Arterial Performance Measures in a Connected Vehicle Environment

Noah J. Goodall
Virginia Center for Transportation Innovation and Research
noah.goodall@vdot.virginia.gov

Brian L. Smith
University of Virginia
briansmith@virginia.edu

Ramkumar Venkatanarayana
University of Virginia
ramkumar@virginia.edu

Paper presented at the 18th World Congress on Intelligent Transport Systems, Orlando, FL, October 2011.

ABSTRACT

Wireless communication between vehicles and the transportation infrastructure will provide significantly more timely and comprehensive information about arterials and their performance. However, most measures-of-effectiveness were developed based on data available from traditional "point" sensors. The information made available in a connected vehicle environment requires new metrics that can fully utilize the data. This paper identifies several new arterial performance metrics made available in a connected vehicle environment, as well as several existing metrics that can be evaluated more accurately and frequently than before. The new metrics are person-delay, sudden deceleration, change in lateral acceleration, and aggregate regulation compliance. Person-delay measures a vehicle's lost time multiplied by the number of passengers, and allows for more efficient movement of high-occupancy vehicles and sophisticated transit signal priority. Sudden deceleration and change in lateral acceleration measure activities such as unexpected braking and swerving, which may be leading indicators of unsafe conditions. Aggregate regulation compliance detects unsafe driving behavior that is difficult to collect in the field, such as speeding and illegal U-turns. Engineers can address problem areas through signal timing changes traffic calming, and other measures. The proposed metrics all require high-resolution detection, and are difficult or impossible to measure with existing point detection. For each new metric, its compatibility with connected vehicles is discussed, and required SAE J2735 DSRC Message Set Dictionary data elements are identified.

INTRODUCTION

Traditional measures of effectiveness (MOEs) for arterial systems include delays, stops, queue lengths, throughput, crashes, energy use and emissions. These MOEs have been developed primarily to interpret the data available from in-pavement sensors and video detection, which can only detect vehicle presence. Furthermore, these metrics were intended to measure the effectiveness of traffic control strategies based on traditional sensor data.

However, with the advent of wireless communication between vehicles and traffic control infrastructure, performance metrics can utilize more recent, dynamic, and comprehensive vehicle data, including but not limited to speed, location, acceleration, braking status, and acceleration.

This new data has several advantages. First, the traditional performance measures such as speed and headway can be collected across a much greater area. Instead of determining headway at a single loop detector and extrapolating that information over a corridor, connected vehicles allows the same data to be collected directly over the entire corridor, eliminating the need for extrapolation and improving accuracy.

Secondly, with connected vehicles engineers can collect a much broader array of data than the speed and presence data available with loop detectors. Virtually any information measured by a vehicle's diagnostic system is available for capture. This includes brake pressure, anti-lock brake status, windshield wiper status, transmission status, tire pressure, steering wheel angle, and many more. The new information allows the collection of entirely new and useful performance measures that are impossible to collect with point detection. Some of the new metrics presented in this paper, such as sudden deceleration and change in lateral deceleration, can be leading indicators of unsafe conditions, allowing agencies to improve the arterial facilities before a crash study is needed. Other proposed metrics can indicate areas of non-compliance in need of further investigation.

Most information on driver behavior is there average expected behavior based on previous studies conducted at specific locations over a short period of time. By collecting connected vehicles data continuously, researcher can build a database of driver behavior that can be cross-referenced against location, weather, and light conditions. The behavior of drivers can be quickly localized by region, intersection, and weather conditions to provide much more accurate estimates of how drivers will behave at a given time and place. With this information, engineers could develop localized timing plans, optimized for any scenario.

Given the above-mentioned advantages made possible by connected vehicles, this paper proposes several new useful arterial performance metrics which fully utilize the new data, and suggests existing metrics that could be evaluated more accurately and more often.

MEASURES-OF-EFFECTIVENESS AND SUPPORTING DATA

The new data from connected vehicles will benefit transportation agencies in measuring and improving system performance in three diverse ways. The metrics described in this paper are grouped according to the ways they can perform the following tasks:

1) provide a foundation for more accurate measurement of traditional metrics,
2) support a new family of metrics, and
3) enable the collection of environmental and contextual information that will provide a information to improve the accuracy of other metrics by analyzing data specific to time, location, vehicle characteristics, and weather conditions.

The primary communications media for connected vehicle applications is expected to be dedicated short-range communications (DSRC) (1). DSRC is high speed and low latency, and operates on a dedicated bandwidth. The Society of Automotive Engineers (SAE) J2735 DSRC Message Set Dictionary (2), which is still in draft form and most recently updated in November 2009, is a standard that specifies the types of information to be included in any safety and mobility messages sent and received with DSRC in an connected vehicle environment. The standard defines specific information that may be exchanged between vehicles and the infrastructure as "data elements." These elements are then further grouped into "data fields," and also further grouped into messages. There are several messages, but two most directly pertain to traffic signal operations. These are the Basic Safety Message Part I and the A La Carte Message. The Basic Safety Message (BSM) Part I transmits a vehicle's position, heading, speed, and acceleration, and is often referred to as a ***Here I Am*** message. The BMS Part I includes the following data elements:

SAE J2735 Basic Safety Message Part I Data Elements (2)

- MsgCount
- TemporaryID
- DSecond
- PositionLocal3D
    - Latitude
    - Longitude
    - Elevation
    - PositionalAccuracy
- Motion
    - TransmissionAndSpeed
    - Heading
    - SteeringWheelAngle
    - AccelerationSet4Way
- Control
    - BrakeSystemStatus
- VehicleBasic
- VehicleSize

The A La Carte Message (ACM) transmits other information as requested, and less frequently. For the performance measures identified in this paper, the required messages are listed, along with the specific ACM data elements (if needed).

While many of the arterial performance metrics identified in this paper are based primarily around DSRC, other communications media may be used instead, as these metrics do not have demanding requirements for latency, bandwidth, or message priority.

The sections below describe each type of metric in detail. Each section describes its metric, and provides several examples of its potential, application, and utility with connected vehicles. Finally, a few specific sample metrics are provided, and the required data elements from the SAE J2735 DSRC Message Set Dictionary are listed.

IMPROVED MEASUREMENT OF EXISTING METRICS

The metrics described in this section consist of MOEs used today. Some metrics are measured in the field, such as speed and headway, while others are measured analytically or in simulations. Vehicle to infrastructure communications made possible in a connected vehicle environment allows for continuous measurements, made over a broader area, often at a higher level of accuracy than field measurements.

Vehicle Delay

Delay, while the primary measure of effectiveness for signalized intersections, remains difficult to measure in the field. Accurate delay measurement requires a vehicle's starting point, destination, the vehicle's travel time to the destination, and the unimpeded travel time to the destination. Because delay is so difficult to measure, it is instead often estimated using Highway Capacity Manual methods (1) based on typical vehicle arrival rates, lane configurations, the signal timing plan, and several other factors.

Information available in a connected vehicle environment allows a much more dynamic measurement of delay. Vehicles can provide speed and heading information, which can be compared to a database of expected travel times and speeds at each vehicle's current location. Not only would this measurement provide the traditional delay values measured over a period of time through a length of roadway, connected vehicles would allow several new types of delay measurement.

Example Metrics

- **Instantaneous vehicle delay.** This metric reports the delay of a group of vehicles over a very short time period, such as one second. While not particularly useful in traditional signal timing and evaluation applications, delays over shorter periods can be used in real-time adaptive traffic signal timing.
- **Average instantaneous delay on a link.** This metric uses the short term delays of vehicles to develop an average delay of all vehicles approaching one movement of a traffic signal, or along any link of interest. This metric is especially useful in real-time adaptive traffic signal timing, by allowing signals to measure delay at all approaches and adjust signal timing to minimize delay. This metric is also useful in the operation of traffic signals in over-saturated conditions, where abnormally high delays at certain road segments may indicate incidents or backups.
- **Cumulative vehicle delay on a link.** This metric measures the total delay of vehicles along a link over a set time period. By specifying the location of the delay, traffic signal timing plans can respond adaptively to the location of greatest delay.
- **Average cumulative vehicle delay on a link.** This metric uses the cumulative vehicle delay to determine the average delay per vehicle on a link. It is especially useful in the evaluation of a traffic signal's effectiveness in serving each traffic movement. Unusually

high delay at a link may indicate a geometric or timing problem at the intersection, warranting further study.

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I

Headway

The spacing between vehicles is a metric that has been studied and utilized by traffic engineers for years. Connected vehicles allows the direct measurement of both time headway (i.e. the time difference between the fronts of two vehicles) and space headway (i.e. the time difference between the rear of the leading vehicle and the front of the following vehicle). By measuring the instantaneous locations and speeds of vehicles, as well as individual vehicle lengths, traffic engineers can determine headways at any location within range of Road Side Equipment (RSE).

Headway information may also provide a leading indicator of intersection safety, as it does for highway safety. Engineers may be able to implement traffic calming countermeasures on sections of roadway with very short headways, where drivers may not be providing themselves adequate stopping time.

Example Metrics

- Average time headway
- Average space headway
- Individual headways

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I

Speed

Vehicle speed is a very useful metric, and is utilized in some way by several other metrics mentioned in this report, including headway, anticipated driver behavior, queue length, and delay. In a connected vehicle environment, vehicles will be able to send accurate speed data to roadside units. Discussion of the value of speed data is covered in the other metrics, and will not be covered here.

Example Metrics

- Average vehicle speed

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I

Turning Movements

The vast majority of traffic signal timing plans are based on predicted vehicular volumes at intersections. These predicted volumes are themselves based on turning movement counts, where vehicles are counted not only by arrival, but also by the number of vehicles turning left, right, or traveling straight through an intersection. However, turning movements are difficult to capture automatically with sensors, and expensive and time consuming to capture manually through field counts.

The data available with connected vehicles will allow the much more sophisticated and comprehensive collection of vehicle turning movements at intersections. Vehicles can report their location and heading every second, allowing the recording of each vehicle's path through an intersection. Turning movements can be recorded continuously throughout the year, unlike the current practice of recording turning movements during only the peak mid-week hours.

Example Metrics

- Number of vehicles turning in each direction from each approach
- Expected number of vehicles turning in each direction from each approach

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I

Queue Length

Similar to vehicle delay, queue lengths are often difficult to measure in the field directly. This metric is therefore estimated, based on available data, such as the upstream discharge volumes and assumed speeds. However, using connected vehicle data such as vehicle location, heading, and time stamp, many characteristics about queues can be determined with greater accuracy. An intersection's queue lengths, evolution of queues, and the number of vehicles in a queue could all be directly measured in the field. Such an accurate observation of queues allows mitigation of their impact on upstream intersections.

Based on queue information, the market penetration equipped vehicles can be estimated (3). By measuring the number of equipped vehicles in a queue and the position of the last vehicle in the queue, an algorithm can evaluate vehicle spacing and estimate the number of all vehicles in the queue, thereby estimating the percentage of vehicles equipped with communications hardware.

Example Metrics

- Average queue length at an intersection
- Queue length at an approach
- Standard deviation of queue length at an intersection

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I

Travel Time

One of the most useful metrics in evaluating a signalized corridor is the average time required for a vehicle to travel the length of the corridor. By minimizing this travel time, while simultaneously minimizing the delay of vehicles on side streets, a signalized corridor can provide smooth, coordinated flow and a high level of service.

By measuring the difference between the first and last time a vehicles communicates its location to an connected vehicle RSE, traffic engineers can begin to build a clearer picture of the time required for a vehicle to travel through a corridor. This travel time information can be used first to evaluate the performance of the corridor offline, as reduced travel time is a main goal of a coordinated signal system. Li et al. were able to measure travel time along an arterial with an average error of 13.9 percent with only 5 percent of vehicles communicating (4).

Example Metrics

- Average vehicle travel time through the corridor

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I

NEW METRICS

This section describes several metrics that are not currently measured or analyzed. These metrics are uniquely suited to a connected vehicle environment, and provide a much clearer understanding of the performance of an arterial or signalized intersection, as well as provide information that can be used to optimize the signal in real-time.

Person Delay

Traditionally, signalized intersection performance has been evaluated based on average vehicle delay, defined as the average time that a vehicle takes longer than an unobstructed passage through a corridor or intersection. However, vehicle delay considers the delay of a bus with many passengers equivalent to the delay of a vehicle with a single passenger. A delay measure that can differentiate these situations is person-delay, i.e. the average delay experienced by each individual at the intersection or corridor. Although the current SAE J2735 standard does not have provision for number of passengers carried on a vehicle (2), it may be possible to add this provision in the future. Transit vehicles, however, may transmit the relative occupancy of the vehicle under SAE J2735, but not the exact number of passengers.

Person delay data would be very useful in developing more effective timing plans, particularly with respect to transit signal priority. Under most transit signal priority systems today, buses are given priority regardless of the number of passengers. With person delay information, buses could be given higher priority if they truly reduce actual person delay, leading to a much more accurate and effective transit signal priority system.

Example Metrics

- Average person delay
- Short-term person delay (for use in signal optimization)
- Cumulative person-delay

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I
- A La Carte Message
  - DE_TransitStatus
  - Number of passengers in passenger vehicles (not covered in J2735 Standard)

Sudden Decelerations

Crashes are the primary indicator of the safety of a signalized intersection or corridor. However, in other industries, such as manufacturing, safety experts study near accidents or "unsafe acts" that do not result in accidents, as these occurrences are often leading indicators of more serious incidents. In microscopic simulations, where driver behavior is relatively predictable, several predictive safety measures have been found including time to collision, postencroachment time, deceleration rate, maximum speed, and speed differential (5). In a connected vehicle environment, vehicles can now report behavior that may be even more indicative of crashes or near misses. One of these behaviors is sudden decelerations. If a vehicle's rate of forward deceleration is above a predetermined threshold, or if a vehicle's applied brake pressure is above a threshold, the vehicle can be considered to have experienced a sudden deceleration.

A sudden deceleration may indicate unsafe conditions that can be corrected with improved signal timing plans, better lane markings, or improved intersection geometry. Some issues that sudden decelerations may make apparent include the following:

- Inadequate site distance for vehicles turning right on red,
- Inadequate site distance for vehicles with permitted left turns,
- Dilemma zone issues (e.g. incorrect yellow and/or all red times), and
- High levels of conflicts with pedestrians.

Sudden decelerations will most likely be leading indicators of unsafe intersections, allowing traffic engineers to correct signal timing plans and intersection configurations much sooner than if decisions were based on accumulated crashes only.

Example Metrics

- Number of instances of applied brake pressure above threshold
- Number of instances of antilock brake activations
- Number of instances of deceleration rates above threshold

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I
- A La Carte Message
    - DE_BrakeAppliedPressure
    - DE_Acceleration
    - DE_AcclerationConfidence
    - DE_AntiLockBrakeStatus

Change in Lateral Acceleration

Similar to sudden decelerations, intersections and corridors with many vehicles reporting sudden lateral movements or drastic changes in steering wheel angle may have correctable unsafe lane configurations, geometries, and/or signal timing plans.

Example Metrics

- Number of instances of changes in lateral acceleration above threshold
- Number of instances of steering wheel rates of change above threshold

- Number of instances of stability control activation

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I
- A La Carte Message
    - DE_StabilityControlStatus
    - DE_SteeringWheelAngleRateOfChange
    - DE_SteeringWheelAngleConfidence

Aggregate Regulation Compliance

All data received from vehicles using connected vehicles are anonymous, and therefore cannot be used in the regulation of individual vehicles. However, by examining anonymous driver behavior, traffic engineers can measure the aggregate level of compliance of traffic regulations at intersections and along corridors. For example, data available from connected vehicles can determine intersections and movements with high levels of illegal U-turns, excessive speeding through work zones and school zones, and red-light running. With this information, traffic engineers can effectively target problem areas with countermeasures such as traffic calming improvements, signal timing adjustments, and redesigned intersection geometries to improve safety and compliance.

Example Metrics

- Number of illegal U-turns per day
- Percentage of vehicles exceeding speed threshold
- Percentage of vehicles entering intersection illegally during red phase

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I

ENVIRONMENTAL AND CONTEXTUAL INFORMATION

This section describes metrics that provide information that can be used to improve the accuracy of the metrics described in previous sections. Metrics in this section allow a greater understanding of vehicle behavior in various conditions. This information can then be applied to other metrics to improve realism.

Driver Behavior

Driver behavior influences much of traffic engineering and traffic signal timing plan design. Saturation flow rates, free flow speed, lane changing behavior, turning movements, and a variety of other behavior are used in the Highway Capacity Manual to determine an intersection’s level of service and recommend a timing plan (6). These factors are also used to model vehicle behavior in microscopic traffic simulation software used to evaluate signal timing plans.

Driver behavior data is often based on several studies, and then generalized to all drivers. Connected vehicles, by contrast, allows the collection and analysis of individual driver behavior in an aggregate manner, without compromising privacy, specific to certain regions and intersections, specific to different weather and daylight conditions, and updated continuously. The driver behavior assumptions used to design and evaluate signal timing plans could be localized to the intersection and specific to current weather and light conditions. Driver behaviors that can be studied and refined include:

- Gap acceptance (7),
- Allowable headways,
- Threshold headway for a group of vehicles to be considered a platoon,
- Time required to change lanes,
- Free flow speed,
- Rates of acceleration and deceleration,
- Saturation flow, and
- Reaction times.

Furthermore, this data can be sorted specifically be a range of factors, including:

- Location of intersection,
- Vehicle type,
- Time-of-day,
- Weather conditions, and
- Presence of daylight.

Not only will better information on driver behavior provide more data for the Highway Capacity Manual methodology and macroscopic simulation to draw from, it will also improve the realism of the microscopic simulation software packages used to evaluate signal timing plans before they are implemented in the field. Finally, improved driver behavior data may allow a traffic signal to alter its signal plan in real-time. By understanding how vehicles behave, a signal timing plan can be adjusted to minimize the anticipated delay of approaching vehicles. As understanding of driver behavior under a range of conditions improves, signal timing plans will be able to adapt to changing conditions in real-time, and with greater effectiveness.

Example Metrics

- Median gap acceptance
- Gap acceptance distribution
- Median allowable headway
- Allowable headway distribution
- Threshold headway for individual vehicles in a platoon
- Median time required to change lanes
- Time to change lane distribution
- Typical acceleration and deceleration rates of different vehicle types in different conditions
- Average saturation flow
- Median reaction time
- Reaction time distribution

Required SAE J2735 Messages and Data Elements

- Basic Safety Message Part I

Weather/Light Conditions
Safe and efficient signalized intersections and corridors require adequate understanding of how vehicles behave in a variety of conditions. For example, vehicles require extra time to decelerate in wet conditions, and have less visibility in fog. Inclement weather has been found to impact saturation flow rates, significantly altering a signal's operation (8, 9). Furthermore, many microscopic simulation models are able to change driver behavior to reflect adverse weather conditions (10). If weather conditions could be determined in real-time, with a high degree of accuracy, traffic signals could be designed to take weather into account and improve safety. For example, the dilemma zone may need to be adjusted to compensate for drivers' inability to stop in wet weather.

A connected vehicle environment allows vehicles to transmit many in-vehicle instrument readings that indicate weather and light conditions (2). For example, many new vehicles have built in moisture detection to assist automatic wiper blades, as well as exterior light sensors to assist in automatically turning headlights on and off. By communicating this information with road-side units, traffic signal control algorithms could adjust their timings to reflect the changes in vehicle behavior brought on by adverse weather.

Example Metrics
- Presence of sunlight
- Presence of precipitation
- Presence of fog

Required SAE J2735 Messages and Data Elements
- A La Carte Messages
  - DE_SunSensor
  - DE_RainSensor
  - DE_ExteriorLights
  - DE_WiperRate
  - DE_WiperStatusFront
  - DE_WiperStatusRear

CONCLUSIONS

Although connected vehicles allows transportation agencies to collect more sophisticated data than with traditional detectors, there has been no very little research or discussion of the specifics of how the measures will be collected, or what new measures are made possible. Collection of the existing and new measures is both feasible and realistic according to the protocols identified in the SAE J2735 DSRC standard. The new metrics proposed in this paper have the potential to dramatically alter the way transportation agencies address safety, signal timing, geometric design.

REFERENCES

1. Research and Innovative Technology Administration (RITA), "About IntelliDrive: DSRC Frequently Asked Questions", *IntelliDrive^{SM}*, http://www.intellidriveusa.org/about/dsrc-faqs.php, 2009

2. Society of Automotive Engineers (SAE), J2735, "Dedicated Short Range Communications (DSRC) Message Set Dictionary", November 2009

3. Brian L. Smith, Ramkumar Venkatanarayana, Hyungjun Park, Noah Goodall, Jay Datesh, and Corbin Skerrit, "IntelliDrive^{SM} Traffic Signal Control Algorithms Task 4: Report on Evaluation Results of Traffic Signal Control Algorithms in the Simulated IntelliDrive^{SM} Environment", IntelliDrive^{SM} Pooled Fund Study, 2010

4. Meng Li, Zhi-jun Zou, Fanping Bu, and Wei-bin Zhang, "Application of Vehicle-Infrastructure Integration (VII) Data on Real-Time Arterial Performance Measurements", *Transportation Research Board 87th Annual Meeting*, Transportation Research Board, 2008

5. Douglas Gettman and Larry Head, "Surrogate Safety Measures from Traffic Simulation Models", *Transportation Research Record: Journal of the Transportation Research Board*, Volume 1840, Transportation Research Board of the National Academies, 2003

6. Transportation Research Board, *Highway Capacity Manual*, National Research Council, 2000

7. Alec Gorjestani, Arvind Menon, Pi-Ming Cheng, Craig Shankwitz, and Max Donath, "Determination of the Alert and Warning Timing for the Cooperative Intersection Collision Avoidance System-Stop Sign Assist Using Macroscopic and Microscopic Data: CICAS-SSA Report #1", Report No. CTS 10-31, Federal Highway Administration, Minnesota Department of Transportation, 2010

8. S.M. Lin and H.C. Lieu, "Assesment of Weather Effects on Arterial Traffic Under an Actuated Signal Control System", *Proceedings of the ITE 2004 Annual Meeting and Exhibit*, Institute of Transportation Engineers, 2004

9. Adel W. Sadek and Seli J. Amison-Agbolosu, "Validating Traffic Simulation Models to Inclement Weather Travel Conditions with Applications to Arterial Coordinated Signal Systems", Report No. NETCR 47, New England Transportation Consortium, 2004

10. Hesham Rakha, Daniel Krechmer, Gustave Cordahi, Ismail Zohdy, Shereef Sadek, and Mazen Arafeh, "Microscopic Analysis of Traffic Flow in Inclement Weather", Report No. FHWA-JPO-09-066, Federal Highway Administration, 2009