APPENDIX C

DRIVER-VEHICLE PERFORMANCE MEASURES IN WORKLOAD ASSESSMENT

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MOTIVATION

Driver-vehicle performance measures are measures of various aspects of lateral and longitudinal control. Because these measures are closely related to vehicle trajectories in space and over time, such measures are closely related to safety. Visual allocation and other in-vehicle behaviors may ultimately result in changes in driver-vehicle performance measures, thereby affecting safety. Consequently, examination of driver-vehicle performance while the drivers perform in-vehicle tasks may give an indication of safety relevance. Each of several key classes of measures will be introduced briefly below.

Uncontrolled or inappropriate lane excursions are the precursor to a great many crashes each year, including lane change crashes (Chovan, Tijerina, Alexander, and Hendricks, 1994), opposite-direction crashes (Chovan, Everson, Hendricks, and Pierowicz, 1994), and single vehicle roadway departures (Hendricks, Allen, Tijerina, Everson, Knipling, and Wilson, 1992; Mironer and Hendricks, 1994). From a safety perspective, lanekeeping performance during in-vehicle device use merits scrutiny in a workload evaluation. There is evidence that various lane keeping measures have demonstrated sensitivity to workload demand, both primary driving task demand and in-vehicle distraction, as well as value as part of a set of indicators or driver fatigue or incapacitation (e.g., Wierwille, 1994).

Lane keeping measures have played a prominent role in driver workload assessment. Zwahlen, Adams and DeBald (1988) evaluated CRT touch panels in an automobile driven on a closed airport runway and recorded path deviations over a short distance while the vehicle maintained a 40 mph forward speed. Using paper mock-ups of the CRT touch displays, the path standard deviation significantly increased with in-vehicle tasks, even though drivers had the opportunity to glance to the road ahead. Green (1993) has correctly noted that in this study there was no traffic and so lanekeeping was probably given lower priority than might have been the case under realistic driving conditions. In a series of simulator studies of in-vehicle visual and auditory displays, Noy (1990) reported that lane standard deviation increased with auxiliary cognitive tasks. Perhaps because participants knew they were in a simulator, they may have altered their prioritization of performance such that in-vehicle tasks were accorded more attention than in actual driving. Green, Hoekstra, and Williams (1993) conducted on-the-road data collection in an instrumented vehicle to assess the workload effects of using route guidance and car phone devices and generally found no significant effects of in-vehicle device use on either mean lane position or lane position standard deviation. Dingus, Hulse, Fleischman, McGehee, and Manakkal (in press) reported that older drivers made a significant number of lane deviations (exceedences) and that these varied reliably with the nature of the in-vehicle route guidance display. Older drivers also tended to drive more slowly and cautiously. Dingus, Mollenhauer, Hulse, McGehee, and Fleischman (in press) reported that the results of the TravTek evaluation showed that the number of unplanned lane deviations decreased from a local driver's first to second drive with TravTek. This varied pattern of results suggests that, while lane keeping measures have safety relevance as well as intuitive appeal as workload measures, these measures are subject to the influence of many factors besides workload. Therefore, interpretation of such measures must be conducted with care and in combination with other measures taken to converge on a more accurate device assessment.

Excessive speed is involved in many crashes, particularly those involving younger drivers (Lonero, Clinton, Brock, Wilde, Laurie, and Black, 1995). In addition, it has been noted that older drivers often drive more slowly as a compensation for slower reflexes or reduced capacity to monitor driving conditions (Dingus, Mollenhauer, Hulse, McGehee, and Fleischman, in press). Speed measures for workload assessment often uncover a "slowing" of the vehicle with increased attentional demand. For example, Monty (1984) reported that speed maintenance deteriorated with in-vehicle device use. A similar finding was reported by Noy (1990) in a simulator study. Labiale (1990) carried out an on-the-road study to compare auditory and visual displays of motorist advisory information of different complexity levels. Labiale reported that approximately half of the drivers in the experiments reduced vehicle speed during long vs. short messages and more reduced speed with visual messages than with auditory messages. On the other hand, Dingus, Antin, Hulse, and Wierwille (1989) found no impact on speed measures with the use of the ETAK navigator in various modes. Verwey (1991) conducted a simulator study that involved visual and auditory secondary (in-vehicle) tasks and also reported no impact of secondary task on speed measures. These varied results illustrate that many other factors besides workload enter into speed maintenance. These include driving style, road disturbances (e.g., vertical roadway alignment), and driver workload management strategies, to name a few. Thus, changes in speed measures, like many others in workload assessment, must be interpreted with caution.

Inadequacies in car following performance are directly related to rear-end crashes (Knipling, Mironer, Hendricks, Tijerina, Everson, Allen, and Wilson, 1993), the single most common crash type in the United States. The vast majority of these crashes involve driver inattention and/or following too closely. Furthermore, Evans and Wasielewski (1982) showed that time headway adopted on a section of highway was a significant discriminator of traffic violators from non-violators, that time headways were often below 1.0 s for the traffic violators, and that such short headways greatly increase the risk of rear-end crashes. Thus, there is at least some archival evidence that car following measures such as time headway have safety relevance. The principles of physics also can be used to relate close car following to crash involvement (Mironer and Hendricks, 1994). In particular, more aggressive evasive braking or steering maneuvers are required if the following vehicle is following too closely and/or closing fast on the lead vehicle.

The literature on car following measures is somewhat limited but does indicate the value of considering such measures in a workload assessment protocol. Colbourn, Brown, and Copeman (1978) reported that drivers adopt longer headway distances, on average, when traveling at higher speeds and that the variability of following distance increases with increased travel speed as well.

Noy (1990), in a simulator study, reported that adding an auxiliary task of visually scanning a CRT as associated with degraded headway distance maintenance and that following distance mean error (from a desired following distance) was sensitive to different levels of auxiliary task difficulty.

One potential difficulty with car following measures is that because they are closely related to safety, ethical data collection will require that the evaluation safeguard against car following deterioration. For example, one requirement may be to insure that there is at least, say, 150 ft of car following distance before an in-vehicle task can be presented to the driver. This type of safeguard may eliminate any effects of the in-vehicle device distraction. Another consideration is that the driver may elect to adopt a risky car following behavior (e.g., time headway less than 1 s); engagement in in-vehicle device use may be ill-advised under such circumstances.

INSTRUMENTATION NEEDS

The instrumentation needed to capture lateral and longitudinal driver-vehicle performance measures is discussed below.

SENSOR SUITE

Lane Tracker. Optical sensors (including video cameras) are available that sense the luminance difference between the lane marker line and the surrounding pavement. In sophisticated systems, machine vision processing is applied to determine the location of the vehicle over time. An alternative to this approach is the use of a video camera followed by video post-processing. In post-processing, a data reducer could, with a digitizing tablet, encode the lane line position manually. Other types of lane tracking technologies make use of radar that senses special retroflective material used for the lane line markings. Such approaches are generally only suitable for closed courses or test tracks that can be fitted with cooperative infrastructure modifications. It should be noted that optically-based lane trackers are susceptible to numerous sources of noise and data loss. These sources include specular reflections from the pavement, shadows or dappled sunlight, precipitation build-up on the road surface, and worn lane line markings. Furthermore, it should be noted that the lane tracker will track the lane line at exit and entrance ramps, a phenomenon that leads to momentary errors. The Department of Transportation has invested in Small Business Innovative Research (SBIR) to fund the development of cheaper and more reliable lane trackers. If video or optical means are used for capturing lane position, suitable light sources will be required to illuminate the sensor/camera's field of view. Mounting hardware for the lane tracker is also required. The sample rate should be equal to the video frame rate (e.g., 30 samples per second for NTSC or 25 samples per second for PAL video). The resolution should be ± 1 inch.

Accelerometers A longitudinal accelerometer is needed to capture decelerations (e.g., effective braking levels) or accelerations in the x-axis. A lateral accelerometer is needed to capture lateral accelerations (e.g., magnitude of evasive steering). Finally, yaw rate may be computed from the difference of front and rear-body lateral accelerometer signals, by means of an angular accelerometer, or by means of a rate gyroscope. The lateral and longitudinal accelerometers should be capable of recording 0 - 2 g's with resolution to ±0.001 g. The yaw rate system should be capable of recording 0-20 deg/sec and resolution of 0.01 deg/sec. If only a single set of accelerometers can be installed in the vehicle, it should be located at or near the vehicle center of mass. The sampling rate should match that of the (concurrent) video frame rate.

Speed Sensor. Speed may be measured by means of a fifth wheel tachometer or by a magnetic or inductive pickup on a wheel or the drive shaft. The speed measurement should be over a range from 0 to 80 mph and accurate to within ±0.5 mph. The sampling rate should match that of the (concurrent) video frame rate, i.e., be between 25 and 30 Hz.

Headway and Closing Rate Sensors. The headway distance or distance between the subject vehicle and a lead vehicle can be measured by means of a laser rangefinder or a radar rangefinder. Since these are line-of-sight systems, they are prone to data loss or noise caused by horizontal and vertical roadway geometry, roadside appurtenances, and the like. Furthermore, the headway distances can jump suddenly with cut-in maneuvers by other vehicles in adjacent lanes moving into the subject vehicle's travel lane. Closing rate or relative velocity can be measured by means of a Doppler radar system. The system should have a distance range of up to 350 ft and resolution of ± 1ft. The closing rate or relative velocity sensor should have a range of up to 60 mph and a resolution of ± 1 mph. A sampling rate of 25 to 30 Hz should be sufficient for driver workload assessment.

DATA CAPTURE AND CONTROL

As was explained in the Appendix on steering, accelerator, and manual activity measurement, the efficient capture of sensor data for driver-vehicle performance measures is best managed by means of a computer on-board the instrumented vehicle. Two possible options for data capture and control of sensor data are Pulse Code Modulated (PCM) data recorders or Data Acquisition computers with analog-to-digital (A/D) converters. The PCM option provides the highest bandwidth, highest data storage density, and easiest means for data transport. The data acquisition computer has the advantage of converting all data to digital form at the time of data collection. With this option, a set of anti-aliasing filters must be incorporated to ensure that digitized data have high fidelity. Additionally, an external storage device is essential, especially if a data collection run is to last for any appreciable length of time. Examples of mass data storage devices include high density disk drives and magnetic tape cartridges. It must be noted also that there is more limited bandwidth associated with an affordable direct-to-digital system.

Table B-1 in Appendix B presents the advantages and disadvantages of the two options (Battelle, 1994). As with other parts of the data capture system, power must be available, conditioned to avoid data loss or error. A time-code generator is needed as the basic common reference point for all data channels.

DATA REDUCTION AND FILTERING

The analysis of driver-vehicle performance data , like that for steering and pedal inputs, depends first on appropriate filtering and data reduction. To examine the data, software that allows for the simultaneous examination of multiple data streams is helpful, including an examination of a videotape. One type of system that can facilitate this type of data analysis is the Intelligent Transportation System Test Performance Assessment and Evaluation System (ITS TEST PAES) software prepared under government contract by Calspan (for general information see Gawron, 1994).

FUNDAMENTAL DATA

The following sensed data are required for workload measures based on driver-vehicle performance: lane position, yaw rate, speed, following distance, and closing velocity. From these fundamental data, the measures provided in Table C-1 may be derived. As with similar tables in other appendices, this table consists of the following elements:

- Operational definitions of each Measure Of Performance (MOP);
- A workload interpretation, i.e., a prediction of how the MOP may vary with increased workload.

The analysis of MOPs may be conducted using traditional inferential statistical methods. Specific statistical methods that are applicable include t-tests, analysis of variance (ANOVA), and various multivariate procedures (e.g., regression methods, multivariate analysis of variance, cluster analysis). In addition, graphical depictions of univariate and multivariate data are applicable. The references for this appendix provide examples of various analytical procedures.

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Table C-1. Driver-Vehicle Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver.

Lane PositionVariance (LANEPVAR) and Standard Deviation (LANEDEV):

These are two measures of the variation in lane position over a sample interval of time.

$$LANEPVAR = \frac{\sum_{i=1}^{n} (y(i) - \bar{y})^2}{n}$$

$$LANEDEV = \sqrt{LANEPVAR}$$

where LANEPVAR is lane position variance in inches^2
LANEDEV is lane position standard deviation in inches
y(i) is lane position at sample i
y-bar is mean lane position for the sample interval
n is the number of samples in the sample interval

Workload Interpretation: While no driver maintains the vehicle perfectly at a selected lateral position in the lane, normally the attentive driver makes continuous, smaller steering corrections that yield a certain variability in lane position. With increased attention to in-vehicle tasks (or other distractions), the frequency of steering corrections per unit time tends to decrease. Since small steering corrections decrease, the vehicle tends to drift farther from the selected lane position and this requires a larger corrective steering input subsequently. If this pattern of behavior is exhibited, lane position variance (or standard deviation) might be expected to increase with increased attentional demand.

Note: Variance measures may be more sensitive in a statistical sense because of the wider range of values that result with the variance calculation. The advantage of the standard deviation measure is that it is in common engineering units, not squared units.

Table C-1. Driver-Vehicle Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

Mean Lane Position (LANEPOSM):

$$LANEPOSM = \frac{\sum_{i=1}^{n} y(i)}{n}$$

The mean lane position is the sum of individual lane position samples, y(i), in the sample interval divided by the number of samples in the sample interval, n. (The zero position of y(i) corresponds to having the vehicle perfectly centered in the lane.)

Workload interpretation: With increased attentional demand away from the lanekeeping task, the driver may drift laterally. If so, then the average lane position during such inattentive moments would perhaps be further from the lane center than under conditions of less attentional demand.

Table C-1. Driver-Vehicle Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

Lane RMS Deviation (RMSLANE):

$$RMSLANE = \sqrt{\frac{\sum_{i=1}^{n} y(i)^2}{n}}$$

Workload Interpretation: Lane RMS deviation would be expected to increase with increased attentional demand away from the lanekeeping task, as explained under the lane position variance and standard deviation measures. (As indicated earlier, the zero position of y(i) corresponds to having the vehicle perfectly centered in the lane.)

Note that RMS measures are identical to the square root of variance measures only if the mean of the measured variable is zero. It can be demonstrated that variance measures are not affected by a constant offset, a useful property if such a noise source is present in the data stream.

Peak Lane Deviation: (PKLANDEV)

$$PKLANDEV = \max(|y(i)|);\ i = 1,2,\ldots,n$$

Workload Interpretation: As attentional demand increases, the driver may inadvertently allow the vehicle to veer farther from the center portion of the lane . Thus, the maximum lane deviation in the sample may be expected to increase with increased attentional demand.

Table C-1. Driver-Vehicle Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

Number of Lane Exceedences:	This is defined as the number of occurrences when any part of the vehicle is extended beyond either lane boundary.
Mean Lane Exceedence Duration:	This is the average time spent in a lane exceedence.
Workload Interpretation:	The interpretation of these measures is that with increased attentional demand away from the driving task, the number of lane exceedences might increase and the average duration of lane exceedences might increase. This interpretation follows from the assumption that less attention would be allocated to the lane-tracking task (Dingus et al., 1986).
Yaw Standard Deviation:.	$$YAWSTDEV = \sqrt{\frac{\sum_{i=1}^{n}(\psi(i) - \bar{\Psi})^2}{n}}$$ Where $\psi(i)$ is the angular difference, in degrees, between the vehicle longitudinal axis and the instantaneous roadway tangent (measured in the horizontal plane) at sample i; $\bar{\psi}$-bar is the mean of the yaw samples.
Workload interpretation:	In a moving base simulator, Hicks and Wierwille (1979) found yaw standard deviation to be a sensitive measure of primary driving task workload where the driving task workload was increased by simulated crosswind gusts. With increasing attentional demands, yaw standard deviation might be expected to increase. It is possibly a more sensitive measure than lane position measures because of the dynamics of the vehicle. However, lane position measures are more directly related to safety and are preferred.

Table C-1. Driver-Vehicle Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

Peak Lateral Acceleration:
(PKLATACC) This is the maximum lateral acceleration, a_y, observed in a sample interval.

$$PKLATACC = \max\left(a_y(i)\right);\ i = 1,2,\ldots,n$$

Peak Longitudinal Deceleration(PKLNGDEC): This is the maximum longitudinal deceleration, a_x, observed in a sample interval.

$$PKLNGDEC = \max\left(-a_x(i)\right);\ i = 1,2,\ldots,n$$

Workload Interpretation: Abrupt lateral maneuvers are taken to be indicative of a vehicle which is off lane-center track due to driver inattention (Dingus and Hulse, 1993). As such lateral acceleration measures should be correlated with steering measures. The workload prediction is that peak lateral accelerations, indicative of abrupt lateral maneuvers, may increase with increased attentional demand.

Abrupt braking maneuvers have also proven to be sensitive to in-vehicle device workload (Monty, 1984). If drivers look away from the road scene and glance back to discover an unexpected object or event, then the deceleration level is anticipated to be higher than under conditions of normal attention.

Table C-1. Driver-Vehicle Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

Mean Speed (MEANSPEED):

$$MEANSPEED = \frac{\sum_{i=1}^{n} u(i)}{n}$$

where

MEANSPEED is the average speed over the sample interval;
u(i) is the measured forward velocity at sample i; and
n is the number of samples in the sample interval.

Workload Interpretation: Previous research has shown that under conditions of increased attentional demand, the driver often slows the vehicle. Thus, the workload prediction is that with increased attentional demand, average speed may decrease.

Table C-1. Driver-Vehicle Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

Speed Variance (SPEEDVAR)
or **Speed Standard Deviation**
(SPEEDEV): These are two measures of the variation in travel speed over the a sample interval of time.

$$SPEEDVAR = \frac{\sum_{i=1}^{n} (u(i) - \bar{u})^2}{n}$$

$$SPEEDEV = \sqrt{SPEEDVAR}$$

where SPEEDVAR is speed variance in $(ft/s)^2$
SPEEDEV is speed standard deviation in ft/s
u(i) is forward travel velocity at sample i
u-bar is mean travel velocity for the sample interval
n is the number of samples in the sample interval

Workload Interpretation: With increased attentional demand away from the driving task, the driver may exhibit more erratic longitudinal control. If so, then the variability of speed might be expected to increase with increased attentional demand.

Table C-1. Driver-Vehicle Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

Mean Following Distance (FOLDISTM):

$$FOLDISTM = \frac{\sum_{i=1}^{n} d(i)}{n}$$

where d(i) is the following distance measured at sample i;
n is the total number of following distance measures in the sample interval.

Minimum Following Distance: (MNFOLDIS) This is the shortest following distance recorded in the sample interval.

$$MINFOLDIS = \min(d(i));\ i = 1,2,\ldots,n$$

Workload Interpretation: If the driver is not attending to the primary driving task, it is possible that car following performance will be adversely affected. In this case, the lack of attention to the car following task leads to closer (i.e., smaller) mean following distances, on average, with increased attentional demand. Minimum following distance is expected to be closer with increased attentional demand.

Peak Closing Velocity: (PKCLOSV) This is the maximum closing rate during a sample interval, i.e.,

$$PKCLOSV = \max(u_c(i));\ i = 1,2,\ldots,n$$

Where $u_c(i)$ is the closing velocity in ft/s for sample i (positive for following vehicle gainaing on lead vehicle).

Workload Interpretation: The hypothesis is that with increased attentional demand, peak closing velocity may be expected to increase due to deterioration of car following performance.

Table C-1. Driver-Vehicle Measures of Performance (MOPs) used for Driver Workload Research. Note: All measures are taken within a sample interval of time (i.e., across n samples) and, unless otherwise indicated, are defined with respect to a single driver. (Continued)

Mean Time Headway (MHEADWAY):

$$MHEADWAY = \frac{\sum_{i=1}^{n} headway(i)}{n}$$

where headway(i) is the measured headway in sample i_j,
n is the number of samples in the sample interval.

Minimum Time Headway: (MINHDWY) This is the smallest time headway in the sample interval.

$$MINHDWY = \min(headway(i));\ i = 1,2,\ldots,n$$

Workload Interpretation: Time headway is the instantaneous following distance divided by the instantaneous subject vehicle velocity (not closing velocity) and is measured in time units. For example, if the following distance is 240 ft and the subject vehicle (following vehicle) velocity is 60 ft/s, then the time headway is 4 s. The general prediction for time headway is that may decrease with increased attentional demand under the rationale given for following distance. Minimum time headway might decrease with increased attentional demand away from the car following task.