A Comparison of Real-time and Short-term Aggregated Metrics of Potential Accident Risk and Severity

C. Arthur MacCarley
Electrical Engineering Department
California Polytechnic State University
San Luis Obispo, CA 93407 USA
Ph: (805) 756-2317 amaccarl@calpoly.edu

Abstract. We review commonly used indirect metrics of traffic safety, including conventional aggregated measures and metrics derived from comprehensive individual vehicle records. Using individual vehicle records acquired over a two year study period on a high speed highway, we compare moving averages of vehicle speed and speed standard deviation, and a dynamic estimator of potential collision speed (PCS). PCS is a function of the vehicle speed, separation distance, and sight distance which can be calculated for each vehicle. It may be interpreted as the hypothetical impact speed in a collision if the vehicle encounters an unexpected obstruction on the highway.

Among the noteworthy observations were that traffic safety conclusions inferred from mean speed, speed variance and PCS often differ significantly. This is especially true in the presence of natural or management-related influences on driver behavior, such as reduced visibility, traffic congestion, or driver response to dynamic message signs. Over a two-year period of observations, all periods during which external influences on driver behavior were present, mean speed decreased an average of 1.2 mph, while PCS increased an average of 9.8 mph, inferring opposite conclusions about potential collision risk. Speed standard deviation between sets of temporally proximate vehicles was found to be relatively invariant with fluctuations in either mean speed or PCS, typically averaging 6.5 mph.

BACKGROUND

This study was conducted utilizing data acquired during an evaluation of the effectiveness of dynamic message signs on 15-mile stretch of Interstate 5 and State Route 120 in central California during 2002-2004. This area is known for seasonal Tule fog, leading to enhanced risk of rear-end collisions, although most data used for this analysis were taken during non-fog periods. Comprehensive individual vehicle records of time of detection, speed and length were accumulated for a period of two years at four locations in this area. The reaction of drivers to warning messages in this study area were previously discussed in (1,2,3). The behavioral response of drivers to traffic management interventions of all types has been the topic of research for many years, for example (4,5,6).

The present examination of this raw data was motivated by the possible need for improved real-time indirect measures of relative safety, especially as a potential input for traffic management decision-making and intervention, either manual or automated. The comparison of short-term-aggregated conventional metrics and metrics based upon the dynamic relationship between vehicle pairs provides insight into the relative validity in particular situations.

AGGREGATED AND DISAGGREGATED METRICS OF TRAFFIC SAFETY

In general, roadway measurements may be used to generate numeric metrics using 1. traffic data accumulated and reduced (aggregated) into composite numbers prior recording, or 2. individual vehicle records (measurements for each vehicle).

It must be noted that there is not a consensus as to the threshold at which traffic data is considered to be “aggregated” as opposed to “disaggregated”, e.g., one-hour field-aggregated periods of observation have been referred to as both disaggregated and microscopic aggregated (7).
Aggregated Metrics

Much of the existing roadway monitoring infrastructure cannot support measurement of metrics requiring individual vehicle data. Traffic metrics derivable from field-aggregated data which have been used for safety assessment include:

Mean Traffic Speed

The mean vehicle speed is calculated over all vehicles detected during the polling interval or longer. The mean speed during the polling period may then be estimated calculated by summing all detected vehicle speeds and dividing by the total number of vehicles. Alternatively, mean speed may be estimated from field-aggregated speed bin counts. In this case, if \( n(i) \) equals the number of vehicles detected during the polling period with speeds in the \( i^{th} \) speed bin, and \( v_i \) is the assumed mean speed for the \( i^{th} \) speed bin, the overall mean traffic speed \( \hat{v} \) may be estimated as:

\[
\hat{v} = \frac{\sum_{i=0}^{9} n(i)v_i}{\sum_{i=0}^{9} n(i)}
\]

It is widely assumed that accident risk and cumulative accident rates are monotone increasing functions of individual and mean traffic speed, for example (8). This is the primary justification for statutory speed limits and the usual focus of enforcement efforts. This assumption is based on simple physics: at increased speed, available driver reaction time is reduced which increases the probability of a collision, and vehicle kinetic energy is increased, which is dissipated in destructive form in an inelastic collision. Vehicle dynamics (e.g., centrifugal force in a curve) and vehicle-to-road surface relationships (e.g., tire coefficient of friction) also change in ways that increase the probability of loss of control or reduced ability to avoid accident situation.

However, the significance of speed alone as a predictor of accidents has been increasingly called into question. As early as 1950 (9), it was observed that over a sample of 40,000 accidents, if every accident in which speed was the only violation could have been prevented, the number of accidents would have been reduced by less than 10 percent. An investigation in Canada in 1972 (10) concluded that speed is not necessarily an important cause of accidents, but it is a determinant of severity. In 1964 (11), the FHWA studied a large sample of accidents on rural highways and observed that vehicle speed and crash incidence were related by a U-shaped curve, with the minimum accident rate occurring near the mean traffic speed. Garber and Gadiraju (12) in 1989 concluded that accident rates generally increased with increases in speed variance, and that speed variance increases with the difference between the posted speed limit and the highway design speed. They recommended that posted speed limits should be no more than 5-10 mph below the highway design speed, and that artificially low posted speed limits consequently increase accident rates. This was reinforced by observations such as (13) that in the absence of enforcement, drivers generally selected speeds more consistent with their own perceptions of safety, which are more closely related to the highway design speed and driving conditions than the posted speed limit.

An FHWA Synthesis 2002 (14) addressed the role of traffic speed on traffic safety, concluding that collision risk was not a monotone increasing function of speed, but a function of the difference of the vehicle speed above or below the mean traffic speed, and that accident rates tend to increase with the difference between the 85th percentile of the mean traffic speed and the posted speed limit. The synthesis document also concluded that drivers travel at speeds they fell are reasonable and safe for the road and traffic conditions, regardless of the posted speed limit. As noted in (3), conclusions regarding the diminished direct role of speed in accident risk may be less valid under limited visibility conditions. As discussed by Hauer (15,16,17), it is natural to emphasize the importance of dynamics (the physics of stopping) in assessing traffic safety. The dominant effect of speed is via damage severity and injury production. The higher the speed, the larger the proportion of accidents that occur that are reportable and reported.

Speed Variance

Speed variance is the most commonly used metric of turbulence in traffic flows. Its physical link to traffic safety is intuitive, since the conditions favorable to a collision increase as the speed difference between interacting vehicles
increases. “Speed variance” is typically used generically and actually reported as the sample standard deviation $\hat{\sigma}$ of speeds with respect to the mean. Standard deviation is the square root of the statistical variance.

If speed bin data are field aggregated, it is possible to derive an approximation of the spread of vehicle speeds over the polling interval. Let $n(i)$ equal the number of vehicles detected during the polling period with speeds in the $i^{th}$ speed bin, and $v_i$ is the assumed mean speed for the $i^{th}$ speed bin. An estimate of the sample standard deviation would

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=0}^{9} n(i)(v_i - \hat{v})^2}{\sum_{i=0}^{9} n(i)}}$$

Intuitively, if all vehicles in a common traffic flow drive at nearly the same speed, crash risk is minimized. However, the literature is not unanimous on the relationship between individual accident risk and traffic speed variance. For example, Davis (18) presents a minority argument that positive correlations between crash rates and the dispersion of vehicle speeds do not necessarily support the hypothesis that an increase in speed variance increases individual accident risk.

Mean Gap
Mean (or average) traffic gap is measured simply as the average off-time of an inductive loop. It may also be calculated from the average occupancy (normalized fraction valued 0 to 1) and the polling period in seconds:

$$\tau_{gap} = \tau_{off\ time,\ avg} = \tau_{period}(1 - \text{occupancy})$$

Inter-vehicle Gap (in seconds) normalizes the effect of vehicle speed with vehicle separation, and therefore serves as an indicator of potential accident severity and/or risk.

Prior Use of Aggregated Data to Assess Safety
A recent example of the use of aggregated data available from the existing roadway infrastructure to assess relative traffic safety is the work of Golub and Ritchie (19). The authors used data from simplex loops on California freeways to establish a relationship between traffic accidents and the traffic conditions near the time and detector station most proximate to each accident. Among the conclusions was that relatively high crash rates were associated with high traffic turbulence when mean speed is relatively low.

Individual Vehicle Metrics
With the availability of records for each vehicle, it is possible to more accurately calculate the previous metrics, and to consider additional metrics based upon vehicle-vehicle interactions.

Moving-Average Traffic Speed
Individual vehicle speeds are measured, communicated with a central server, and recorded. They may be analyzed in post-processing to generate, for example, mean speed over a given period of observation. Let $v(i)$ equal the measured speed of the $i^{th}$ vehicle, and $N$ equal the total number of vehicles considered over some sample period. The mean traffic speed $\hat{v}$ over a given period is calculated as:

$$\hat{v} = \frac{\sum_{i=1}^{N} v(i)}{N}$$

For our present study, we consider a time-moving average of vehicle speeds over sample durations of 45 seconds, updated every 15 seconds as a potential near-real-time indirect metric or safety. The 3:1 overlap between the period of observation and the time of calculation helps to smooth plotted measurements without obscuring valuable discontinuities.
**Proximate Variance of Vehicle Speeds**

Measured from individual vehicle records, the sample standard deviation $\hat{\sigma}$ is calculated over a given period of observation as

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^{N} (v(i) - \bar{v})^2}{N}}$$

where $v(i)$ equal the measured speed of the $i^{th}$ vehicle, and $N$ equal the total number of vehicles.

“Proximate”, in this case, implies a restriction on the period of observation or sample size which requires that vehicles actually have some possibility of interacting. Intuitively, the physical link between traffic turbulence and accident rates or risk is the potential for interactions between vehicles; the greater the difference in speeds between proximate vehicles (either in the same or adjacent lanes), the greater the possibility of a collision. Proximity would best be determined by physical analysis of each situation under, e.g., consideration of the traffic density and/or volume. A practical compromise as a surrogate for physical proximity is temporal proximity – vehicles detected at a fixed position on the highway in all lanes within a small enough period of time to admit the possibility of interactions. For periods longer than this, the variance calculation is increasingly diluted by non-interacting vehicles, reducing the validity of this metric as a measure of risk of collision. A lower limit also exists on the period of observation and number of samples to avoid sample noise and assure statistical significance. A tradeoff therefore exists in optimum sample size or period of observation, if collision risk is to be inferred from speed variance. For our study, we capture a rolling view over a period of 45 seconds, updated every 15 seconds.

**Skewness and Kurtosis**

With individual vehicle records recorded, the calculation of any statistical measure is possible, including skewness, and indicator of the symmetry of the speed distribution, and kurtosis, an indicator of how sharply the distribution is peaked. In a study of the driver behavior effects of a Variable Message Sign (VMS) in an area of recurrent fog, Martin et. al. (20) utilized the mean, standard deviation, skewness and kurtosis of the speed distribution.

**Individual Vehicle Gap or Headway**

Calculated for each vehicle pair in a lane, for vehicle $i$, gap is a simple time calculation

$$\tau_{\text{gap},i} = \tau_{\text{headway},i} - \tau_{\text{presence},i} \approx \frac{X_{i-1} - X_i}{v_{0,i}}$$

where $\tau_{\text{headway},i}$ is the time separation between the arrival times of each consecutive pairing of vehicles in a particular lane, and $\tau_{\text{presence},i}$ is the presence time over the loop for the first-to-arrive vehicle in each pairing. Also, $X_{i-1}$ is the position on the highway of the first-to-arrive vehicle and $X_i$ is the position of the trailing vehicle at the moment of observation, usually the time of arrival of the trailing vehicle. $v_{0,i}$ is the velocity (speed) of the vehicle at the time of detection.

Over sufficiently long periods of observations, the average of individually calculated vehicle gaps is equal to the average gap as defined previously.

**Time to Collision (TTC) and Related Metrics**

Time-to-Collision, like individual vehicle gap (in seconds), is one of several metrics based upon physical relationships between consecutive vehicles, either in the same lane or adjoining lanes. Van der Horst and Hogema (5,21) in 1992-4 and Minderhoud (22) in 2001 sought to relate the difference in speed between proximate vehicles with accident risk. They adopted and modified a version of the Time-To-Collision (TTC) metric originally proposed by Hayward in 1971 (23) for this purpose. As defined originally by Hayward, TTC:

$$TTC_i = \frac{X_{i-1} - X_i - l_{i-1}}{v_i - v_{i-1}}, \quad v_i > v_{i-1}$$
where $x_{i-1}$ is the position of the lead vehicle, measured at the front bumper. $x_i$ is the position of the trailing vehicle. $l_{i-1}$ is the length of the trailing vehicle. $v_{i-1}$ is the velocity of the lead vehicle. $v_i$ is the velocity of the trailing vehicle. All values are taken at the same moment in time, at which the trailing vehicle starts to brake in response to the braking, already in progress, of the lead vehicle.

In their evaluation of driver behavior in fog, Hogema and Van der Horst redefined $v_{i-1}$ as the free speed of the lead vehicle, measured at the point of detection on the highway, and assumed constant until the detection of the trailing vehicle with velocity $v_i$. The defining equation above remains the same, but the times of measurement of $v_i$ and $v_{i-1}$, are now different; both velocities are measured via time-of-flight using duplex inductive loops.

$$\text{TTC}_i = \left\{ \begin{array}{ll}
(t_i - t_{i-1})v_{i-1} - 3.6l_i & v_i > v_{i-1} \\
v_i - v_{i-1} & v_i \leq v_{i-1} \\
\infty &
\end{array} \right.$$  

where $t_i$ = time of arrival of trail vehicle (seconds)  
$t_{i-1}$ = time of arrival of lead vehicle (seconds)  
$v_i$ = velocity of trail vehicle at point of detection (km/h)  
$v_{i-1}$ = velocity of lead vehicle at point of detection (km/h)  
$l_i$ = length of the trail vehicle (meters)

Redefined in this way, TTC was a surrogate for lane speed variance measured only between immediately proximate vehicles. Higher values of TTC infer safer situations. A TTC value of 1.6 seconds or higher was considered a distinguishing limit between dangerous and normal conflicts.

Note, however, that the metric is non-infinite only when the trailing vehicle speed is greater than the lead vehicle speed at the point of detection, even if there is nearly zero separation between the vehicles. Thus TTC defines the extrapolated time until a hypothetical collision between these vehicles if the rear vehicle does not brake, despite the fact that it is approaching an impending collision with the lead vehicle (whose speed is also assumed constant). This metric is not relevant for vehicles in a platoon traveling at approximately the same speed. It served, rather, as a type of per-vehicle measurement of speed turbulence, and they selectively applied this metric only between the last vehicle in a lead platoon (vehicle $i-1$) and the first vehicle in the following trail platoon (vehicle $i$) or between sufficiently separated independent vehicles.

Hogema, van der Horst and others (24) used this form of TTC for consecutive vehicles to evaluate the safety ramifications of variable speed limits on the A16 in the Netherlands 1992-94. Minderhoud and Bovy (22) in 2001 defined additional situation-specific metrics, loosely based upon TTC:

- **TET = Time Exposition Time-to-Defined** as the fraction of the overall time that each vehicle travels with TTC below a critical value, typically 4.0 seconds suggested by Hirst (25) in 1997.
- **TIT = Time Integrated Time-to-Collision.** Similar to TET except instantaneous values of TTC for each vehicle are integrated over time to produce a cumulative metric over a given period of observation.
- **DTS = Deceleration-to-Safety Time.**
- **TTA = Time-to-Accident.**
- **PET = Post-Encroachment-Time.**

Heijer et al (26) defined a roadway-measurable safety criteria based on five types of traffic disturbances, described as “obviously dangerous (and therefore disturbing) events that must lead to either a braking maneuver or a lane changing maneuver to avoid a collision with a span of 3 s after the measurement of a passing vehicle”:

1. **TTC < 2**
2. **Dangerous proximity 1:** Vehicle speeds the same, and vehicle separation < 5 meters
3. Dangerous proximity 2: If first vehicle brakes strongly \(6 \text{ m/s}^2\), the second vehicle cannot avoid a collision. A 1 second driver reaction time was assumed.

4. Overtaking on the wrong side, if executed at elevated speed \(> 80 \text{ km/h}\)

5. Simultaneous encroachment of two vehicles in adjacent lanes upon a third vehicle in one of those lanes, in such a way that they will want to overtake the third vehicle at the same moment

The disturbance events were calculated as a 100-second moving average to estimate the ongoing frequency (events/second). Typical values were between .005 and .02 for most traffic, with peaks as high as .05 at the time of an accident.

**Real-time indirect indicators of rear-end collision risk and potential severity**

We can build on this view of traffic safety and derive one or more measures of the severity of some subset of the “disturbance” events defined by Heijer, et al. Disturbances 1, 2, and 3, all relate to vehicle following distances. Based upon TASIS records (27), 1563 collisions occurred from between January 1997 and December 2003 on segments of the highway in which our test sites were located. Of these 491 or 31.4% were classified in the CHP officer’s report as “rear end” collisions, and 466 or 29.8% were classified as “hit object” (often debris from a prior accident). These cases all involved a vehicle approaching another vehicle or obstruction and being forced to brake. We therefore focus on these classes of vehicle collisions as the premise for a real-time indirect metric of traffic safety.

Safe following distances based upon vehicle stopping dynamics are well-established, e.g., 1943 AASHTO Standards (28). The same approach may be used to predict the vehicle speed at time of impact in a potential rear-end collision, based upon the initial vehicle speed, and the minimum of either the separation or sight distance. Kinetic energy release at the time of collision, a surrogate for collision severity, has a square-law relationship with differential impact speed. In suggesting that collision risk may be inferred from potential collision speed, much is ignored, since risk or danger consider, among other things, the probability of a disturbance that sets up a potential collision situation, the ability of the driver to avoid it, and the damage or harm consequences of the hypothetical collision. Further, driver reaction time, the tire-to-pavement coefficient of friction, and roadway grade are variables that for practical reasons must be assumed to be reasonable constants.

However, the potential collision speed (PCS), can be easily calculated in real time using simple kinetic relationships which require knowledge of the individual vehicle speed and time of detection records. The use of stopping dynamic calculations in vehicular automated collision warning, active braking and car-following cruise controls is already well establish, one of numerous product examples being (29). Two fundamental collision scenarios are considered:

**Scenario 1 – Isolated rear-end collision, or first collision in a multi-car chain collision**

This scenario applies to the first vehicle behind another vehicle that brakes to a full stop. The following vehicle does not abruptly change lanes during the braking maneuver. This scenario is the most forgiving, allowing the shortest safe following distance or sight distance. The lead vehicle, initiates a stop and maintains its maximum possible deceleration (braking) rate until it comes to a stop, without impacting any object in its path. The driver of the following vehicle reacts as quickly as possible, and decelerates at its maximum possible deceleration rate until it either comes to a stop or impacts the lead vehicle. The vehicle stopping dynamics associated with this scenario are described in Volume 2 of (3). As an overly conservative metric which would evaluate to zero for gaps exceeding the driver reaction time, it was discarded as a potential predictor of collision risk/severity.

**Scenario 2 - Collision with stopped vehicle, stationary object, or later collisions in a multi-car chain collision**

A stationary obstruction or existing pile-up ahead becomes suddenly visible to a driver. The vehicle does not abruptly change lanes, or the blockage extends across multiple lanes, preventing evasive action to avoid the blockage. This scenario is the least-forgiving, requiring the longest safe following distance or sight distance. It is, however, the situation that describes all but the first collision in a multi-car pileup.

The driver of the vehicle i, reacts as quickly as possible, and decelerates at the maximum possible braking rate until it either comes to a stop or impacts the blockage or stopped vehicle ahead. Structural assumptions:
For \(v_{\text{impact},i} \) to equal zero, vehicle \(i \) must come to a complete stop within its following distance. If \(x_{\text{separation},i} \leq x_{\text{react},i} \), then a collision will occur with an impact velocity of \(v_{0,i} \). This is a far more demanding scenario than that of Scenario 1, requiring that the separation distance \(x_{\text{separation},i} > x_{\text{react},i} + x_{\text{brake}} \) in order to avoid a collision. After initiation of braking, the remaining distance between the two vehicles determines the velocity at the time of impact. The relationship between the impact velocity and the required separation distance is given by equation (1) below.

\[
v_{\text{impact},i} = \begin{cases} 
  v_{0,i} - \sqrt{\frac{\min\{x_{\text{vis}}, x_{\text{separation},i}\} - x_{\text{react},i}}{x_{\text{brake},i}}}, & \min\{x_{\text{vis}}, x_{\text{separation},i}\} \geq x_{\text{react},i} \\
  v_{0,i}, & \min\{x_{\text{vis}}, x_{\text{separation},i}\} < x_{\text{react},i}
\end{cases}
\]

\[
(1)
\]

\(v_{0,i} = \) initial velocity of following vehicle

\(x_{\text{vis}} = \) visibility site distance

\(x_{\text{react},i} = t_{\text{react}}v_{0,i} = \) reaction distance of vehicle \(i\), \(t_{\text{react}} = \) driver reaction time

\(x_{\text{separation},i} = (t_{0,i} - t_{0,i-1})v_{0,i-1} = \) separation between vehicle \(i\) and \(i-1\)

\(t_{0,i}\) and \(t_{0,i-1}\) are the detection times for each vehicle

\(x_{\text{brake},i} = \frac{v_{0,i}^2}{2gk_{\text{friction}}} = \) braking distance of vehicle \(i\)

The maximum possible value of PCS is the initial vehicle speed \(v_{0,i}\). The relationship between the impact velocity and the initial separation distance is shown graphically in FIGURE 1.

Following distances greater than the visibility distance \(x_{\text{vis}}\) add no incremental margin of safety. For this reason, it is necessary to use the smaller of the following distance \(x_{\text{separation}}\) and the sight distance \(x_{\text{vis}}\). The condition necessary to avoid a collision is:

\[
\min(x_{\text{separation},i}, x_{\text{vis}}) \geq x_{\text{brake},i} + x_{\text{react}} = \frac{v_{0,i}^2}{2gk_{\text{friction}}} + t_{\text{react}}v_{0,i}
\]

**FIELD COMPARISON METHODOLOGY**

Using duplex inductive loop detectors in each of three southbound lanes, we comprehensively recorded individual vehicle records of time of detection, speed, and length for two-year period during 2002-2004 at four proximate locations on Interstate 5 in central California, shown in the aerial view of FIGURE 2. From the individual records, we calculate 45-second moving averages of vehicle speeds and speed standard deviation, and PCS, with values plotted every 15 seconds.

Two values are plotted for each metric: the average from the first two sites, labeled BCMS (Before the CMS) and the average of the second two sites, labeled ACMS (After the CMS). Traffic volume is reported as the four-site...
average using the same moving average window and update rate, since volume did not ever change significantly over the 2.4 mile test section. Using forward-dispersion fog/particulate sensors, real-time visibility (in feet) is also reported BCMS and ACMS; see (3) for sensor and reporting standards. The visibility affects the reported PCS values whenever visibility distance was less than the vehicle separation, which typically occurs only during very dense fog. A variable message sign capable of displaying fog and traffic warning messages, or “Amber Alerts”, was located midway between sites 3 and 4.

OBSERVATIONS AND CONCLUSIONS

FIGURE 3, FIGURE 5 and FIGURE 6 present a time sequence of three two-hour periods in the same day, November 16, 2003, representative respectively of night, night/day transition, and daylight conditions, containing both clear and restricted visibility conditions and traffic ranging from very light (night) to rush hour (night/day) transition. The CMS was disabled this day, so this period represents the natural response of drivers to the range of environmental and traffic conditions.

Referring to FIGURE 3, the yellow trace at the bottom of the plot indicates the average traffic volume in all three lanes, displayed in vehicles per minute (veh/min). The single trace is the average over all sites, since volumes differed very little between the four successive sites. Traffic volume during this late night period was reasonably constant at $8 \pm 3$ veh/min, decreasing as time progressed. PCS and mean speed are shown on the lower part of the plot, and speed variance on the upper part of the plot. BCMS measurements of each are plotted in red and ACMS measurements are in blue. The common unit of measurement for each metric is miles per hour (mph). This includes the moving average vehicle speed (referred to as mean speed), proximate sample standard deviation of speed with respect to the mean (referred to as speed variance), and Potential Collision Speed (referred to as PCS). Visibility is reported on the upper part of the plot in feet.

During the first 1.5 hours, visibility is clear. Mean speed at all sites is reasonably constant at $71 \pm 3$ mph, and speed variance fluctuates from 2 to 14 mph, maintaining a mean of approximately 7 mph. PCS fluctuates between zero and 8 mph at all sites, with a mean of 4 mph, consistent with the sparse traffic conditions.

At approximately 1:30AM, a significant reduction in visibility due to fog occurs at the ACMS sites while remaining clear at the BCMS sites. The moving average mean speed at the ACMS sites drops approximately 10 mph to approximately 61 mph (which also eventually slows traffic at the BCMS sites). PCS at the ACMS sites increases to a maximum of 50 mph fluctuating about a mean of 40 mph, a 36 mph increase. The mean and apparent random pattern of speed variance at the ACMS sites does not seem to be affected. During the period of limited visibility, the dichotomy between the mean speed and PCS may be explained by the observation that the modest decrease in mean speed was accompanied by either a much greater decrease in vehicle separation or visibility distance, revealed by the much larger increase in PCS. Another possible explanation for this may be extracted from FIGURE 4, a travel-time-adjusted diagram showing the same vehicle platoon in the BCMS (clear visibility) and later in the ACMS (limited visibility) segments. It seems to show the apparent effect of a single vehicle slowing down, creating a platoon of increased density behind it. The net effect manifests as a reduction in mean speed, and a decrease in speed variance (both suggestive of improved safety), but PCS reveals the compression of vehicle separation inside the platoon (clearly a less-safe situation). In traffic slow-down situations similar to this, PCS may be a superior indicator of relative traffic safety compared with either mean speed or speed variance.

FIGURE 5 depicts the 6:00 to 8:00AM night-day transition, including the commuting rush hour, with a mid-way increase in fog resulting in moderate visibility limitations. Noteworthy during the fog period is the large increase in PCS, from an initial value of 10 mph to a temporary mean of 55 mph at the ACMS sites between 6:40 and 7:30AM, while mean speed and speed variance showed virtually no change. Since the ACMS visibility never fell below 200 ft., equivalent to a 2-second vehicle headway, it is unlikely that the large increase in the PCS calculation can be attributed to the visibility distance falling below the vehicle separation for all vehicles. Reductions in vehicle separation were also occurring. Neither distance effect were revealed by the mean speed or speed variance.

FIGURE 6 depicts the 8:00–10:00AM daytime period that immediately follows the period of FIGURE 5. Visibility was relatively good throughout. A traffic blockage at the BCMS sites occurred between 8:15 and 8:33AM, possibly due to a disabled vehicle or unreported collision (no TASAS record). During this incident, mean speed dropped abruptly from approximately 72 to 30 mph, and speed variance increased from approximately 7 to 13 mph. PCS
also decreased, from approximately 22 to 6 mph. In this case, mean speed and PCS suggest similar safety trends (PCS less pronounced than mean speed), while speed variance suggested the opposite trend. The concurrent but disproportional trends between mean speed and PCS in this case suggest that while passing through the congested area, drivers were selecting safer separation distances for the reduced speed, revealed by the vehicle stopping dynamics relationship of the PCS metric.

Over the entire two-year study period, time periods during which any form of external influence on driver behavior caused a transition from the norm were isolated. Influences could be naturally-occurring such as traffic congestion or visibility reduction, or induced by traffic management efforts such as the display of an advisory message on the CMS. During these periods, mean speed reductions averaged 1.2 mph less than the normal condition mean speed of 70 mph over all lanes, while average PCS increased an average of 9.8 mph greater than the normal condition mean of 23 mph. On average, speed standard deviation decreased (insignificantly) only .23 mph from the normal condition average of 6.5 mph during these periods. There are obviously many additional ways by which these metrics may be compared using the available microscopic traffic data, and these may be explored in future work.

An attempt was made to relate the mean speed, speed variance and PCS to collision statistics. Using TASAS data, over the two year period in which comprehensive individual vehicle records were recorded, only seven collisions occurred within or just outside of the 2.4 mile instrumented segment. Two of these resulted in injuries, none fatal. All occurred in clear atmospheric conditions and on dry road surfaces. Six of the seven fell within collision categories for which PCS could be a relevant estimator of collision severity or risk.

However, exact collision times as recorded in TASAS are not sufficiently resolved in time or location to reliably identify the particular vehicle(s) involved with a specific value of either individual or 45-second averaged PCS, speed, or speed variance measured at a fixed instrumented site. PCS values can differ greatly between individual vehicles, regardless of proximity (e.g., a random subset of drivers choose to tailgate, which leads to individually high PCS values). We also noted how significantly even the 45-second moving average of PCS can differ between the four test sites and how rapidly it can change. Aware of these experimental limitations and the excessively small sample set, we did not feel that valid inferences could be drawn between the collision data and the metrics under test.

ACKNOWLEDGEMENT AND DISCLAIMER

This work was funded by the California Office of Traffic Safety and administered by the California Department of Transportation, Division of Research and Innovation. All statements and opinions expressed herein are the responsibility of the authors, and do not reflect the official views or policies of Caltrans, the OTS, or the State of California.

REFERENCES

27. Traffic Accident Surveillance and Analysis System, California Department of Transportation, online at http://www.dot.ca.gov/hq/traffops/signtech/signdel/chp3/chp3.htm#3-03
LIST OF FIGURES

Figure 1. Potential collision speed (impact velocity) vs. the minimum of the separation or visibility distance. ........12
Figure 3. Night, light traffic, both clear and restricted visibility. .................................................................14
Figure 4. Vehicle positions as visibility progressively decreases, from clear at the BCMS sites to approximately 200 feet at the ACMS sites. ........................................................................................................15
Figure 5. Night-day transition, including rush-hour traffic, both clear and reduced visibility. ......................16
Figure 6. Daytime, moderate-heavy traffic, good visibility. Traffic incident at approximately 8:15 AM causes congestion at the BCMS sites. ..........................................................................................17
FIGURE 1. Potential collision speed (impact velocity) vs. the minimum of the separation or visibility distance.
FIGURE 2. Location of monitoring sites, Interstate 5 near Stockton, California. Composite photograph created from satellite photographs obtained from terraserver.microsoft.com.
FIGURE 3. Night, light traffic, both clear and restricted visibility.
FIGURE 4. Vehicle positions as visibility progressively decreases, from clear at the BCMS sites to approximately 200 feet at the ACMS sites.
FIGURE 5. Night-day transition, including rush-hour traffic, both clear and reduced visibility.
FIGURE 6. Daytime, moderate-heavy traffic, good visibility. Traffic incident at approximately 8:15 AM causes congestion at the BCMS sites.