	Definition	Units
t	time	s
T	specific moment of time	s
a_i	acceleration	m/ s²
ϕ_i	heading angle of vehicle i, where i is the vehicle number (1, 2)	deg
x_i	X coordinate	m
y_i	Y coordinate	m
v_i	speed	m/s
TTC	Time to Collision	s
S	area of intersection	m²
l_i	length of vehicle i	m
w_i	width of vehicle i	m
d_i	distance from front of vehicle i to area S	m
TTCA	TTC based on constant acceleration and heading angle	s

A.4 ADDITIONAL INFORMATION NOT IN VAN DER HORST (1990)

In a vehicle following situation, where both vehicles are traveling in the same lane, the time to collision calculation is much simpler. For the velocity only method it is equal to the distance gap divided by the difference in velocity of the two vehicles. For the method that includes acceleration, time to collision includes the acceleration of the two vehicles.

APPENDIX B - CALCULATION OF MINIMUM TIME TO COLLISION (TTC_{MIN})

B.1 BACKGROUND

Larger values of minimum time to collision (TTC_{min}) indicate a greater margin of safety. TTC_{min} as defined in 8.2.2 is the minimum duration required for one vehicle to strike another vehicle or object over some time period on the order of seconds.

B.2 COMPUTATIONAL METHOD FOR OPTION A (ACCELERATION AND VELOCITY)

B.2.1 Introduction

The method for calculating minimum *TTC* is taken almost verbatim from van der Horst (1990) p. 170–171.

The minimum *TTC* when two road users are on a collision course at a certain moment is determined by comparing all TTC values that are present in the encounter. No separate computation is needed to obtain TTC_{min}.

B.2.2 Accelerating Toward a Fixed Object

To illustrate how TTC_{min} depends on acceleration, consider the simple example of a car having a constant acceleration approaching a fixed object. At time $t = 0$ the constant acceleration (deceleration) is instantaneously in effect. For a movement with a constant acceleration, the following equations hold:

$$\text{Acceleration: } a(t) = -a \ m/s^2 \tag{B1}$$

$$\text{Speed: } v = v_0 + at \tag{B2}$$

$$\text{Distance travelled: } d = v_0 t + 0.5a t^2 \tag{B3}$$

where:

v_0 is initial velocity at t=0.

The *TTC* at moment *t* is given by:

$$TTC = (d_0 - d)/v \tag{B4}$$

where:

d_0 is the initial distance to the fixed object at t=0.

Substituting Equation B2 and B3 in Equation B4 gives:

$$TTC = (d_0 - v_0 t - 0.5a t^2) / (v_0 + at) \tag{B5}$$

The moment the minimum *TTC* is reached ($t = t_{min}$) is determined when the derivative of *TTC* equals zero:

$$d/dt\,(TTC) = 0$$

or

$$\{(v_0+at)(-v_0 - at) - (d_0 - v_0 t - 0.5a t^2)\} / (v_0 + at)^2 = 0$$

resulting in:

$$0.5 a^2 t^2 + a v_0 t + v_0^2 + d_0 a = 0 \tag{B6}$$

The condition of no collision is only valid if Equation B7 and B8 are both satisfied, i.e.,:

$$-a \geq v_0^{\,2} / (2 \cdot d_0) \quad \text{(B7)}$$

and

$$t < -a / v_0 \quad \text{(B8)}$$

resulting in:

$$t_{min} = - v_0 / a + (- v_0^{\,2} - 2\, d_0 a)^{1/2} / a \quad \text{(B9)}$$

Substituting t = t_{min} in equation B5 gives:

$$TTC_{min} = (d_0 - v_0 t_{min} - 0.5a\, t_{min}^{\,2}) / (v_0 + a\, t_{min}) \quad \text{(B10)}$$

In Equation B10, TTC_{min} is given as a function of the acceleration (a) and the distance and speed at moment t = 0. But TTC_{min} can also be expressed as a function of the speed and distance at moment $t = t_{min}$, viz.:

$$TTC_{min} = d_{min} / v_{min} \quad \text{(B11)}$$

As it can easily be derived, that d_{min} also equals $- v_{min}^{\,2} / a$, Equation B11 results in:

$$TTC_{min} = - v_{min} / a \quad \text{(B12)}$$

The time it takes to come to a stop from moment t_{min} on, also equals $- v_{min} / a$. This implies that at time t_{min}, TTC_{min} is equal to the time it takes from the current moment to come to a complete stop. From this, a simple decision rule may be derived, viz. if *TTC* is less than the remaining stopping time, continue braking. After *TTC* reached its minimum, *TTC* will be greater than the remaining stopping time, implying that the deceleration may decrease.

B.3 LIST OF SYMBOLS

Symbol	Definition	Units
a	acceleration	m/s^2
d	distance travelled	m
d_{min}	distance travelled at time t_{min}	m
TTC	Time to Collision	s
TTC_{min}	minimum TTC	s
V	speed	m/s
$V_{t\,min}$	speed at t_{min}	m/s

APPENDIX C – CALCULATION OF MINIMUM ADJUSTED TIME TO COLLISION

C.1 BACKGROUND

Adjusted time to collision as defined in 8.2.3 “is the amount of spare time the driver had based on the avoidance response chosen by the driver. Positive values indicate the amount of extra time the driver had based on the deceleration profile. Negative values indicate how much earlier the driver would have needed to begin the response in order to have avoided the collision” (Brown, 2005, p. 42). Adjusted TTC takes into account the relative velocity at time of collision, and the mean accelerations of the lead and following vehicles.

C.2 COMPUTATIONAL METHOD FOR OPTION A (ACCELERATION AND VELOCITY)

The calculation method shown here is almost verbatim from Brown (2005, p. 42-43). Brown computes adjusted minimum TTC using the acceleration-based TTC value (option A, 8.2.1.1), which he refers to as Type II TTC.

C.2.1 Procedure

C.2.1.1 No collision

C.2.1.1.1 Lead vehicle decelerating

In the case of no collision, minimum adjusted TTC is the minimum value of TTC. When both vehicles are moving and the lead vehicle is decelerating, TTC is derived from the following equation of motion assuming continued travel at the current speed by the driver’s vehicle.

$$-R = \frac{1}{2}\alpha \times TTC^2 + \dot{R} \times TTC \qquad \text{(C1)}$$

where:

R = Range

$\dot{R}$ = Lead Vehicle Velocity – Following Vehicle Velocity

α = Lead Vehicle Acceleration

TTC is then derived using the quadratic formula as follows:

$$TTC = -\frac{\dot{R} + \sqrt{(\dot{R})^2 - (2\alpha)(R)}}{\alpha} \qquad \text{(C2)}$$

C.2.1.1.2 Lead vehicle - constant speed or stationary

Using the same definition of range rate, when the lead vehicle is stationary or travelling at a constant speed, TTC is simply a function of range and range rate expressed as follows:

$$TTC = R / -\dot{R} \qquad \text{(C3)}$$

The above calculations for minimum adjusted TTC would result in a value of zero in the case where a collision occurs, regardless of whether the differential velocity between the two vehicles at the time of collision is very small or very large. As a result, minimum TTC is restricted in range to non-negative values, and the distribution of TTC_{min} becomes non-normal as more crashes occur in the dataset.

C.2.1.2 Collision

C.2.1.2.1 Lead vehicle stopped

To calculate the adjusted minimum TTC in the case of a crash, the situation preceding the crash is considered. If the lead vehicle is stopped:

$$\text{Adjusted Minimum TTC} = V_F / \bar{a}_F \tag{C4}$$

where:

V_F = Following Vehicle Velocity at the Time of Collision

$\bar{a}_F$ = Mean Acceleration of the Driver's Vehicle from Brake Onset to Collision

C.2.1.2.2 Lead vehicle decelerating

If the lead vehicle is moving and the following vehicle is decelerating as quickly as the lead vehicle or greater:

$$\text{Adjusted Minimum TTC} = (V_F - V_L) / (\bar{a}_F - \bar{a}_L) \tag{C5}$$

where:

V_F = Following Vehicle Velocity at the Time of Collision

V_L = Lead Vehicle Velocity at the Time of Collision

$\bar{a}_F$ = Mean Acceleration of the Following Vehicle from Brake Onset to Collision

$\bar{a}_L$ = Mean Acceleration of the Lead Vehicle from Brake Onset to Collision

By definition, if the lead vehicle is moving and the following vehicle is not decelerating as quickly as the lead vehicle, the driver could not have avoided the collision based on the current response, and:

$$\text{Adjusted Minimum TTC} = -\infty \tag{C6}$$

C.2.2 Example

An example provided in Brown (2005) and summarized here illustrates the differences between TTC_{min} and adjusted TTC_{min}. Brown simulated two scenarios differing primarily in their assumed deceleration levels in order to obtain different mixtures of crashes and non-crashes. Figure C1 shows normal probability plots for TTC_{min}, relative velocity at collision, and adjusted TTC_{min} for the two scenarios. For the top row of plots (deceleration = 0.4 g), only 2 collisions occurred, resulting in very little difference between TTC_{min} and adjusted TTC_{min}. For the bottom row of plots (deceleration = 0.75 g) there were many more collisions (a total of 15), resulting in significant differences between TTC_{min} and adjusted TTC_{min}. The adjusted TTC_{min} values are normally distributed, enabling use of parametric statistics to analyze them.

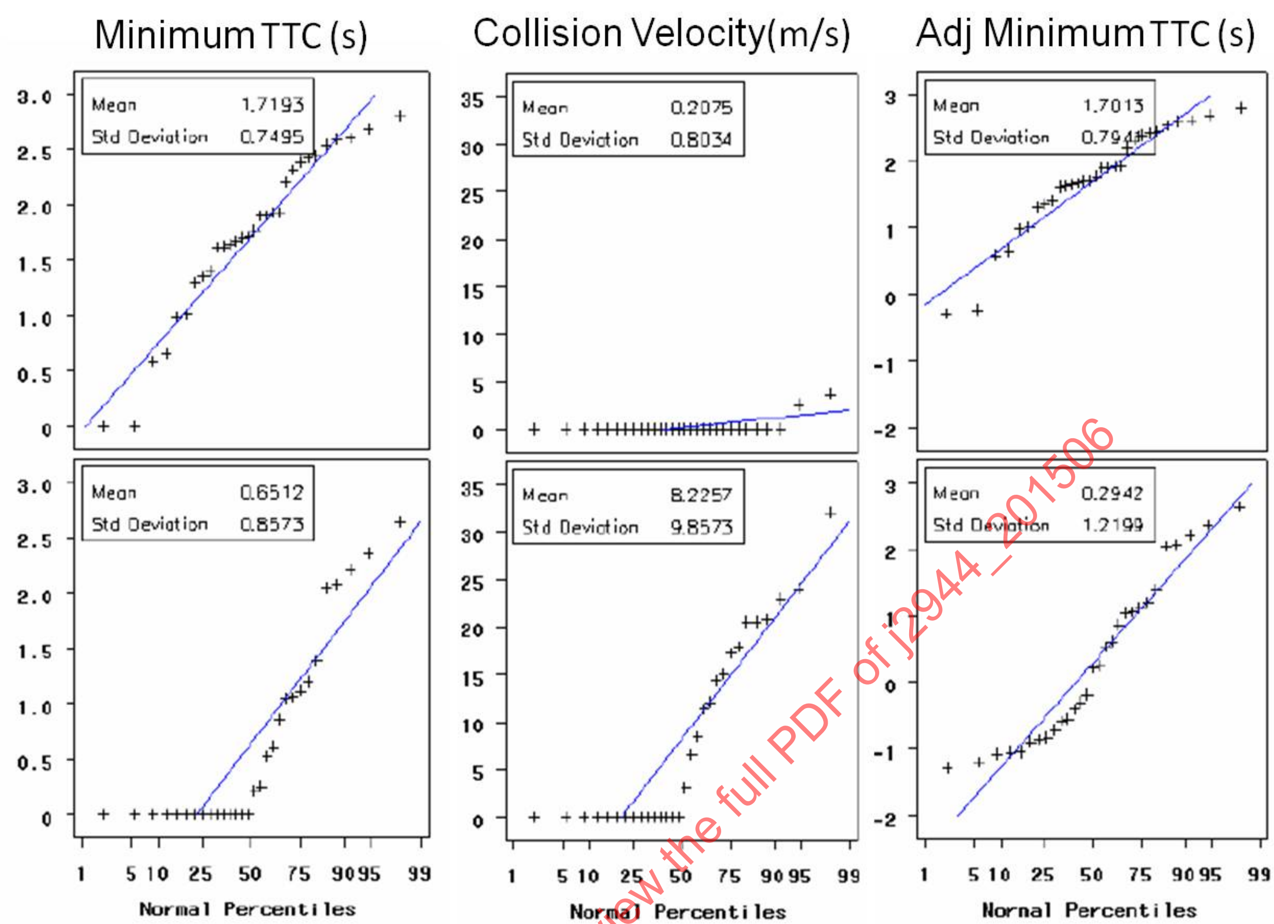

Figure C1 - Normal probability plots for TTC_{min}, relative velocity at collision, and adjusted TTC_{min} for assumed decelerations of 0.4 g (top row) and 0.75 g (bottom row)
Source: Brown (2005), p. 46

C.3 LIST OF SYMBOLS

Symbol	Definition	Units
TTC	Time to Collision	s
TTC_{min}	Minimum Time to Collision (for crashes, TTC_{min} = 0)	s
Adjusted TTC_{min}	Adjusted Minimum Time to Collision (for crashes, Adjusted TTC_{min} < 0)	s
R	range	m
$\dot{R}$	lead vehicle velocity – following vehicle velocity	m/s
a	lead vehicle acceleration	m/s^2
V_F	following vehicle velocity at the time of collision	m/s
$\bar{a}_F$	mean acceleration of the following vehicle from brake onset to collision	m/s^2
V_L	lead vehicle velocity at the time of collision	m/s
$\bar{a}_L$	mean acceleration of the lead vehicle from brake onset to collision	m/s^2

APPENDIX D - CALCULATION OF TIME EXPOSED TIME TO COLLISION (*TETTC* OR *TET*)

D.1 BACKGROUND

Time Exposed Time-to-Collision as defined in 8.2.4 is the duration of time over which the time to collision measure is below some undesired threshold. *TET* is a more safety-relevant measure than TTC alone because it considers exposure time. It can be applied to a single driver, a specified user class, or all vehicles that pass the road segment during a time period, and can distinguish impacts per lane. The original definition in the literature of *TET* does not indicate if acceleration is considered.

D.2 COMPUTATIONAL METHOD

The calculation method shown here is almost verbatim from Minderhoud and Bovy (2001), p. 92-94.

D.2.1 Procedure

Calculation of Time Exposed Time-to-collision requires collection of the position and speed of all vehicles entering and leaving a road section bounded by X_1 and X_2, over time period H, from which trajectories and time-to-collision profiles (Figure D1) can be established.

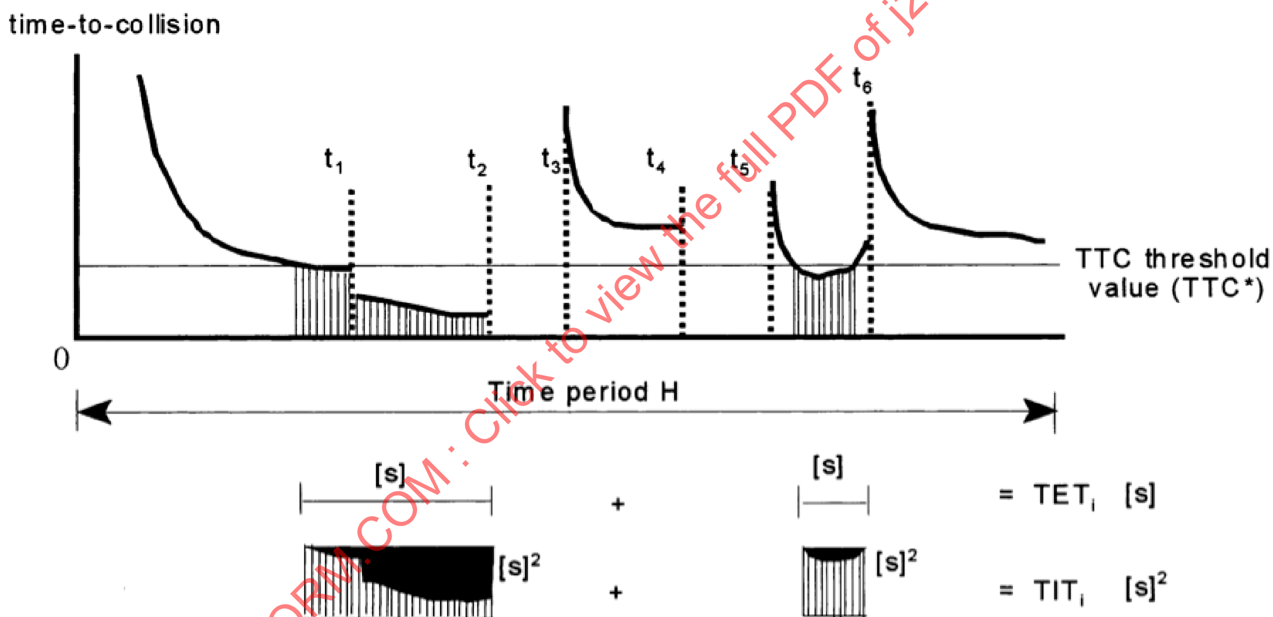

Figure D1 - Example time-to-collision profile of a driver-vehicle combination in motorway traffic

Vertically shaded areas represent safety-critical approach conditions.

(TIT = Time Integrated Time to Collision. See 8.2.5 and Appendix E.)

Source: Adapted from Minderhoud and Bovy (2001), p. 92

One assumption is that the measured TTC values at any instant t do not change during a small time step τ_{sc} (e.g., 0.1 s), the spacing between vertical lines in Figure D1. Over the time period H there are $T = H/\tau_{sc}$ time instants t (t = 0, 1, 2 … T) to calculate TTC values.

TET is a summation of all moments (over the time period H) that a driver approaches a front vehicle with a TTC value below the threshold value TTC*, the latter is considered to be the boundary between safe and safety-critical approaches. Thus, the lower the *TET* value, the more safe the situation (on average over period H). This safety measure does not take into account the variation in safety levels of different time-to-collision values below the threshold value.

The *TET** value (seconds) for a driver/vehicle i can be expressed as follows:

$$TET_i^* = \sum_{t=0}^{T} \delta_i(t) \cdot \tau_{sc} \tag{D1}$$

where δ is an indicator variable defined as

$$\delta_i(t) = \begin{cases} 0 & \text{else} \\ 1 & \forall\ 0 \le \mathrm{TTC}_i(t) \le \mathrm{TTC}^* \end{cases}$$

When driver i at instant t experiences a TTC value between 0 and the specified threshold value TTC*, the value of δ is 1. Otherwise, the value of δ is 0.

The total *TET** for a population of N vehicles (drivers) can be expressed as

$$TET^* = \sum_{i=1}^{N} TET_i^* \tag{D2}$$

where the superscript * indicates the *TET* value is calculated with respect to the threshold TTC value.

A *TET* value can also be calculated separately per user class, e.g., trucks and passenger cars, or vehicles equipped and not equipped with intelligent driver support systems, by adding an extra index and summation per user class.

D.2.2 Summary Values For *TET*

A mean *TET** value per vehicle can be computed as

*Mean TET** = *TET** / N (s/vehicle) (D3)

in order to standardize *TET* across sample size and duration of the observations.

The mean value still includes the time period over which the *TET* value has been determined. To overcome this dependency, an indicator *P** can be established, expressing the probability that a vehicle encounters a safety-critical approach situation, which is defined as a moment with a TTC value between 0 and TTC* seconds. The *TET** probability per vehicle is calculated by dividing the mean indicator value of Equation D3 by the maximum attainable time period H.

*TET P** = 100 (Mean *TET**) / H (%) (D4)

The probability indicator can be interpreted as the percentage of time that a random driver on average drives with TTC values below the threshold TTC*.

D.2.3 Threshold Values For TTC*

A three-second threshold TTC* is considered an adequate level for discriminating dangerous approach situations from acceptable situations, as has been observed by Hirst and Graham (1997). Nevertheless, other TTC threshold values can be used.

D.3 LIST OF SYMBOLS

Symbol	Definition	Units
TTC	Time to Collision	s
TTC*	Time to Collision threshold value	s
TET	Time Exposed Time-to-collision	s
*TET**	*TET* value for a population of N vehicles	s
*P**	probability that a vehicle encounters a safety-critical approach situation (a moment with a TTC value between 0 and TTC* seconds)	%
t	time	s
δ	indicator variable	
N	number of vehicles (or drivers)	
H	time period	s
T	number of time steps in H	
τ_{sc}	small time step	s

APPENDIX E - CALCULATION OF TIME INTEGRATED TIME-TO-COLLISION (TITTC OR TIT)

E.1 BACKGROUND

Time Integrated Time-to-Collision as defined in 8.2.5 is the duration over which the time to collision is below some undesired threshold weighted by how far below that threshold the time to collision is at each moment. One disadvantage of the TETTC measure is that a TTC value much less than the threshold TTC value does not have a greater affect on the TETTC value. However, it may be expected that an extremely small TTC value (e.g., smaller than 0.5 s) represents an approach situation with a relatively high probability of a collision compared to greater TTC values (e.g., 2 or 3 s). For that reason, the Time Integrated Time-to-collision (TIT) measure has been developed.

E.2 COMPUTATIONAL METHOD

The method for calculating TIT is almost verbatim from Minderhoud and Bovy (2001, p. 92-94).

E.2.1.1 Procedure

E.2.1.1.1 Continuous time interval

In continuous time, the TIT measure *(TIT*)* for a population of vehicles is the integral of the time-to-collision profile over time periods when the TTC value is below the threshold value *TTC*.*

$$TIT^* = \sum_{i=1}^{N} \int_0^T [TTC^* - TTC_i(t)]dt \qquad \forall 0 \le TTC_i(t) \le TTC^* \tag{E1}$$

The vertically shaded areas in Figure D1 represent situations in which the driver approaches the front vehicle with TTC values below *TTC*.* As low TTC values represent more dangerous situations, it holds that the smaller the shaded area, the higher the risk of collisions. To be consistent with the TET-indicator, the shaded area should be subtracted from the area below the threshold value, resulting in a time integral with an interpretable meaning. This area is shown in Figure D1 by a dark surface. A high TIT value means a greater exposure to less safe TTC values.

E.2.1.2 Discrete time intervals

The individual TIT for driver/vehicle i in discrete time can be calculated with:

$$TIT_i^* = \sum_{t=0}^{T} [TTC^* - TTC_i(t)] \cdot \tau_{SC} \qquad \forall 0 \le TTC_i(t) \le TTC^* \tag{E2}$$

Summation over all vehicles (i = 1…N) present in the road section of interest during time period H, results in the following discrete-time aggregate TIT (in s^2)

$$TIT^* = \sum_{i=1}^{N} TIT_i^* \tag{E3}$$

The mean duration that a vehicle encounters an unsafe situation is

$$\text{Mean } TIT^* = TIT^* / \text{N} \quad (s^2/\text{vehicle}) \tag{E4}$$

The TIT* probability indicator can be calculated by dividing the mean *TIT** in Equation E4 by the theoretically maximum attainable TIT value per vehicle (H • *TTC**)

$$\text{TIT } P^* = 100 \text{ (Mean } TIT^*) / (TTC^* \cdot \text{H}) \ (\%) \tag{E5}$$

E.3 LIST OF SYMBOLS

Symbol	Definition	Units
TIT	Time Integrated Time-to-collision	s^2
*TIT**	TIT value for a population of N vehicles	s^2
t	time	s
TTC	Time to Collision	s
*TTC**	Time to Collision threshold value	s
TET	Time Exposed Time-to-collision	s
N	number of vehicles	
*P**	probability that a vehicle encounters a safety-critical approach situation (a moment with a TTC value between 0 and *TTC** seconds)	%
H	time period	s
T	number of time steps in H	

APPENDIX F – CALCULATION OF STEERING WHEEL REVERSALS

F.1 BACKGROUND

When drivers are paying attention to driving, they typically make small steering corrections to maintain their path. However, when distracted, steering corrections may be fewer in number, but often are larger in magnitude. Thus, the pattern of steering reversals changes when distracted. A reversal involves turning the steering wheel in the opposite direction from its current (non-zero) position, with the intent to change the heading angle and lateral position of the vehicle. Steering reversals are defined in detail in 9.2.1.

F.2 COMPUTATIONAL METHOD USING AN AMPLITUDE THRESHOLD (OPTION A)

The method shown here for calculating steering wheel reversals is reproduced from Markkula and Engström (2006), which was developed as part the AIDE project (Ostlund, Peters, Thorslund, Engstrom, Markkula, Keinath, Horst, Juch, Mattes, and Foehl, AIDE D2.2.5, 2005, p. 126-128).

Roughly, given a steering wheel angle signal $\theta(t)$, a steering wheel reversal is taken to be a portion $[t_1; t_2]$ of the signal such that θ is stationary at both t_1 and t_2 (i.e., $d\theta(t_1)/dt = 0$ and $d\theta(t_2)/dt = 0$), and such that $|\theta(t_1) - \theta(t_2)| \geq \theta_{min}$, where θ_{min} is the gap size (amplitude threshold). .Reversals cannot be overlapping. Note that a stationary point can be a local minimum, a local maximum, a saddle point, or a point on a constant segment of the steering wheel angle signal. Figure F1 shows an example of a steering wheel angle signal, with calculated reversals for a gap size (θ_{min}) of 1 degree.

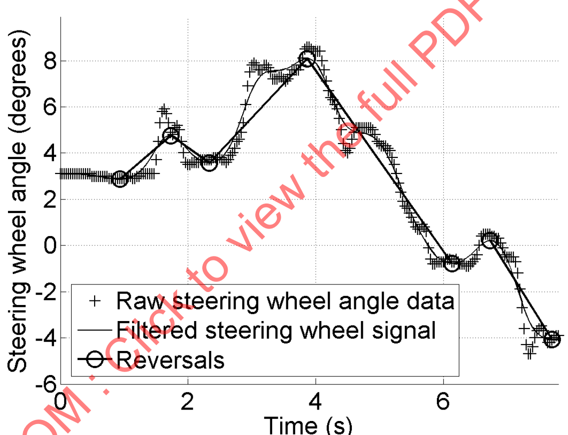

Figure F1 - Example of steering wheel reversals.
Reversals are marked as lines extending between their respective
starting and ending stationary points, marked with circles.

Below, the different steps of the algorithm for reversal rate calculation are described in detail. The steps are applied to the steering wheel angle signal.

F.2.1 Apply Low-Pass Filter

A low-pass second-order (or higher) Butterworth filter with cut-off frequency 0.6 Hz is applied. The filter reduces high-frequency noise in the steering wheel angle signal, and makes it possible to find stationary points (local maxima and minima) using the method described below.

F.2.2 Find Stationary Points

Let Θ_i be the value of the low-pass filtered steering wheel angle signal at time step *i*, with *i* = {1, 2, 3,…, *T*}, where *T* is the total number of samples in a measurement. Calculate the following quantity:

$$\theta_i' = \begin{cases} 0 & i = 1 \\ \theta_i - \theta_{i-1} & i > 1 \end{cases}$$

where:

θ'_i is a scaled version of θ'_i / Δt, an approximation to the first-order derivative of the steering wheel signal at time step *i*.

Δt is the difference in time between two time steps. It's not needed in order to find the stationary points.

Instead use θ'_i directly, and find all *i* such that either:

$$\theta_i' = 0 \qquad 2 \le i \le T \tag{F1}$$

or:

$$| \, sign(\theta_i') - sign(\theta_{i+1}') \, | = 2 \qquad 1 \le i \le T - 1 \tag{F2}$$

where:

$$sign(x) = \begin{cases} -1 & x < 0 \\ 0 & x = 0 \\ 1 & x > 0 \end{cases}$$

Any *i* satisfying equation Equations F1 or F2 is thus a position in the steering wheel angle signal where the approximate first-order derivative of the steering wheel angle is either zero (Equation F1), or just about to pass zero (Equation F2). Any such point is a stationary point. This procedure is illustrated in Figure F2.

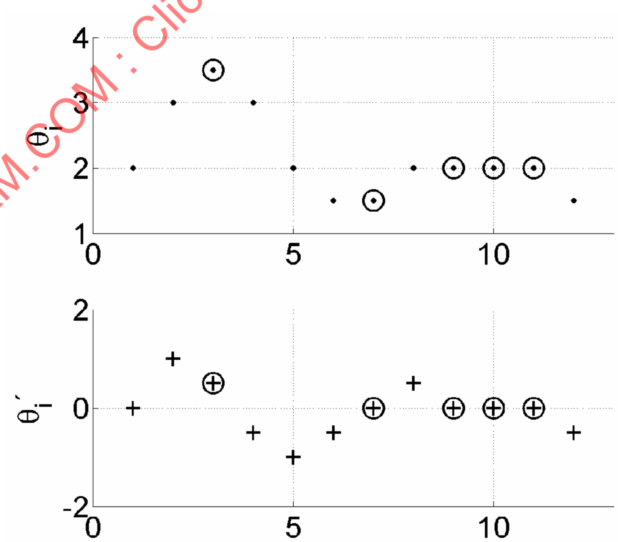

Figure F2 - Illustration of the method for finding stationary points of the steering wheel angle signal.

An example signal θ_i is plotted in the top graph, and corresponding values of θ'_i are plotted in the bottom graph. i = 3 satisfies equation F2, and i = {7, 9, 10, 11} satisfies equation F1, so i = {3, 7, 9, 10, 11} are stationary points of the steering wheel angle signal.

F.2.3 Identify and Count Steering Wheel Reversals

Let $e(k)$ be the k^{th} value of i such that i is a stationary point, sorted in time order so that $e(k) > e(l)$ if $k > l$. For the example of Figure F2, $e(1) = 3$, $e(2) = 7$, $e(3) = 9$, $e(4) = 10$, and $e(5) = 11$. Let N be the total number of stationary points.

F.2.3.1 Count upward reversals

Then the following algorithm counts all upward reversals (from a stationary point of lower angle value to one of higher angle value, e.g., from a local minimum to a local maximum) in the steering wheel angle signal that are bigger than the gap size threshold θ_{min}, which is set to 3 degrees[3].

1. $k \leftarrow 0$
2. $N_r \leftarrow 0$
3. For l = [2, 3, 4, …, N]
   a. If $\theta_{e(l)} - \theta_{e(k)} \geq \theta_{\min}$:
      i. $N_r \leftarrow N_r + 1$
      ii. $R(N_r) \leftarrow [e(k), e(l)]$
      iii. $k \leftarrow l$
   b. Else if $\theta_{e(l)} \leq \theta_{e(k)}$
      i. $k \leftarrow l$

This algorithm positions k at the first stationary point (k=1), and then iterates through the subsequent stationary points until either a stationary point l is found that is more than θ_{min} degrees greater than the stationary point at k, or a stationary point l is found that is smaller in angle value than the stationary point at k. In the first case an upward reversal has been found. In either case, k is set to l and the iteration is continued through higher values of l. Setting k to l in the latter case, when l is a stationary point with smaller angle value than k, ensures that an upward reversal will be found as soon as possible, as this will require a lower angle value in subsequent stationary points for a reversal to be counted.

When the algorithm above has terminated, N_r is the number of upward reversals, and $R(m)$ is a vector with two elements, where the first is the time step where the m^{th} reversal begins, and the second element is the time step where it ends. $R(m)$ is useful for visualizing the results of the algorithm, as in Figure F1, but if this is not needed, step 3.a.ii of the algorithm can be omitted.

F.2.3.2 Count downward reversals

To count also the downward reversals, the same algorithm is then applied on the negative of the steering wheel angle, $-\theta_i$, instead of on θ_i.

F.2.3.3 Compute total number of reversals

The total number of reversals in the steering wheel angle signal is obtained as the sum of upward and downward reversals.

F.2.4 Calculate Steering Wheel Reversal Rate

[3] This calculation uses 3 degrees for the steering reversal threshold. As noted in 9.2.1, 9.2.2, and 9.2.3, other threshold values have been used as well.

The steering wheel reversal rate is calculated as the total number of reversals detected in the steering wheel angle signal, divided by this signal's total length in minutes or seconds. The steering reversal rate can also be computed over a specified distance traveled.

F.2.5 Steering Wheel Reversal Continuous Measure

Suppose you want a measure of steering reversals and steering reversal rate calculated as a continuous measure over a data set. This may be desirable if specific events are not defined; but one wants to compare steering reversal performance between arbitrary parts of the drive. This section modifies the procedure above to calculate continuous measures.

In the algorithm outlined in F.2.3, construct an indicator array, *I*, which is an array of length *T* that is initialized to all zeroes. Every time the condition

$$\theta_{e(l)} - \theta_{e(k)} \geq \theta_{\min}$$

is met, in addition to the other operations in step 3a, set the *e(k)*-th value of *I* to one.

Then, pick a window size, *W*, over which the number and rate of reversals may be calculated. The number of steering reversals is just the number of ones in a window of the indicator array, while the rate is the number divided by the window length, *W*. By applying these calculations over a running window from the beginning of the data to the end, we obtain the continuous measures.

Define a uniform window, *w(i)*, of length *W*, that has values of one inside the window and zero everywhere else. Then the running sum of steering reversals may be interpreted simply as the convolution of *I* with *w(i),* and written

$$SR(i) = I * w$$

Steering reversal rate is obtained from the running average over the window, which is written as

$$SRR(i) = {I * w}/{W}$$

F.3 MATLAB CODE FOR MARKKULA / ENGSTROM METHOD

Several files are available to help users implement the Markkula/Engstrom steering reversal method described above. A readme.txt file describes the files, which include the MATLAB code for implementing the steering reversal rate measure, several pre-calculated Butterworth filters, and a sample test script with an associated data file containing three steering wheel angle test sequences. These files are available at www.umich.edu/~driving.

F.4 LIST OF SYMBOLS

Symbol	Definition	Units
Θ_i	value of the low-pass filtered steering wheel angle signal at time step *i*, with *i* ={1, 2, 3,…, *T*}, where *T* is the total number of samples in a measurement	deg
θ'_i	scaled version of θ'_i / Δ*t*, an approximation to the first order derivative of the steering wheel signal at time step *i*	deg/s
θ_{min}	minimum gap size or threshold (set to 3 degrees)	deg
Δt	difference in time between two time steps	s
T	total number of sample points in Θ_i	
N	total number of stationary points in Θ_i	
$e(k)$	k^{th} value of time step *i* such that *i* is a stationary point, sorted in time order so that $e(k) > e(l)$ if $k > l$	
I	indicator variable of length T that has the value 1 at a reversal, and 0 elsewhere	
W	length of running window *w(i)* applied over variable *I*	
w(i)	uniform window that has value one for i={1,2,3,…,W} and zero elsewhere	

F.5 COMPUTATIONAL METHOD USING VELOCITY AND AMPLITUDE THRESHOLDS (OPTION B)

F.5.1 Procedure

This method is from Ranney, Mazzae, and Baldwin (2007, p. 88-90). It includes an amplitude threshold like the amplitude method, but differs by also incorporating a threshold for steering wheel angle rate in the form of a dead band about the zero velocity value. The steering wheel velocity signal must be recorded as part of the data collection, or derived by differentiating the steering wheel angle signal.

"The hand wheel steering position and positional rate were first filtered using a 4-pole Butterworth low pass phaseless digital filter with a 3.6 Hz cutoff frequency. The rationale for this cut-off frequency is that this cut-off frequency reflects the maximum frequency an average human driver can exert. Extreme maneuvers are inherently low frequency (<1.0 Hz). A cut-off frequency of 3.6 Hz is sufficient to smooth data, keep steering magnitude not reduced within maximum human capacity, and reduce signal noise to negligible values. Doing so, we preserved steering frequency content relevant to drivers' performance.

Steering reversals were determined using both the steering wheel rate and position data. A reversal was defined as when the steering wheel rate exceeded the steering rate dead band and the steering wheel amplitude changed by more than an amplitude threshold value. The parameters (threshold values) for this measure are defined based on vehicle type and subjective judgments.

Steering threshold values used should not be considered universal, as they depend on vehicle testing speed and steering system mechanical properties. For example, a steering system with a higher steering free-play should have a higher steering amplitude threshold value. A vehicle that responds fast to steering input (e.g., sports car) should have a minimal steering rate dead band. For this project, the steering rate dead band was ±1.5 deg/sec and the positional threshold value was ±1.0 degree."

The source code (written by Salaani) for computing the steering reversal function is as follows:

```
function StrRev = get_SteerRev(x, xr, t0, show_plots)
%
% Computing steering reversal
% Written by Kamel Salaani at VRTC - VRTC Track Study
%
global Vnoise ampl_thresh
%
% finding number of reversals
%
indx = find( xr > Vnoise/2 | xr < -1*Vnoise/2 );
%
nn = length(indx);
StrRev = 0;
str1 = 0;
for i=1:(nn-1)
  if (xr(indx(i))*xr(indx(i+1)) < 0)
    if str1 == 0
      str1 = x(indx(i));
    else
     str2 = x(indx(i));
     if abs(str2-str1) > ampl_thresh
       StrRev = StrRev + 1;
       indx2(StrRev) = indx(i);
     end
     str1 = 0;
    end
    %
  end
end
```

For additional details about Option B, see 9.2.1.2 and Figure 40.

F.5.2 Results

The mean number of steering reversals per second was used as a dependent measure in the analysis of variance. The authors found that the steering reversal rate was significantly affected by the secondary tasks. The steering reversal rate was lowest in a baseline condition. All secondary task conditions had significantly greater steering reversal rates; however, there were no differences among the various secondary tasks.

F.6 LIST OF VARIABLES FOR OPTION B

Variable	Definition	Units
x	steering wheel angle	deg
xr	steering wheel velocity	deg / s
t0	time to begin counting reversals	s
Vnoise	width of dead band for steering wheel velocity	deg / s
ampl_thresh	amplitude threshold for steering wheel angle	deg
StrRev	count of the number of steering wheel reversals	
indx(i)	time steps for which steering wheel velocity exceeds the dead band	
indx2	time step at which a steering reversal occurs	
nn	number of time steps in indx	
str1	temporary variable, value of steering wheel angle at a reversal	deg
str2	temporary variable, successive value of steering wheel angle until the next reversal	deg