IntelliDrive^{SM} Traffic Signal Control Algorithms

Final Report

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EXECUTIVE SUMMARY

The objective of this project was to develop and evaluate new traffic signal control algorithms using the new data made available in an IntelliDrive^{SM} environment. The project was organized into five tasks:

- **Task 1: Investigation of the IntelliDrive^{SM} Data Sources:** This task investigated the potential data sources available in an IntelliDrive^{SM} environment, and the potential and limitation of those sources. Two data elements were identified that are beneficial to signalized intersection operations, but are not included in the SAE J2735 DSRC Message Set Dictionary: number of passengers and real-time delay. The results of this investigation are included in *Task 1: Report on the Investigation of IntelliDrive^{SM} Data Sources.*
- **Task 2: Development of New Traffic Signal Control Algorithms under IntelliDrive^{SM}:** This task proposed three traffic control strategies using IntelliDrive^{SM} data as the primary data source. The three algorithms were: oversaturated conditions, vehicle clustering, and predictive microscopic. *Task 2: Development of New Traffic Signal Control Algorithms under IntelliDrive^{SM}* provides more information on the developed algorithms.
- **Task 3: Development of Tools for Generating Arterial MOEs from IntelliDrive^{SM}:** This task investigated the effect that IntelliDrive^{SM} data would have on the collection of signalized intersection measures-of-effectiveness (MOEs), and proposed new performance metrics. The new metrics included person delay, sudden decelerations, changes in lateral acceleration, network connectivity, aggregate regulation compliance, driver behavior modeling, and weather/light conditions. The results of this task are included in *Task 3: Report on Measures of Effectiveness and their Collection in the Simulated IntelliDrive^{SM} Environment*.
- **Task 4: Evaluation of the Developed Traffic Signal Control Algorithms:** This task evaluated the traffic signal control algorithms developed in Task 2 on a virtual IntelliDrive^{SM} test bed, at a range of levels of vehicle connectivity. The algorithms showed a significant improvement over coordinated-actuated signal control, with between 6% and 28% reductions in delay. All three algorithms began to experience benefits at 25% market penetration. More results are provided in *Task 4: Report on Evaluation Results of Traffic Signal Control Algorithms in the Simulated IntelliDrive^{SM} Environment.*
- **Task 5: Deployment Analysis:** This task investigated the potential implications of a large-scale real-world implementation of IntelliDrive^{SM} at signal systems. The task included a cost-benefit analysis of IntelliDrive^{SM} signal control versus a system using loop or video detection. Benefit-cost ratios between 1.1 and 42.2 were found. The task is described in more detail in *Task 5: Deployment Analysis of Traffic Signal Control Algorithms in an IntelliDrive^{SM} Environment.*

Each of the task reports are presented in this document.

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Task 1: Report on the Investigation of IntelliDrive^{SM} Data Sources

OBJECTIVE AND SCOPE OF THE DOCUMENT

This task report investigates the data sources available in an IntelliDrive^{SM} environment, as defined by the SAE J2735 DSRC Message Set Dictionary, and suggests a limited number of new data elements that are not part of the latest standard, but would be useful for signal control.

CURRENTLY DEFINED INTELLIDRIVE^{SM} DATA SOURCES

IntelliDrive^{SM} allows for information exchange using several different communications platforms, including:

- Dedicated short range communications (DSRC)
- Wi-Fi
- Worldwide Interoperability for Microwave Access (WiMAX)
- Cellular
- Bluetooth
- 3G/4G

Of the communications media, only DSRC has latency of less than one second. The US Department of Transportation has committed to DSRC as the primary platform for safety applications, and one of several platforms for mobility applications. The advantages of DSRC over Wi-Fi, as determined by USDOT, are as follows:

- It operates in a licensed frequency band
- It is primarily allocated for vehicle safety applications by FCC Report & Order – Feb. 2004 (75 MHz of spectrum)
- It provides a secure wireless interface required by active safety applications
- It supports high speed, low latency, short range wireless communications
- It works in high vehicle speed mobility conditions
- Its performance is immune to extreme weather conditions (e.g. rain, fog, snow, etc.)
- It is designed to be tolerant to multi-path transmissions typical with roadway environments
- It supports both inter-vehicle and vehicle-to-infrastructure communications (RITA, 2009)

The traffic signal control applications developed in Tasks 2 and 4 of this report were based primarily around DSRC. Given that DSRC is expected to be heavily used for safety applications on signalized arterials, this work assumed that DSRC, and associated standards, would be the primary data source for signal control. Thus, all traffic signal control algorithms developed in this project require data to be transmitted once per second, which may be difficult with non-DSRC communications with 1.5 to 5 second latencies. In contrast, DSRC's latency is 0.002 seconds.

SAE J2735 DSRC STANDARD

The vast majority of data required for effective implementation of the proposed signal control algorithms is available through the Society of Automotive Engineers (SAE) J2735 DSRC Message Set Dictionary (SAE, 2009). This standard, which is still in draft form and most recently updated in November 2009, specifies the types of information that would be included in any safety and mobility messages sent and received with DSRC in an IntelliDrive[SM] 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.

Basic Safety Message Part I

The most common message is the Basic Safety Message (BSM) Part I, which transmits a vehicle's position, heading, and speed. This message is often referred to as a ***Here I Am*** message. The BSM Part I is transmitted ten times per second, much more frequently than is required by the traffic signal control algorithms developed in this project. Latency is estimated to be less than one second, and typically between 10 and 20 milliseconds. The BSM Part I consists of the following data elements:

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

As the research team investigated new signal control algorithms, it became clear that this Here I Am message is sufficient to support innovations in control. A limited number of additional data elements were identified as desirable – particularly for performance measurement. These are described below.

A La Carte Messages

Several potential signal applications may require data beyond what is in the Basic Safety Message, and would instead require an “a la carte” message (ACM). The ACM can use any data elements listed in the J2735 standard, but are encouraged to limit extraneous information as bandwidth is a sometimes scarce resource.

Several of the new performance measures available with IntelliDrive^{SM} described in the Task 3 report would require data elements from the ACM. These performance measures, and their required data elements, are described below:

Sudden Deceleration

Sudden deceleration is a safety performance measure where a hard braking event or sudden deceleration may indicate a recent crash, congestion, or unsafe roadway. Required data elements in the ACM include:

- DE_BrakeAppliedPressure
- DE_Acceleration
- DE_AcclerationConfidence
- DE_AntiLockBrakeStatus

Change in Lateral Acceleration

This measure evaluates sharp turning movements or swerving events, which may indicate hazards in the roadway, recent crashes, ice, etc. Required data elements in the ACM include:

- DE_StabilityControlStatus
- DE_SteeringWheelAngleRateOfChange
- DE_SteeringWheelAngleConfidence

Weather Conditions

This performance measure is used to collect aggregated driver behavior data in a variety of moisture and light conditions, to better understand how saturation flow and deceleration rates change during adverse weather. Required data elements in the ACM include:

- DE_SunSensor
- DE_RainSensor
- DE_ExteriorLights
- DE_WiperRate
- DE_WiperStatusFront
- DE_WiperStatusRear

Data Elements not Included in SAE J2735

Although the SAE J2735 standard is comprehensive, there are some data elements that have been theorized during Tasks 2, 3, and 4 that were not included in the standard. These data elements would be useful either in signal timing or performance measurement.

Number of Passengers

Often the objective in signal timing is to minimize average delay of all travelers in the network. However, due to the difficulty of measuring individual travelers, the metric most often minimized is delay per vehicle. In some situations, it may be advantageous to give greater priority to vehicles with several passengers, to encourage transit use and carpooling. However, because there has never been a way to get precise passenger counts, transit signal priority has generally given equal priority to all transit vehicles, regardless of how many passengers are on board.

Although the data element DE_Transit currently provides an approximate measurement of percentage of seats occupied on transit vehicles, a more precise count of the actual number of passengers could be used to develop much more sophisticated transit signal priority systems.

Similarly, a data element providing the number of passengers in non-transit vehicles would also be useful. Real-time signal timing plans could use the number of approach *persons* instead of vehicles to minimize person-delay. Although there is currently no foolproof way to measure passengers in a vehicle, there are several concepts under development for high-occupancy toll lane applications.

Real-time Delay

In developing signal timing plans in an IntelliDrive^{SM} environment, it may be useful to know directly the delay that vehicles are experiencing second-to-second. See the Task 3 report for more information on the importance of real-time delay. Delay is not only related to a vehicle's speed, but to the speed at which a vehicle would travel unobstructed. In many situations, the speed limit is an effective substitute for a vehicle's unobstructed speed. However, when a vehicle is turning at an intersection, its maximum allowable speed is a factor of vehicle size and the radius of the turn. A vehicle's size is already listed as a data element, and turning radii are included in the Map data. By combining this information with a vehicle's speed, the second-to-second delay could potentially be determined.

By introducing real-time delay as a new data element, this information could be shared among nearby traffic signals to develop cooperative timing plans that respond immediately to changes in demand.

CONCLUSIONS

Although several communications media are available for traffic signal operation, DSRC currently has the most documentation and standardization. With its low latency and high transmission rate, it is the preferable platform for signal operations. The SAE J2735 standard contains a broad array of data elements, and its Basic Safety Message I is all that is required for the majority of the traffic signal control algorithms and performance measures described in the Task 2, 3, and 4 reports. Several new data elements are suggested here to improve the standard.

REFERENCES

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

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

Task 2: Development of New Traffic Signal Control Algorithms under IntelliDrive^{SM}

OBJECTIVE AND SCOPE OF THE DOCUMENT

In line with the second project deliverable mentioned in the project work plan, this interim report details the traffic signal algorithms developed by the project team. These algorithms were developed specifically to utilize the new data made available with IntelliDrive^{SM} and to implement strategies that are either impossible or cost prohibitive with detector data alone. The three algorithms are as follows:

- Oversaturated conditions algorithm
- Vehicle clustering algorithm
- Predictive microscopic simulation algorithm

BACKGROUND OF INTELLIDRIVE^{SM} AND TRAFFIC SIGNAL CONTROL

IntelliDrive^{SM} combines several emerging technological advances, such as advanced wireless communications, on-board computer processing, advanced vehicle sensors, GPS navigation, smart infrastructure etc. to provide a networked environment. This environment allows for high speed information transactions between the vehicles (V2V), between vehicles and the infrastructure (V2I and I2V), and between vehicles and handheld devices (V2D) (MDOT). Several researchers have recently been conceptualizing and investigating various promising applications of the IntelliDrive^{SM} initiative, including the areas of safety (crash prevention, dilemma zone advisory), mobility (lane changing advisory, platoon formation, route guidance), transit, performance measurement, weather information, pavement condition monitoring, etc.

Many of the new vehicle data available with IntelliDrive^{SM} are particularly useful to traffic signal operations. While traditional video and in-pavement detectors generally provide presence information, IntelliDrive^{SM} allows vehicles to transmit a much broader range of information to controller, such as vehicle locations and speeds (SAE, 2009). These new data provide signals a much more complete picture of vehicle behavior and conditions, allowing more dynamic and responsive signal control strategies and much more accurate ways of measuring signal performance.

Several recent research studies have specifically evaluated the application of IntelliDrive^{SM} to arterial networks and signal systems, towards performance measurement (Li et al, 2008; Song et al, 2010), safety (Dickey et al, 2008; Doerzaph et al, 2010; Saleem et al, 2008), route guidance (Lee and Park, 2008), dynamic gap out (Agbolosu-Amison and Park, 2009), dynamic speed control (Abu-Lebdeh and Chen, 2010), and driver behavior (El-Shawarby et al, 2010). However, no studies have investigated a complete reevaluation of signal control logic to best utilize IntelliDrive^{SM}, but instead have investigated incremental improvements in signal control (e.g. dynamic gap out). The algorithms presented in this report are attempts to determine next-level signal control utilizing the full capabilities of IntelliDrive^{SM}.

OVERSATURATED CONDITIONS ALGORITHM

Oversaturated conditions on arterial systems are pervasive and are expected to increase in the future (Wu et al, 2010). The queues that spill back from an intersection experiencing oversaturated conditions could cause de facto red conditions at an upstream intersection, whereby vehicles are unable to pass, even when the light displays green. If this effect cascades to further upstream intersections, the signal timing inefficiency spreads spatially across the network. Therefore, quick identification of these queues, as well as the elimination or mitigation of the de facto reds will significantly increase the network efficiency during oversaturated conditions. Further, the speedy return of the network again to manageable levels of traffic is made possible.

This research study applied the detailed vehicular data available in an IntelliDrive^{SM} environment to address signal system inefficiencies that result from spillback during oversaturated conditions. New algorithms were developed to: (1) monitor queues in real-time, using the location and speed data from IntelliDrive^{SM}-equipped vehicles; and then (2) modify the offset and splits at the upstream intersection, also in real-time. In short, the green phase for the affected approach is either delayed or cut short, as dictated by the real-time queue length on the downstream link. Further, additional time available from the affected approach is transferred to the opposite approach. The algorithms were evaluated using VISSIM microscopic traffic simulations on a 2-intersection test network with one-way streets.

The algorithm is based on a study network consisting of 2 intersections of all one-way streets with 2 lanes each, as depicted in Figure 1. The intersection on the right is designated as node 1, and the other as node 2, with a separation of approximately 330ft. The network links are designated as L1-L7. All the traffic flow directions and their NEMA movement numbers are also presented in the Figure. The Main Street, represented by NEMA 2, is coordinated. The links L3, L4 and L7 were all loaded with vehicles at the rate of 4000 per hour, to simulate high traffic conditions. Further, to simulate oversaturation on links L2 and L3, the right lane on link L1 and the right lane connector between links L1 and L2 were made unavailable to all traffic. Further, the left lane on link L1 included a reduced speed zone. As a result, it can be seen that while L2 is full, movement 2 at intersection 2 continues to get Green signal, but is unusable (i.e. faces de facto red).

One goal of the proposed algorithm therefore is to detect this type of situation, and then avoid or mitigate its effects by cutting off the Green on Main earlier than prescribed and allocate it to the side street. Another goal is to delay the start of Green on Main at intersection 2, if the available “space” on Link L2 is below a threshold.

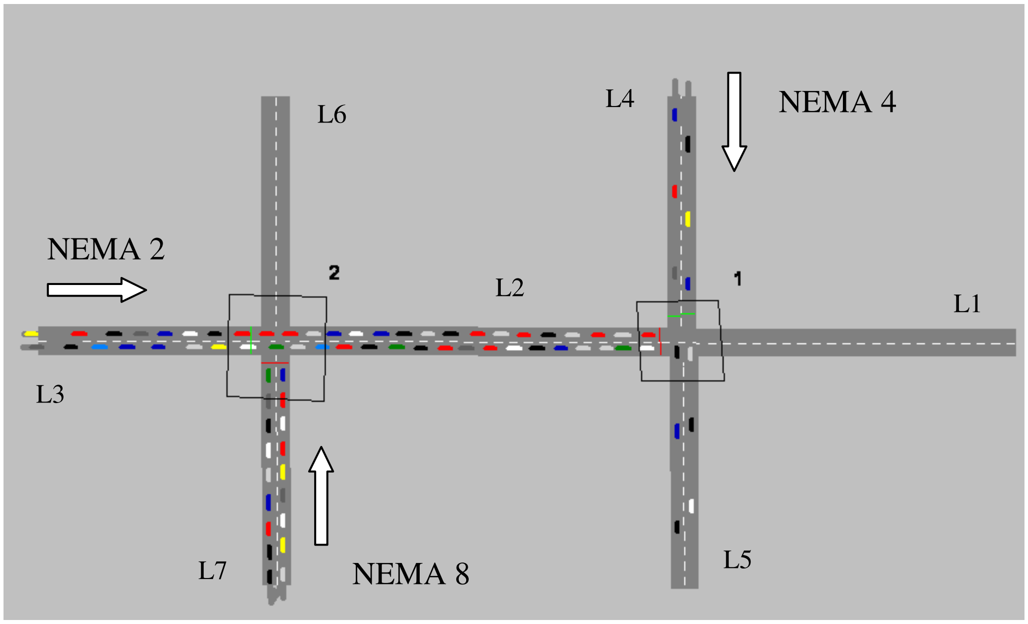


Figure 1: Study Network

In specific, there are 3 main parts of the signal control algorithm developed in this study, as shown by the dashed, red rectangles in Figure 2 below. These parts are:

1. ECG (Early Cut-off of Green on Main): This part is the rectangle on the left. The focus of this part is to monitor the queues on link L2 when the movement 2 at Node 2 has Green, and to cut it off earlier than the original plan, if
    a. The total available "space" across all the lanes on the receiving approach (i.e. L2) is below a certain threshold (shown as 200ft in the flow chart), and
    b. Less than a threshold amount of Green time is left for the movement 2 at Node 2 (shown as 10 seconds in the flow chart).
2. LSG (Late Start of Green on Main): This part is the rectangle in the middle. The focus of this part is to monitor the developing queues on link L2 and delay the start of Green for Node 2, movement 2, if the remaining supply on link L2 is below a certain threshold (shown as 200ft in the flow chart).
3. SSC (Side Street Coordination): This part is the rectangle on the right. The focus of this part is to start the Side Street Green (Node 2, movement 8) no later than the time prescribed by the original plan, so as to not impact coordination on the Side Street (as well as the Main Street). Without SSC, delaying the start of Green on Main through LSG without making adjustments to its Green split will offset the side street Green also. And after a few cycles, the offsets may be so large as to seriously impact the coordination along both streets. Further, if the original plan asks for the start of Side Street Green in the next ***s*** seconds, then, at a minimum, ***s*** must be greater than the amber time. In this study, the amber time is 4 seconds. And the threshold for s is set at ***5*** seconds.

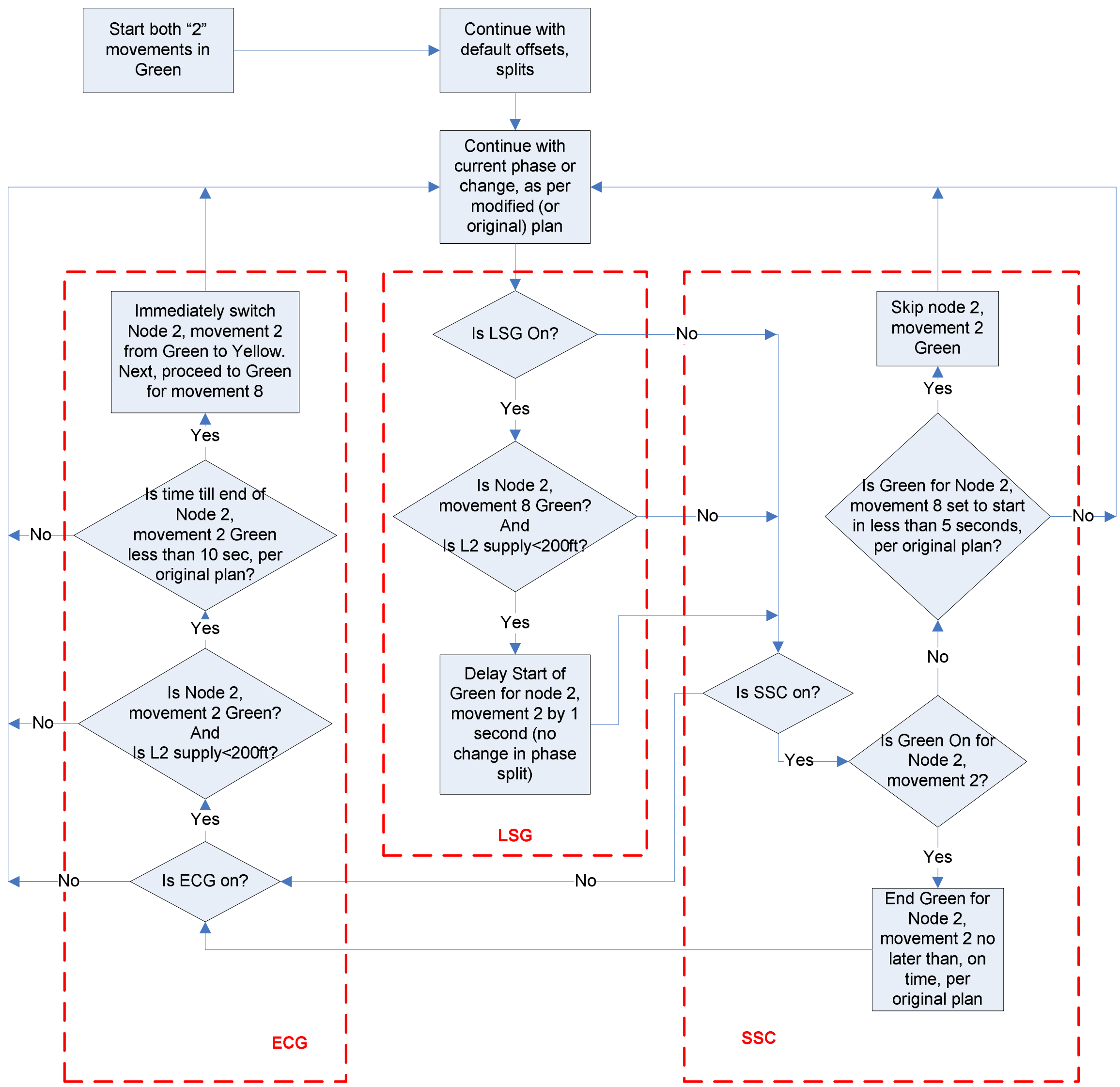
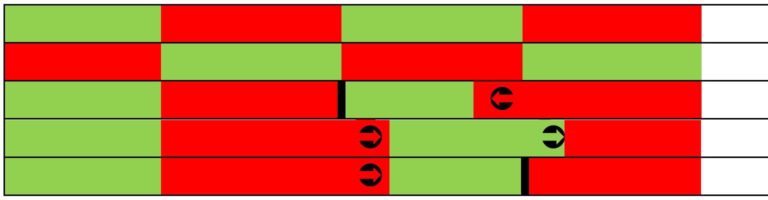


Figure 2: Algorithm Flow Chart

The effect of the combination of the above three parts on the Main Street Greens are presented in Figure 3 below. The arrows indicate the direction in which a particular phase is changed. Bold vertical lines indicate the particular start/end time for that phase remains unchanged. In all the cases, the first Main Street Green phase (first column) is shown as constant, for reference. The effects of the algorithm on the other three phases are noted. For simplicity, only the Main Street phases are shown for cases other than the base case. In all these cases, the Side Street obtains Green phase when the Main Street is Red and vice-versa. Further, for simplicity, the yellow periods are omitted in the Figure.



Main St	Base - Fixed time control
Side St	
Main St	ECG Only
Main St	LSG Only
Main St	LSG+SSC

Figure 3: Effects of Algorithm on the Phases

LSG is the only part that delays the start of Green on the Main. ECG and SSC both define when the Green split on Main is ended. Application of SSC is useful only in combination with LSG, since without a delay in the start of Green on Main, the side street Green split is not reduced, or delayed. Further, only LSG and ECG use IntelliDrive^{SM} data. SSC provides an alternative to ECG, in terminating the Main Street Green, and resetting the offset to default. Owing to these reasons, a total of five possible strategies are possible, using these three parts:

1. ECG Only: The offsets are not adjusted in this strategy. The Main Street Green split starts on time, but may be cut short, and additional time reallocated to Side Street Green split.
2. LSG Only: The offsets progressively increase from one cycle to the next, depending on how much oversaturation on link L2 affects traffic flow on L3. No changes are made to any Green splits.
3. LSG+SSC: In this strategy, the offset is increased for only one cycle at a time, and the Main Street Green split is reduced in that cycle to allow for side street coordination. The next cycle will start at the predetermined time, unless LSG comes into force again. Main Street Green split may be skipped, if there is no room on L2 to receive traffic.
4. ECG+LSG: In this strategy, the offsets increase progressively from one cycle to the next. Additionally, the Main Street Green split is reduced, if enough supply is not available on L2 to accommodate more traffic from L3.
5. ECG+LSG+SSC: In this strategy, in addition to the actions in the LSG + SSC strategy above, the Main Street Green may also be cut short, if there is no room on L2 to receive traffic.

The algorithm has been coded in the IntelliDrive test bed (described further in Task 3 report). Significant preliminary has been completed, and the algorithm presented above is the refined, final version that will be evaluated in Task 4.

VEHICLE CLUSTERING ALGORITHM

The Vehicle Clustering Algorithm (VCA) was designed primarily for urban arterials, where there is a high-speed major corridor crossing low-speed, low-volume side streets, and is decentralized, using only information that is local to the intersection that it controls. The VCA utilizes IntelliDrive^{SM} data regarding the location and speed of every vehicle in order to detect the state of the traffic and respond accordingly. It uses a novel gap out approach, ensures that leftover queues on roads with green lights are cleared, and prevents the breakup of vehicle platoons using a hierarchical clustering algorithm, hence the algorithm's name. These primary aspects produce a robust algorithm that can respond to different traffic volumes and patterns in real time, attempting to reduce average delay and increase throughput. While the was initially designed assuming 100% IntelliDrive^{SM} market penetration, it can easily be adapted for lower adoption rates. Before detailing the manner in which the VCA uses the unique information that IntelliDrive^{SM} provides, an overview of the algorithm is presented.

The VCA works in three phases. In Phase Zero, it computes the cars' cumulative waiting time (CWT in Figure 4) for each movement with a red light, the red-movements, at an intersection. For example, if a vehicle has been waiting at a red light for twenty seconds before another vehicle arrives and both then wait for ten seconds, the cumulative waiting time for that movement would be forty seconds. If the cumulative waiting time for one of the red-movements exceeds a predetermined threshold value (T in Figure 4), this movement requests the green light and Phase One of the algorithm begins; otherwise, the simulation time is advanced. The value for the threshold, T, can depend on the type of intersection and/or the vehicle volumes in the red-movements.

The purpose of Phase One is to clear any remaining queue that may exist in a green-movement. Any car traveling in a green-movement with a speed of less than 5 mph is considered to be part of the leftover queue. If no such queue exists, the algorithm moves directly to Phase Two; otherwise, it waits until the car at the end of the queue passes through the green light before continuing to Phase Two, unless a maximum time is reached in which case it proceeds without clearing the queue to prevent excessively long green times.

In Phase Two, the VCA looks at vehicles farther upstream and uses the single-link clustering algorithm (SLINK) to group them into pseudo-platoons ("pseudo-" is used to distinguish them from platoons as typically defined in the literature). Once these pseudo-platoons have been formed, the algorithm uses the vehicles' distances to the intersection to determine which pseudo-platoon comprises vehicles that are the closest to the intersection, yet farther than a certain threshold distance (D in Figure 5), which depends on the road's speed limit. Currently this distance is the far end of the dilemma zone as defined by Hurwitz (2009). Then, the green-extension time, t_e, is obtained using the following formula:

$$t_e = d_l / v_l \tag{1}$$

where d_l is the distance of the last vehicle in this pseudo-platoon of interest from the intersection and v_l is that vehicle's speed. After the extension time has elapsed, or the maximum time has been reached, the green light switches to the red-movement that had the highest cumulative waiting time, and the non-conflicting movement with the highest waiting time, and the process repeats.

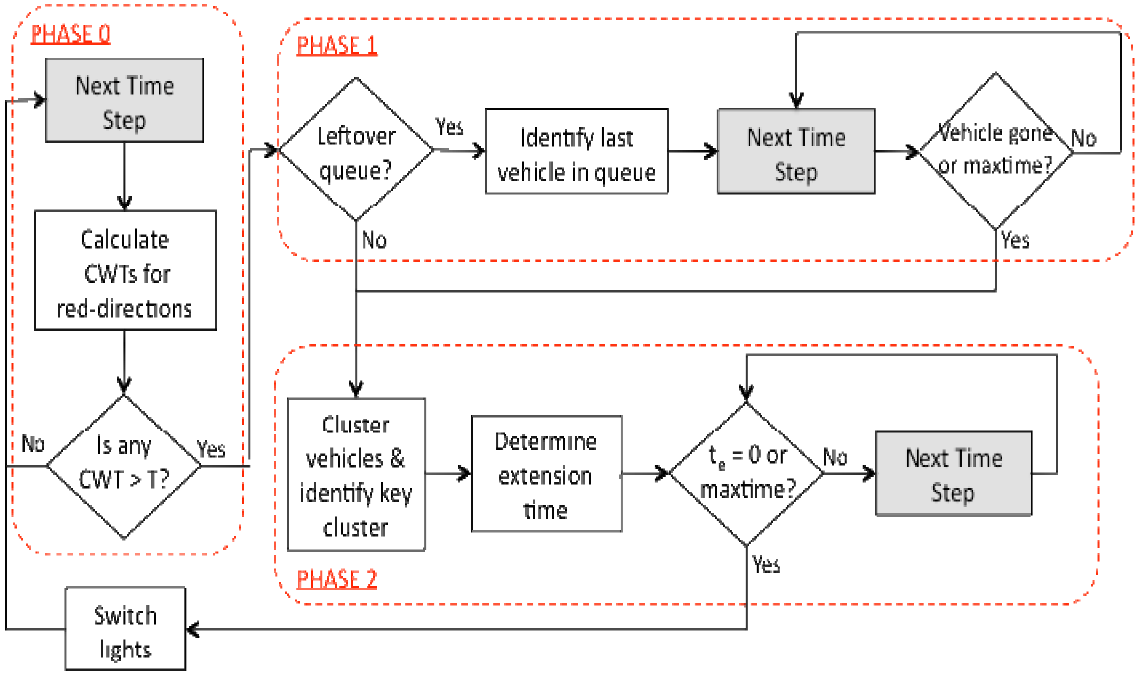


Figure 4: Vehicle Clustering Algorithm Flowchart

In each phase, the Vehicle Clustering Algorithm takes advantage of IntelliDrive^{SM} data, delivering a "smarter" intersection than is currently possible with conventional detectors. In Phase Zero, monitoring the CWT of each red-movement is made possible with V2I communication. To achieve this with loop detectors, each section of road surrounding an intersection would have to contain a detector. The CWT thresholds allow the VCA to switch the traffic lights only when it is necessary – a clear improvement over fixed-time signals – and offers other benefits as well: the threshold values could be different for each movement at an intersection and could be determined using to real-time traffic data or changed in order to account for a traffic incident, such as an accident. This allows for increased adaptability.

Phase One of the algorithm was designed to exploit the unique information that IntelliDrive^{SM} affords. With current detectors, the clearance time of a queue at a green light needs to be estimated. The intersection cannot know with certainty whether or not the last vehicle in the queue has passed through without several seconds of unused green time passing (i.e. the gap out time). This diminishes throughput and increases delays at side streets. The VCA again utilizes V2I communications to ensure that queues at green lights are cleared, and that no green time is wasted during gap out.

Phase Two is intended to provide two interrelated benefits to the VCA. The first is that it limits the breakup of vehicle platoons. Platoons have been traditionally defined by a critical vehicle headway, which depends on a roadway's speeds and traffic volumes. Determining the value for the critical headway is not always straightforward; see Jiang, et al. (2003) for a discussion. After obtaining the distances of all vehicles in the green-movement(s), the VCA clusters the vehicles using SLINK and, from these clusters, infers the distribution of the vehicles upstream in a green-movement to automatically form pseudo-platoons. Once these pseudo-platoons have been formed, the VCA can use instantaneous vehicle speeds, which are not available with traditional detectors, to compute the appropriate green-extension times. This allows the pseudo-platoon to pass through the intersection unimpeded, reducing average delays.

The second potential benefit of Phase Two comes from careful selection of the threshold distance, D (Figure 5). Setting D equal to the far limit of the dilemma zone could eliminate potential conflicts regarding yellow lights by detecting whether vehicles will be present in the dilemma zone at the time that switching will occur. With 100% IntelliDrive[SM] market penetration, a scheme has been proposed that would allow variable yellow lights, and could even skip all-reds in certain situations (Raavi, 2010). The traffic signal would be able to send an early indication to the vehicles whether or not they will make the green light (Figure 5). Extending this concept further, the need for traditional traffic lights could be eliminated all together, as the V2I infrastructure would communicate the (legally binding) signals directly to vehicles. Although possible in theory, the VCA currently does not employ this. The VCA instead sets yellow times and all-reds according to traditional standards, but may attempt variable yellow and red signals in future versions.

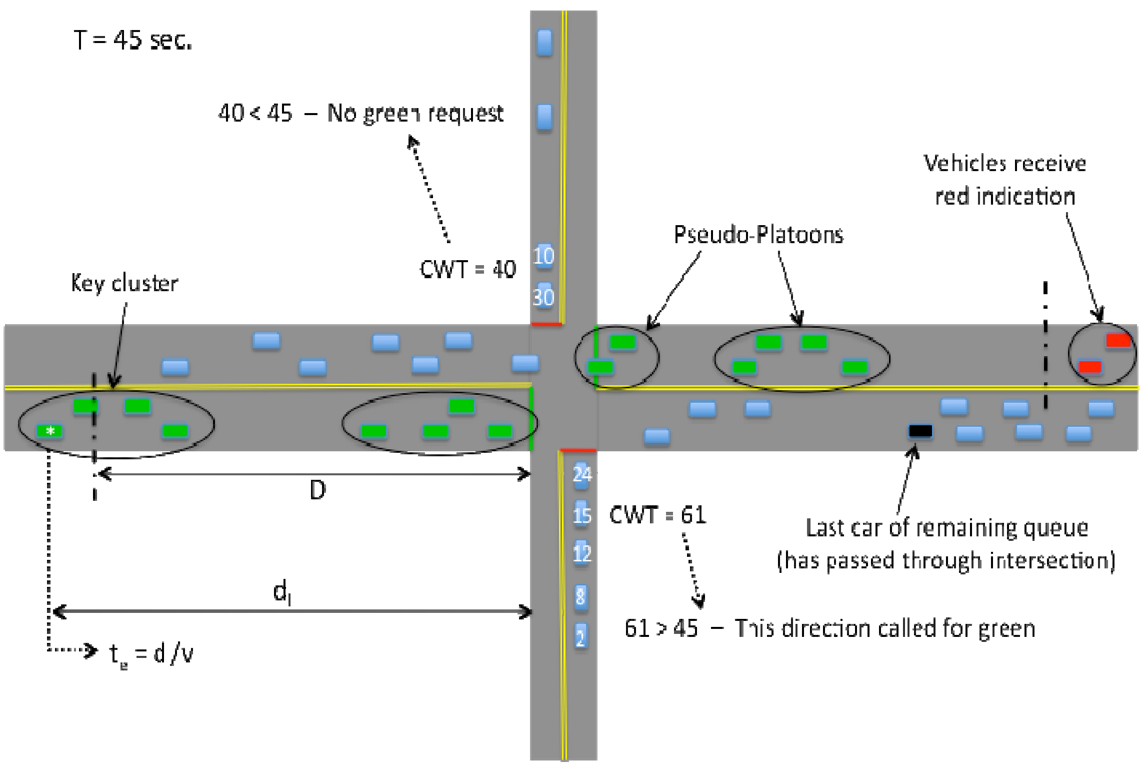


Figure 5: Key features of the Vehicle Clustering Algorithm.

In Figure 5, the white numbers on the vehicles in the red-movements represent the time each vehicle has spent waiting at the red light. These values are used to calculate the cumulative waiting time (CWT) for each movement. The bottom red-movement's CWT has surpassed the threshold, T, and it has called for a green light. Demonstrated by the black vehicle being downstream of the intersection, the algorithm has passed through Phase One and has clustered the vehicles into pseudo-platoons. The last car in the key cluster has been indentified (marked with a white asterisk); its speed and distance to the intersection have been used to determine the green-extension time. The green light will end when this time elapses. Additionally, the intersection has transmitted the signal indications. The green vehicles will be able to pass through the light, while the red vehicles will not make the light. The main street then gets the red light and the green switches to the side street and the process repeats.

The Vehicle Clustering Algorithm incorporates the valuable information that would be available with IntelliDrive^{SM}, and should achieve significant improvements over conventional signal timing plans. Future work on the algorithm include: 1) testing the algorithm on several traffic networks and comparing its performance to more traditional signal timing schemes and 2) improvements that provide coordination between intersections in an arterial. An example would be to account for vehicles that have just received a green upstream and are approaching a red light at an intersection. The effects of market penetration levels on the algorithm's performance will also be investigated.

PREDICTIVE MICROSCOPIC SIMULATION ALGORITHM

The Predictive Microscopic Simulation Algorithm (PMSA) is based on the rolling horizon traffic control scheme, first introduced by Alan Miller (Miller, 1963). In rolling horizon traffic control, the signal is optimized to reduce delay over a very short fixed period of time in the future, called the horizon. As time moves forward, the horizon "rolls" forward as well. A similar strategy was proposed by Roy Sumner, using predicted vehicle locations to determine the next phase and its length (Sumner, 2008). The PMSA uses a similar concept, employing vehicle position and speed data available with IntelliDrive^{SM} to populate a model of the signalized intersection. The algorithm then uses microscopic simulation to continuously predict future vehicle delays over the horizon at a variety of signal phasings.

With the PMSA, in order to determine the next phase, the signal controller determines the speed, heading, and location of all IntelliDrive^{SM}-equipped vehicles. This information, along with the current signal phasing, is recreated in a microscopic simulation of the intersection. Vehicles are simulated 20 seconds into the future, including the necessary yellow and red time for a signal change. This simulation is repeated for every potential possible phase that the current signal timing plan allows, including the current phase. The delay is measured every second and is calculated by subtracting the vehicle's actual speed from the speed limit of the vehicle's road. The phase with the lowest total cumulative delay after 20 seconds is selected as the next phase.

By only looking at delay over such a short interval, occasionally some movements can be skipped indefinitely and never served. For example, a busy three-lane mainline will often take precedence over a low-volume single left turn lane as the delay penalty for the mainline is much higher over 20 seconds. Vehicles that are stopped for an unusually long period of time may worry that the traffic signal hasn't detected them, and may be tempted to ignore a red light. To ensure that all vehicles are served in a timely manner, any movement with vehicles waiting over a certain threshold, tentatively 150 seconds, are given highest priority and must be served at the next phase.

Also, to ensure that turn lanes do not fill with vehicles and block the through lanes, any movement with a vehicle with a speed of less than three miles per hour and located within 40 feet of the beginning of a turn lane, that movement will be given medium priority as the next phase, and will be served next unless there are competing movements with highest priority.

After determining the next phase, that phase is left in place for either the length of the horizon (20 seconds) or until the real-time delay in both movements is zero, whichever situation occurs first. At the end of the phase, the next phase determination process is repeated.

Figure 6 shows an overview of the logic of the Predictive Microscopic Simulation Algorithm.

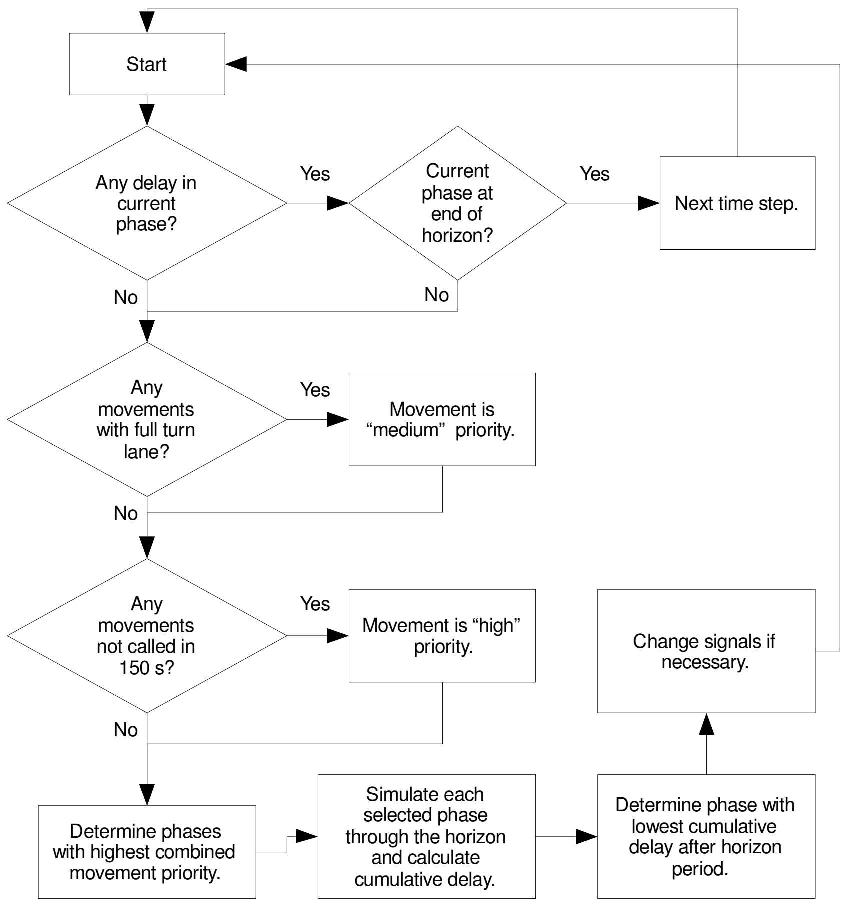


Figure 6: Predictive Microscopic Simulation Algorithm Flow Chart

The PMSA, unlike traditional detector-based algorithms, makes effective use of IntelliDrive^{SM} data, including specific vehicle locations and speeds. The PMSA is designed to optimize the signal based on current vehicles present, instead of estimates from past turning movement studies. Because it is based on real-time vehicle counts, the algorithm can easily and quickly adjust to unusual traffic conditions such as special events and lane closures. The PMSA are that it can effectively measure the penalties of the lost time experienced in changing signals, by simulating not only potential new signal phases, but also the signal change process.

The PMSA as designed operates for a single intersection, with no communication with other signal controllers. Some signal-to-signal communication will likely be required when two intersection are spaced so closely together that a vehicle can travel through both intersections during the horizon time. In this situation, the status at one signal will affect another during the horizon. Some possible solutions include broadcasting a signal's status and likely next status, or using the same PMSA future simulations on both intersections simultaneously.

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Task 3: Report on Measures of Effectiveness and their Collection in the Simulated IntelliDrive^{SM} Environment

OBJECTIVE AND SCOPE OF THE DOCUMENT

This task report identifies several new and existing measures-of-effectiveness (MOEs) well supported by IntelliDrive^{SM} data that are suited for the evaluation and improvement of arterial and signalized intersection performance.

MEASURES-OF-EFFECTIVENESS AND SUPPORTING DATA

The new data from IntelliDrive^{SM}–equipped vehicles will benefit transportation agencies in measuring and improving system performance in three diverse ways. The metrics described in this report 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.

These new and improved metrics available with IntelliDrive^{SM} are listed in Tables 1, 2, and 3 in the Appendix, and described in greater detail later in this section. Tables 1, 2, and 3 list the name of the type of metric, and identify potential applications for the metric (e.g. improved intersection safety, improved signal operations, and improved signal evaluation). These tables also identify the metrics required data elements, both those mandated to be sent with every Basic Safety Message (BSM) Part I specified in the SAE J2735 DSRC Message Set Dictionary, as well as those that would have to be included as optional data elements sent with BSM Part II (SAE, 2009).

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 IntelliDrive^{SM}. 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 with IntelliDrive^{SM} allow 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 based on typical vehicle arrival rates, lane configurations, the signal timing plan, and several other factors.

Information available through IntelliDrive^{SM} 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, IntelliDrive^{SM} 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. Both this measure, and the next one, can also be used in more accurately identifying bottleneck links in a network, paving the way for improved planning/budgeting priorities.
- **Average cumulative vehicle delay on a link.** This metric uses the cumulative vehicle delay to determine the average delay per vehicle on a link. Like the previously mentioned delay metrics, 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.

SAE J2735 Basic Safety Message Part I Data Elements

- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading

Headway

The spacing between vehicles is a metric that has been studied and utilized by traffic engineers for years. IntelliDrive^{SM} 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

SAE J2735 Basic Safety Message Part I Data Elements

- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading
- DF_VehicleSize

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. IntelliDrive^{SM}-equipped 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

SAE J2735 Basic Safety Message Part I Data Elements

- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading

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 IntelliDrive^{SM} 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

SAE J2735 Basic Safety Message Part I Data Elements

- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading

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 IntelliDrive^{SM} 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 of IntelliDrive^{SM}-equipped vehicles can be estimated. 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

SAE J2735 Basic Safety Message Part I Data Elements

- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading
- DF_AccelerationSet4Way

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 IntelliDrive^{SM}-enabled 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. Travel time can also be used in a dynamic signal control algorithm, where the objective function is a combination of reduced travel time through the corridor and reduced delay of all vehicles.

Example Metrics

- Average vehicle travel time through the corridor

SAE J2735 Basic Safety Message Part I Data Elements

- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading

New Metrics

This section describes several metrics that are not currently measured or analyzed. These metrics are uniquely suited to an IntelliDrive^{SM}-equipped 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 IntelliDrive^{SM} standard does not have provision for number of passengers carried on a vehicle (SAE, 2009), 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

SAE J2735 Basic Safety Message Part I Data Elements
- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading

SAE J2735 Basic Safety Message Part II Data Elements
- 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. With IntelliDrive^{SM}, vehicles can now report behavior that may indicate 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 several issues 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

SAE J2735 Basic Safety Message Part I Data Elements

- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading
- DF_AccelerationSet4Way
- DF_BrakeSystemStatus

SAE J2735 Basic Safety Message Part II Data Elements

- 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

IntelliDrive^{SM} Data Elements
- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading
- DF_AccelerationSet4Way

SAE J2735 Basic Safety Message Part II Data Elements
- DE_StabilityControlStatus
- DE_SteeringWheelAngleRateOfChange
- DE_SteeringWheelAngleConfidence

Network Connectivity
During emergencies, several links in a network often become unusable, due to crashes, downed trees, high water, debris, special events, etc. Using IntelliDrive^{SM} data emitted from equipped vehicles traversing a network, the links that continue to provide "connectivity" can be ascertained in real-time. This surrogate connectivity information can then be used to determine alternate network access for emergency response vehicles, and for determining priorities for maintenance activities. The basic IntelliDrive^{SM} data of location and time are sufficient for this measure.

The amount of time taken by an agency to restore full network connectivity can be used as a surrogate measure of system resiliency to such emergencies or special events.

Example Metrics
- Presence of network activity at a location
- Average time until network recover
- Network percentage uptime

SAE J2735 Basic Safety Message Part I Data Elements
- DE_TemporaryID
- DE_Dsec

Aggregate Regulation Compliance
All data received from vehicles with IntelliDrive^{SM} 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 with IntelliDrive^{SM} 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 effective 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

SAE J2735 Basic Safety Message Part I Data Elements
- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading
- DF_AccelerationSet4Way

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. 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 studies several studies, and then generalized to all drivers. IntelliDrive^{SM}, 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 under the IntelliDrive^{SM} paradigm include:
- Gap acceptance,
- 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 improved information on driver behavior provide more data for the Highway Capacity Manual methodology and macroscopic simulation programs like Synchro® 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

SAE J2735 Basic Safety Message Part I Data Elements
- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading
- DF_AccelerationSet4Way

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. 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.

IntelliDrive^{SM} allows vehicles to transmit many in-vehicle instrument readings that indicate weather and light conditions. 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

SAE J2735 Basic Safety Message Part I Data Elements
- None

SAE J2735 Basic Safety Message Part II Data Elements
- DE_SunSensor
- DE_RainSensor
- DE_ExteriorLights
- DE_WiperRate
- DE_WiperStatusFront
- DE_WiperStatusRear

REFERENCES

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

APPENDIX

Table 1: Applications and data requirements for the improved measurement of existing metrics

Improved Measurement of Existing Metrics					
Metric	Safety	Signal Operation	Signal Evaluation	Required Data: BSM Part I	Required Data: BSM Part II
Vehicle delay		X	X	DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading	None
Headway	X	X		DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading DF_VehicleSize	None
Speed	X	X	X	DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading	None

Improved Measurement of Existing Metrics					
Turning movements		X		DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading	None
Queue length		X	X	DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading DF_AccelerationSet4Way	None
Travel Time		X	X	DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading	None

Table 2: Applications and data requirements for new metrics

New Metrics					
Metric	Safety	Signal Operation	Signal Evaluation	Required Data: BSM Part I	Required Data: BSM Part II
Person delay		X	X	DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading	Number of passengers (not covered in J2735 Standard) DE_TransitStatus
Sudden decelerations	X		X	DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading DF_AccelerationSet4Way DF_BrakeSystemStatus	DE_BrakeAppliedPressure DE_Acceleration DE_AcclerationConfidence DE_AntiLockBrakeStatus
Change in lateral acceleration	X			DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading DF_AccelerationSet4Way	DE_StabilityControlStatus DE_SteeringWheelAngleRateOfChange DE_SteeringWheelAngleConfidence

New Metrics					
Network connectivity		X		DE_TemporaryID DE_Dsec	None
Aggregate regulation compliance	X	X		DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading DF_AccelerationSet4Way	None

Table 3: Applications and data requirements for environmental and contextual information

Environmental and Contextual Information					
Metric	Safety	Signal Operation	Signal Evaluation	Required Data: BSM Part I	Required Data: BSM Part II
Driver behavior	X	X		DE_TemporaryID DE_DSec DE_Latitude DE_Longitude DF_PositionalAccuracy DF_TransmissionAndSpeed DE_Heading DF_AccelerationSet4Way	None
Weather/light conditions	X	X		None	DE_SunSensor DE_RainSensor DE_ExteriorLights DE_WiperRate DE_WiperStatusFront DE_WiperStatusRear

Task 4: Report on Evaluation Results of Traffic Signal Control Algorithms in the Simulated IntelliDrive^{SM} Environment

OBJECTIVE AND SCOPE OF THE DOCUMENT

This task report evaluates the new traffic signal control algorithms developed as part of Task 2. The algorithms were tested using microscopic simulation, some on real world models of signalized corridors. All algorithms were tested using various measures-of-effectiveness and at various levels of market penetration. The vehicle data required for algorithms are supported by the IntelliDrive^{SM} communications standard SAE J2735 DSRC Message Set Dictionary, to ensure that the proposed algorithms represent realistic implementations of IntelliDrive^{SM}.

The report discusses the results and conclusions of the analysis of each of three algorithms (oversaturated conditions, vehicle clustering, and predictive microscopic simulation), and then provides a brief discussion of their compatibility with IntelliDriveSMSM. For background information on IntelliDrive^{SM}, traffic signal control, and each of the three algorithms, see the Task 2 report *Development of New Traffic Signal Control Strategies under IntelliDrive^{SM}*, available at: http://cts.virginia.edu/PFS_SIG03_Task2.pdf.

OVERSATURATED CONDITIONS ALGORITHM

The oversaturation algorithm logics, the background explaining the need to develop this algorithm, the Measures of Effectiveness selected to evaluate this algorithm and the network test bed were all described in detail in the Task 2 report. The algorithms have not required any changes since then.

To evaluate the algorithms in detail, a test plan was developed in line with the principles of design of experiments, and is illustrated in the Figure 1 below. This test plan consists of six major steps. All these steps and their results are presented below.

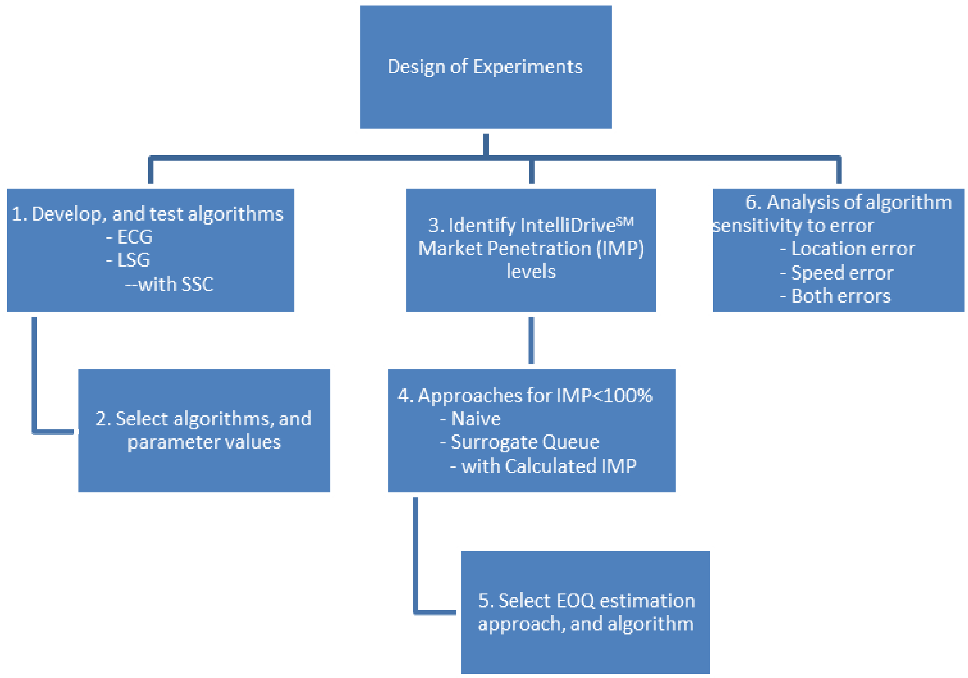


Figure 1: Design of Experiments to Evaluate the IntelliDrive^{SM} Oversaturation Algorithms

STEP 1. Develop and test algorithms

All the three algorithms (ECG, LSG, and SSC) were developed in the microscopic traffic simulation program VISSIM, using the Component Object Model (COM) interface and C#. The 2-intersection test network consisting of 1-way streets, as well as the 5 strategies of interest for evaluation (ECG Only, LSG Only, ECG+LSG, LSG+SSC, and ECG+LSG+SSC), were presented in the Task 2 report. For this network, the program Synchro was used for optimizing the fixed time signal control for the base case scenario. The parameter values obtained from this optimization were: Cycle length = 150 seconds; Amber = 4 seconds (for each phase); Green time = 71 seconds (for each phase); and offset = 13 seconds. Each of these six scenarios (base case-without any strategies applied, and the 5 strategies) was run for 30 replications, with random seeds and IntelliDrive^{SM} market penetration (IMP) of 100%, to obtain statistically valid results.

As described in the algorithm flow chart in the Task 2 report, recommendations need to be developed for the following two important algorithm parameters:

- Distance threshold for ECG, and
- Distance threshold for LSG

The other time threshold values were empirically selected based on simulation observations, and were decided to be evaluated in detail only if they create noticeable congestion, or promise potential congestion reduction.

The network is presented in Figure 2 below, to aid in interpreting the results.

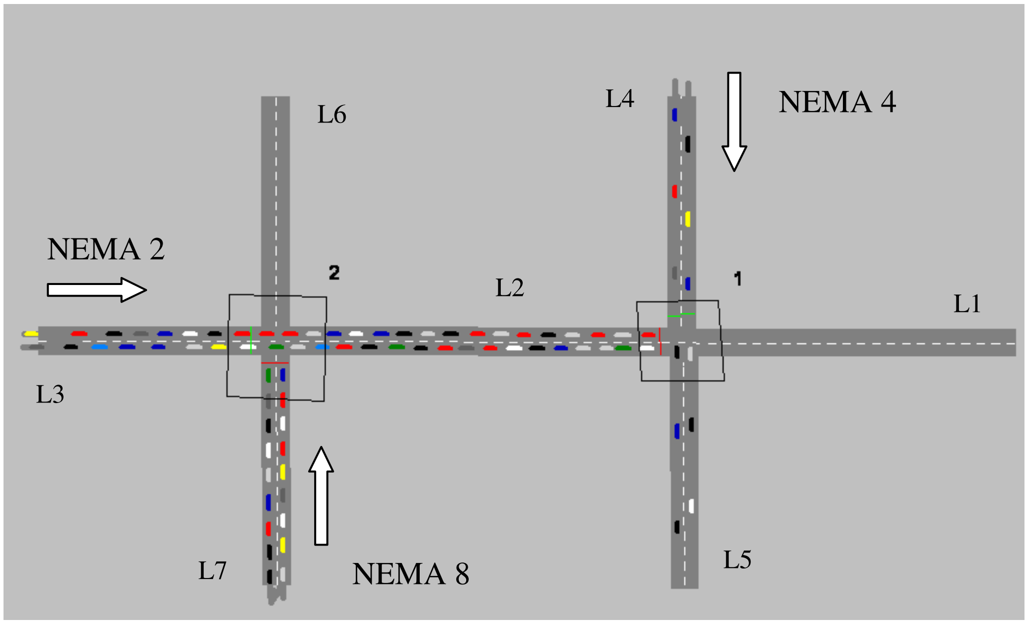


Figure 2: Network used to Evaluate Oversaturation Algorithms

The evaluation results drawn from VISSIM simulations, for 100% market penetration, are summarized in Table 4 and Figure 1. Throughput, average delay and average number of stops were selected as the network measures of effectiveness (MOEs). In addition to these MOEs, throughputs and green times on L3 and L7 are also presented to facilitate detailed interpretation of the results. Whenever the percentage throughput increase for L7 is greater than the percentage increase in its Green time, and the corresponding decrease in throughput on L3 is less than the percentage decrease in its Green time, the algorithm has effectively identified oversaturated conditions and has reallocated "free" Green time from the Main Street to the Side Street.

Table 4: Evaluation Results for 100% Market Penetration.

Strategies		Network-Wide Results			Link-Wise Results			
		Throughput (vehicles)	Average Delay (sec/veh)	Average Number of Stops (stops/veh)	Throughput (vehicles)		Green Times (sec)	
					L3	L7	L3	L7
Baseline	Mean	1720.1	27.9	1.62	204.4	659.3	450.0	450.0
	StdDev	14.4	0.9	0.16	2.8	8.0		
ECG Only	Mean	1930.9	20.1	1.02	192.9	892.8	308.2	591.8
	StdDev	27.2	1.0	0.11	10.9	34.9		
	% Changes	12.3%	-28.1%	-37.1%	-5.6%	35.4 %	-31.5%	31.5%
	p-value	0.00	0.00	0.00	0.00	0.00		
LSG Only	Mean	1714.8	29.2	1.77	204.1	656.3	450.0	450.0
	StdDev	17.8	0.8	0.17	3.1	12.1		
	% Changes	-0.3%	4.6%	9.3%	-0.2%	-0.5%	0.0%	0.0%
	p-value	0.24	0.00	0.03	0.40	0.26		
LSG +SSC	Mean	1799.6	26.3	1.51	202.5	745.3	397.8	502.2
	StdDev	24.8	0.9	0.13	2.9	19.5		
	% Changes	4.6%	-6.0%	-6.7%	-0.9%	13.0 %	-11.6%	11.6%
	p-value	0.00	0.00	0.06	0.07	0.00		
ECG +LSG	Mean	1928.3	20.6	1.02	192.8	888.8	308.9	591.1
	StdDev	35.8	1.1	0.11	10.4	40.9		
	% Changes	12.1%	-26.3%	-36.7%	-5.7%	34.8 %	-31.4%	31.4%
	p-value	0.00	0.00	0.00	0.00	0.00		
ECG +LSG +SSC	Mean	1950.0	20.5	0.96	195.1	903.3	301.6	598.4
	StdDev	29.1	1.0	0.10	11.0	35.3		
	% Changes	13.4%	-26.5%	-40.9%	-4.5%	37.0 %	-33.0%	33.0%
	p-value	0.00	0.00	0.00	0.01	0.00		

Note: The shaded cells indicate the results are statistically significant at the 95% confidence interval.

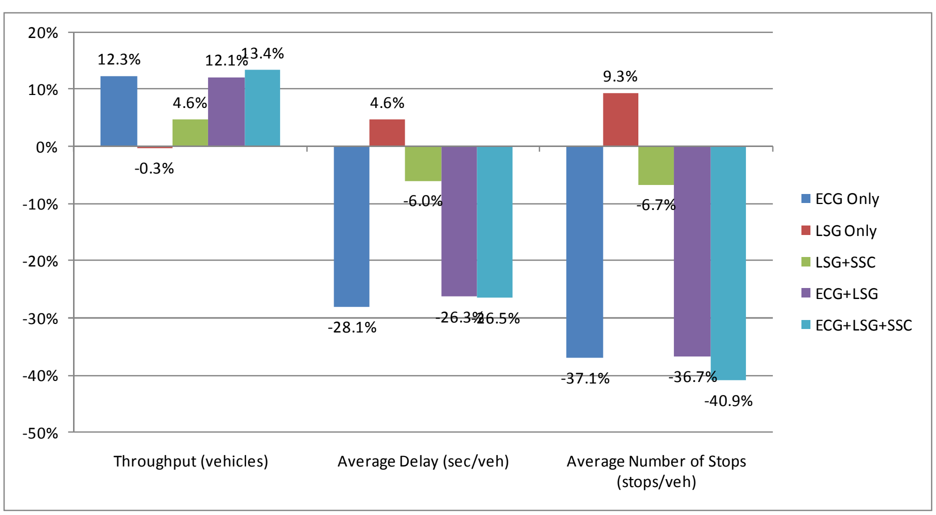


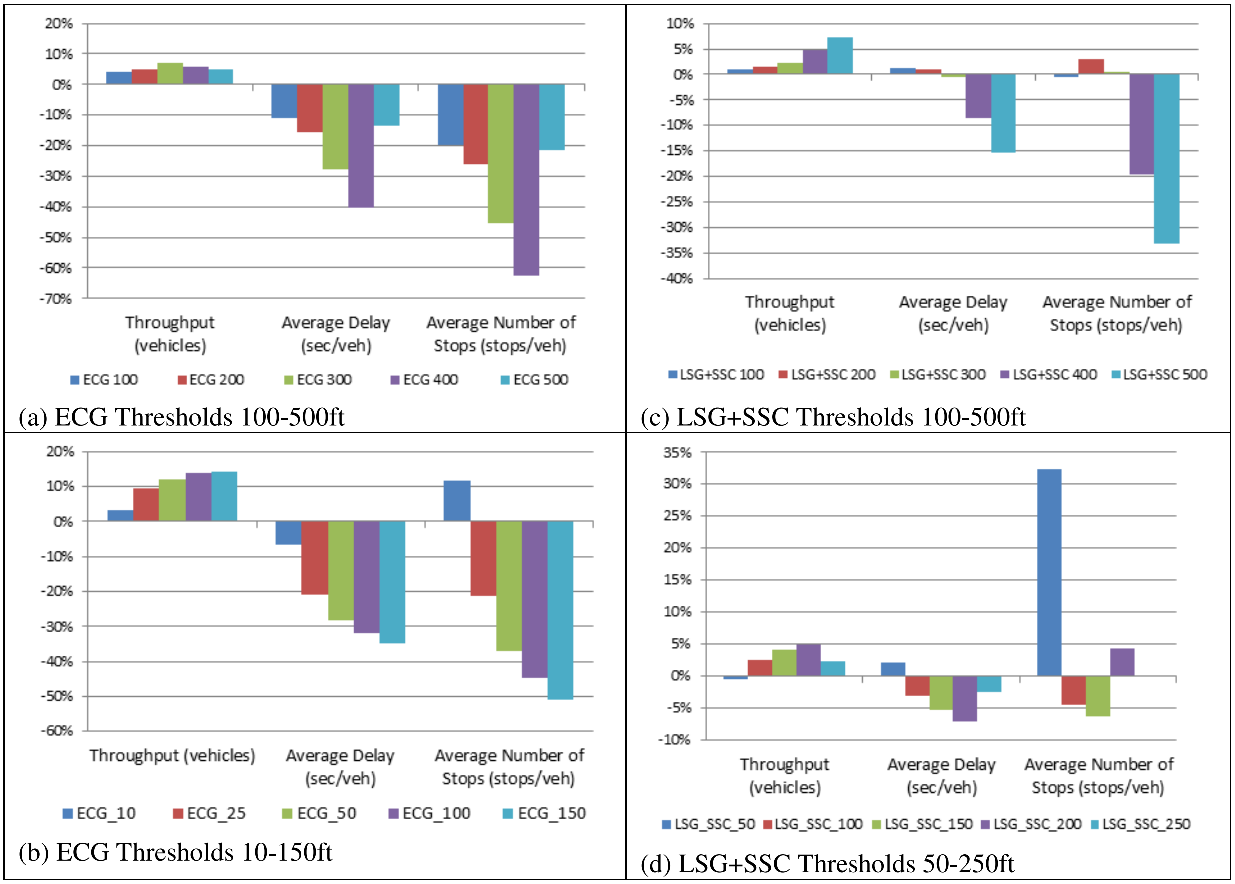
Figure 3: Evaluation of all algorithms at 100% market penetration level, and best thresholds

All the scenarios except the LSG Only strategy improved the network performance by a statistically significant magnitude. The LSG Only strategy actually degraded the performance. Detailed discussion of the results follows:

1. **ECG Only Strategy:** All the metrics improved for the Side Street, at the cost of minimal throughput loss on the Main Street. Therefore this strategy has effectively reallocated unused green times from the Main Street to the Side Street.
2. **LSG Only Strategy:** This strategy actually degraded the network performance in many ways. As the Green on Main Street started progressively late from one cycle to the next, coordination on the Main Street broke down significantly. It follows that even though coordination is not the main goal during an oversaturation condition, it plays a crucial role in network performance immediately after that condition is addressed.
3. **LSG+SSC Strategy:** This strategy addresses the coordination break down problem mentioned in the previous strategy, resulting in significant improvement in the entire network performance.
4. **ECG+LSG Strategy:** This strategy also provided significant benefits. However, this strategy did not perform better than the individual strategies - ECG Only and LSG Only. For, only one of ECG or LSG got usually activated during consecutive phases, as the oversaturation effects were dissipated by whichever algorithm came into play first. Even as these results are slightly worse than “ECG Only Strategy,” better benefits are expected for larger networks, with turning movements.
5. **ECG+LSG+SSC Strategy:** This strategy combined together two better performing strategies (ECG Only and LSG+SSC) and was expected to provide the best results. However, for the same reasons explained in the ECG+LSG strategy above, this strategy performed comparably with the “ECG Only strategy.”

In summary, all the strategies with ECG, i.e. ECG Only, ECG+LSG and ECG+LSG+SSC, provided comparable, high and significant improvements. However, these strategies also reallocated about 30% (about 140 out of 450 seconds) of green time from the Main Street to the Side Street, compared to the 11.6% (about 40 out of 450 seconds) reallocation by the LSG+SSC strategy.

To develop parameter value recommendations for the two parameters mentioned earlier, based on the above results, the ECG Only algorithm, and the LSG+SSC algorithm were selected. The results from these evaluations are presented in Tables 2-5 and Figure 4, and discussed in the next section.



(a) ECG Thresholds 100-500ft

(c) LSG+SSC Thresholds 100-500ft

(b) ECG Thresholds 10-150ft

(d) LSG+SSC Thresholds 50-250ft

Figure 4: Distance Threshold Parameter Value Evaluation

Table 5: ECG Distance Threshold Parameter Value Preliminary Evaluation

Strategies		Network-Wide Results			Link-Wise Results			
		Throughput (vehicles)	Average Delay (sec/veh)	Average Number of Stops (stops/veh)	Throughput (vehicles)		Green Times (sec)	
					L3	L7	L3	L7
Baseline	Mean	1879.3	23.0	1.11	288.4	657.4	450.0	450.0
	StdDev	26.8	1.2	0.16	12.7	8.9		
ECG 100	Mean	1956.9	20.5	0.89	263.6	776.5	379.9	520.1
	StdDev	31.2	1.7	0.15	30.9	74.4		
	% Changes	4.1%	-10.9%	-19.7%	-8.6%	18.1%	-15.6%	15.6%
	p-value	0.00	0.00	0.00	0.02	0.00		
ECG 200	Mean	1974.9	19.4	0.82	244.3	831.5	343.5	556.5
	StdDev	34.7	2.0	0.14	30.1	83.2		
	% Changes	5.1%	-15.6%	-25.9%	-15.3%	26.5%	-23.7%	23.7%
	p-value	0.00	0.00	0.00	0.00	0.00		
ECG 300	Mean	2011.8	16.6	0.60	210.7	934.2	275.6	624.4
	StdDev	42.1	2.6	0.18	43.5	109.0		
	% Changes	7.1%	-27.8%	-45.5%	-27.0%	42.1%	-38.8%	38.8%
	p-value	0.00	0.00	0.00	0.00	0.00		
ECG 400	Mean	1986.0	13.7	0.41	160.4	1007.8	190.1	709.9
	StdDev	40.7	0.4	0.02	14.8	30.1		
	% Changes	5.7%	-40.5%	-62.5%	-44.4%	53.3%	-57.7%	57.7%
	p-value	0.00	0.00	0.00	0.00	0.00		
ECG 500	Mean	1976.0	19.9	0.87	246.6	826.0	349.4	550.6
	StdDev	28.6	1.8	0.13	34.1	85.0		
	% Changes	5.1%	-13.3%	-21.3%	-14.5%	25.6%	-22.4%	22.4%
	p-value	0.00	0.00	0.00	0.00	0.00		

Note: The shaded cells indicate the results are statistically significant at the 95% confidence interval.

Table 6: ECG Distance Threshold Parameter Value Detailed Evaluation

Strategies		Network-Wide Results			Link-Wise Results			
		Throughput (vehicles)	Average Delay (sec/veh)	Average Number of Stops (stops/veh)	Throughput (vehicles)		Green Times (sec)	
					L3	L7	L3	L7
Base	Mean	1720.1	27.9	1.62	204.4	659.3	450.0	450.0
	StdDev	14.4	0.9	0.16	2.8	8.0		
ECG_10	Mean	1773.8	26.1	1.81	201.8	724.5	411.4	488.6
	StdDev	45.2	1.7	0.23	11.5	51.9		
	% Changes	3.1%	-6.7%	11.8%	-1.3%	9.9%	-8.6%	8.6%
	p-value	0.00	0.00	0.02	0.25	0.00		
ECG_25	Mean	1883.0	22.1	1.27	198.6	834.1	346.1	553.9
	StdDev	32.6	1.0	0.16	9.1	36.3		
	% Changes	9.5%	-21.0%	-21.4%	-2.8%	26.5%	-23.1%	23.1%
	p-value	0.00	0.00	0.00	0.04	0.00		
ECG_50	Mean	1930.9	20.1	1.02	192.9	892.8	308.2	591.8
	StdDev	27.2	1.0	0.11	10.9	34.9		
	% Changes	12.3%	-28.1%	-37.1%	-5.6%	35.4%	-31.5%	31.5%
	p-value	0.00	0.00	0.00	0.00	0.00		
ECG_100	Mean	1956.8	19.0	0.89	187.9	925.5	285.9	614.1
	StdDev	31.1	0.8	0.08	11.3	39.3		
	% Changes	13.8%	-31.9%	-44.7%	-8.1%	40.4%	-36.5%	36.5%
	p-value	0.00	0.00	0.00	0.00	0.00		
ECG_150	Mean	1968.3	18.3	0.80	188.5	937.6	277.7	622.3
	StdDev	29.3	0.8	0.07	9.7	33.4		
	% Changes	14.4%	-34.7%	-50.8%	-7.8%	42.2%	-38.3%	38.3%
	p-value	0.00	0.00	0.00	0.00	0.00		

Note: The shaded cells indicate the results are statistically significant at the 95% confidence interval.

Table 7: LSG+SSC Distance Threshold Parameter Value Preliminary Evaluation

Strategies		Network-Wide Results			Link-Wise Results			
		Throughput (vehicles)	Average Delay (sec/veh)	Average Number of Stops (stops/veh)	Throughput (vehicles)		Green Times (sec)	
					L3	L7	L3	L7
Base	Mean	1879.3	23.0	1.11	288.4	657.4	450.0	450.0
	StdDev	26.8	1.2	0.16	12.7	8.9		
LSG+SSC 100	Mean	1895.6	23.2	1.10	282.7	679.9	437.0	463.0
	StdDev	29.0	1.1	0.15	12.9	16.3		
	% Changes	0.9%	1.1%	-0.4%	-2.0%	3.4%	-2.9%	2.9%
	p-value	0.10	0.31	0.47	0.16	0.00		
LSG+SSC 200	Mean	1906.6	23.2	1.14	262.8	734.6	402.1	497.9
	StdDev	33.8	1.0	0.11	11.0	19.4		
	% Changes	1.5%	1.0%	3.0%	-8.9%	11.7%	-10.6%	10.6%
	p-value	0.03	0.31	0.30	0.00	0.00		
LSG+SSC 300	Mean	1922.6	22.8	1.11	257.2	754.4	392.5	507.5
	StdDev	27.6	0.7	0.09	9.2	21.6		
	% Changes	2.3%	-0.6%	0.4%	-10.8%	14.8%	-12.8%	12.8%
	p-value	0.00	0.39	0.47	0.00	0.00		
LSG+SSC 400	Mean	1970.5	21.0	0.89	252.3	815.3	356.1	543.9
	StdDev	23.1	0.6	0.07	10.0	24.9		
	% Changes	4.9%	-8.6%	-19.6%	-12.5%	24.0%	-20.9%	20.9%
	p-value	0.00	0.00	0.00	0.00	0.00		
LSG+SSC 500	Mean	2014.9	19.5	0.74	238.3	885.0	312.1	587.9
	StdDev	28.5	0.4	0.06	6.7	20.6		
	% Changes	7.2%	-15.3%	-33.3%	-17.4%	34.6%	-30.6%	30.6%
	p-value	0.00	0.00	0.00	0.00	0.00		

Note: The shaded cells indicate the results are statistically significant at the 95% confidence interval.

Table 8: LSG+SSC Distance Threshold Parameter Value Detailed Evaluation

Strategies		Network-Wide Results			Link-Wise Results			
		Throughput (vehicles)	Average Delay (sec/veh)	Average Number of Stops (stops/veh)	Throughput (vehicles)		Green Times (sec)	
					L3	L7	L3	L7
Base	Mean	1720.0	27.9	1.62	204.4	659.3	450.0	450.0
	StdDev	14.4	0.8	0.16	2.8	8.0		
LSG_SSC_50	Mean	1712.1	28.6	2.14	201.7	658.0	449.4	450.6
	StdDev	16.3	0.5	0.11	3.3	12.6		
	% Changes	-0.5%	2.2%	32.4%	-1.3%	-0.2%	-0.1%	0.1%
	p-value	0.14	0.03	0.00	0.03	0.39		
LSG_SSC_100	Mean	1762.5	27.1	1.55	203.4	701.7	424.1	475.9
	StdDev	36.9	1.0	0.14	3.3	23.0		
	% Changes	2.5%	-3.1%	-4.5%	-0.5%	6.4%	-5.7%	5.7%
	p-value	0.00	0.02	0.14	0.23	0.00		
LSG_SSC_150	Mean	1791.9	26.5	1.52	202.5	737.6	397.8	502.2
	StdDev	36.9	1.0	0.14	2.9	32.5		
	% Changes	4.2%	-5.3%	-6.4%	-0.9%	11.9%	-11.6%	11.6%
	p-value	0.00	0.00	0.07	0.07	0.00		
LSG_SSC_200	Mean	1804.2	26.0	1.69	202.0	750.2	388.1	511.9
	StdDev	35.6	0.9	0.11	2.8	36.7		
	% Changes	4.9%	-7.1%	4.4%	-1.2%	13.8%	-13.8%	13.8%
	p-value	0.00	0.00	0.13	0.04	0.00		
LSG_SSC_250	Mean	1760.6	27.2	1.62	203.4	704.1	422.1	477.9
	StdDev	22.8	0.8	0.17	3.3	23.2		
	% Changes	2.4%	-2.6%	0.2%	-0.5%	6.8%	-6.2%	6.2%
	p-value	0.00	0.03	0.48	0.25	0.00		

Note: The shaded cells indicate the results are statistically significant at the 95% confidence interval.

It will be noticed that the values in Figure 4a/Table 5 and Figure 4c/Table 6 do not match completely with the final summary Table 4 and Figure 3. This was due to a speed zone restriction implemented in the initial phases of the project to ensure oversaturation conditions, and trying to narrow down the parameter values of interest. Even though the absolute values are different, the relative observations are expected to hold good. Therefore these experiments were not repeated. However, it will be noted that the values in Table 6 for "ECG 50" are similar to the "ECG Only" values in Table 4, and the values in Table 5 for "LSG+SSC 150" are similar to the "LSG+SSC" values in Table 4.

STEP 2. Select algorithms, and parameter values

Two algorithm scenarios – (1) ECG Only, and (2) LSG + SSC – demonstrated significant benefits, compared to the other scenarios. Since they form the basic building blocks of the other scenarios, these two scenarios were selected for further extensive evaluation with different market penetration levels.

For each parameter used by an algorithm, recommendations were developed to identify appropriate parameter values. These recommendations follow directly from the "best" results observed from the Step 1 above, which are identified based on the following four criteria:

1. Statistical significance in total volume changes
2. Amount of volume changes for L3 and L7 (With the ideal thresholds, the L3 volume change will be zero, and L7 volume change will be highest. Practically, all threshold values resulted in some volume loss for L3. Therefore the least loss for L3 volumes and the highest volume gain for L7 were targeted)
3. Amount of Green time changes for L3 and L7 (In addition to the desired volume changes noted above, the ideal thresholds would yield the least Green time change for L3 and L7. For, large changes would undermine the progression and affect the pedestrian green times. It will be noted that the magnitude of Green time percentage change for L3 and L7 are equal, and the direction of change are different, as there is no net addition or deletion of time. It is a zero sum game.)
4. Smallest threshold value (Again, as mentioned above, large changes would undermine the progression.)

Based on the above criteria, there were no clear winners from the preliminary evaluation for threshold values (Figure 4a and 4c, and Tables 2 and 3). Therefore a second round of detailed evaluations were performed, as shown by the results in Figures 4b and 4d, and Tables 4 and 5. Yet, no clear winner was found. However, the distance threshold of 50ft for ECG and 150ft for LSG were selected as the most promising, and are recommended for further study. It is noted that the other threshold values need to be evaluated in detail, in future.

STEP 3. Identify IntelliDrive^{SM} Market Penetration (IMP) levels

All the evaluations in Step 1 were conducted assuming a perfect IntelliDrive^{SM} Market Penetration (IMP) of 100%. This first step was important to understand the upper ceiling of the potential benefits from the algorithms, if their promises are fully realized. Next, the following four different imperfect IMP values (20%, 40%, 60% and 80%) were selected for further evaluations. The fundamental building blocks of the successful algorithms are the "ECG Only" and "LSG+SSC" strategies. Therefore these two strategies were subjected to sensitivity analysis, at different IntelliDrive^{SM} Market Penetration (IMP) levels. In summary, the "ECG Only" scenario results were consistently, linearly and positively correlated with IMP value. However the "LSG+SSC" scenario results under different IMP values were inconsistent. The detailed End-of-Queue (EOQ) estimation approaches and results are presented in step 4.

STEP 4. Approaches for IMP<100%

When the IMP is less than 100%, the EOQ needs to be estimated using the limited data available from equipped vehicles. Three approaches were considered in this study for such estimations:

1. Naïve End-of-Queue (EOQ) estimation approach:
   The locations of the last IntelliDrive^{SM}-equipped vehicles on each lane are considered as the EOQ for that lane. This approach is likely to suffer from severe errors, especially at lower IMP values.

2. Volume-based EOQ estimation with assumed IMP:

Based on the locations of the last IntelliDrive[SM]-equipped vehicles on each lane, the total number of IntelliDrive[SM]-equipped vehicles on the link, an assumed average vehicle length (20ft used in this study) and the IMP value, the EOQ is estimated. The EOQ estimation method is a linear interpolation, as presented in equation 1 below:

$$Space = LL * NumLanes - \frac{Num\_iCars * AVL * 100}{IMP * NumLanes} \qquad \text{……….Eqn.1}$$

Where,
Space = Total available space across all lanes of the link (in feet);
LL = Link length (in feet);
NumLanes = Total number of lanes in the link;
Num_iCars = Total number of all IntelliDrive[SM]-equipped vehicles across all the lanes;
IMP = IntelliDrive[SM] Market Penetration, either assumed or estimated (in percent);
AVL = Average vehicle length (in feet). A constant 20ft was used in this study.

Alternately, the AVL could be estimated using the VehicleSize data element in the SAE J2735 Standard (SAE 2009).

3. Volume-based EOQ estimation with Calculated IMP:
It was noted in this study that the IMP value is not constant across all the time periods and all the links. It is localized. Further, the IMP value for a network may be unknown, in reality. For these reasons, a method has been developed to estimate the actual IMP in the field. During the red phase of an approach, vehicles in the queue on a link are stationary. The total number of IntelliDrive[SM]-equipped vehicles in this stationary queue, and the location of the last IntelliDrive[SM]-equipped vehicle across all lanes of the approach are directly available from the field. It is assumed in this study that the stationary queues on all the lanes are comparable in length. By assuming an average vehicle length (AVL), the total number of vehicles in the stationary queue, up to the last IntelliDrive[SM]-equipped vehicle is calculated. The ratio of these two numbers provides an estimation of the actual IMP value from the field. Further, these estimated IMP values are averaged on a rolling basis over the past several consecutive time periods, to obtain a smoothed number. The actual calculation for this estimated IMP is presented in Equation 2 below:

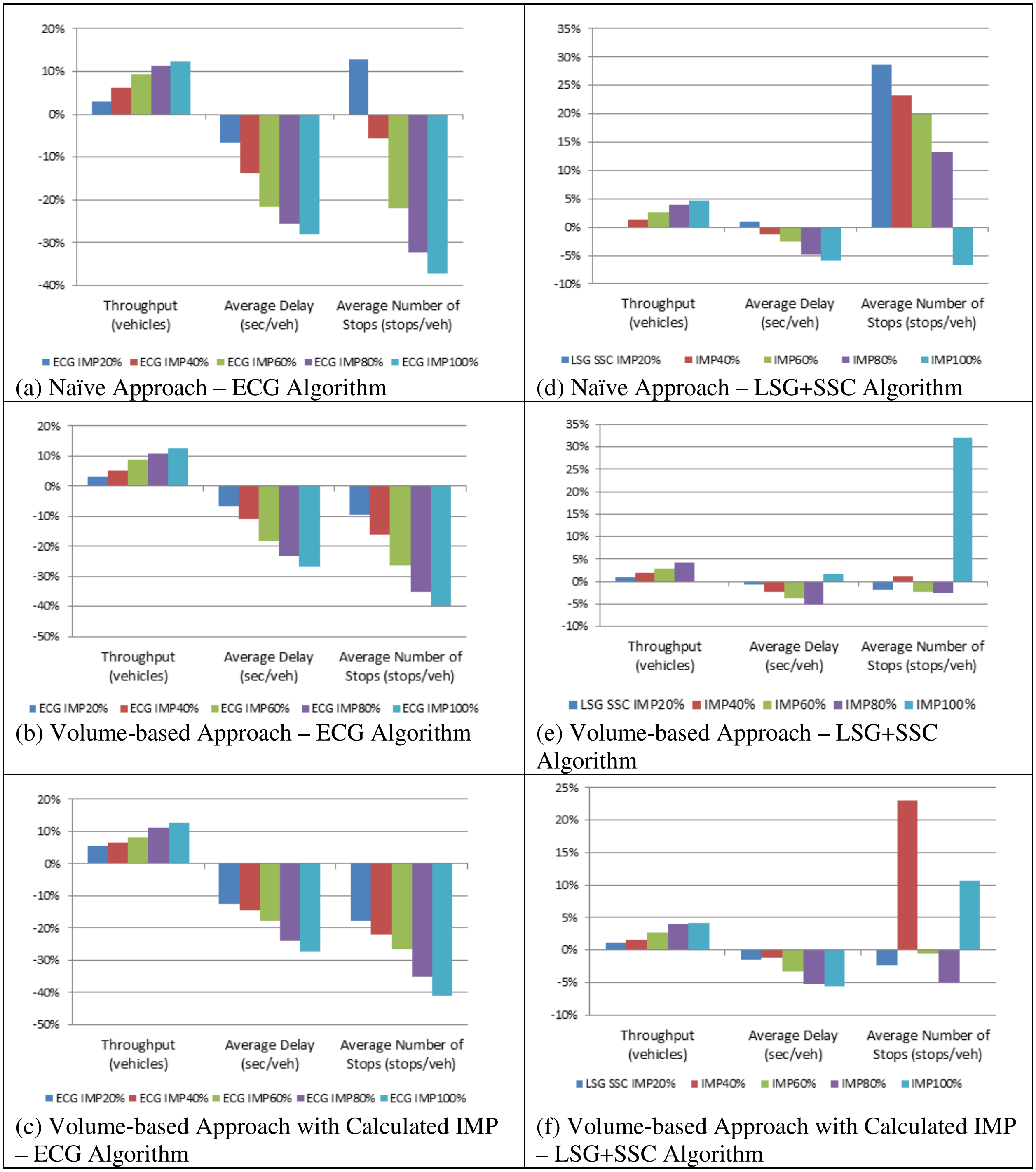
$$IMP_{Estim} = \frac{\sum_{t=1}^{T} Num\_iCars_t}{\sum_{t=1}^{T} \frac{L_t * NumLanes}{AVL}} \qquad \text{……….Eqn.2}$$

IMP_{Estim} = Estimated IntelliDrive[SM] Market Penetration (in percent)
T = Total time period for smoothing (5 seconds considered in this study)
t = time step (1 sec in this study).
Num_iCars_t = Total number of IntelliDrive[SM]-equipped vehicles with speed<5mph, across all lanes of the link, at time t.

L_t = Location of the last IntelliDrive[SM]-equipped vehicle with speed<5mph, across all lanes of the link, at time t (in feet).

Once the IMP value is directly calculated from the field data, the same volume-based EOQ estimation procedure explained in the above approach was used.

The LSG+SSC algorithm, with only 4% improvements at even 100% market penetration did not yield consistent, significant improvements at lower market penetration levels. However, for the "ECG Only" strategy, all these approaches provided comparable, consistent and significant results, as depicted in Figure 5. The benefits generally increased linearly, with increasing IMP value. Further, these benefit trends mirrored the trends of changes in the green times.



(a) Naïve Approach – ECG Algorithm

(d) Naïve Approach – LSG+SSC Algorithm

(b) Volume-based Approach – ECG Algorithm

(e) Volume-based Approach – LSG+SSC Algorithm

(c) Volume-based Approach with Calculated IMP – ECG Algorithm

(f) Volume-based Approach with Calculated IMP – LSG+SSC Algorithm

Figure 5: Sensitivity of Select Algorithms and EOQ Estimation Approaches with Market Penetration

For all the simulation runs considering IntelliDrive^{SM} market penetration (IMP) less than 100%, vehicles were randomly assigned as IntelliDrive^{SM}-equipped.

STEP 5. Select EOQ estimation approach

In summary, only the "ECG Only" scenario illustrated consistent and significant benefits at even low IMP value such as 20%. For this reason, only this scenario was selected for sensitivity analyses based on errors to location and speed values.

From Figure 5, it is also observed that the Naïve approach performed reasonably, in comparison to the other two, more complex EOQ estimation approaches.

The comparable results of the three EOQ estimation approaches validates the algorithm developed in this paper to estimate localized IMP values from field queue conditions as a reasonable and practical approach, for further investigation and application.

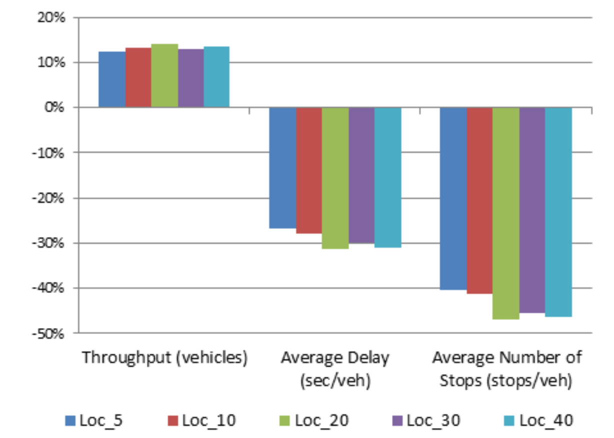
STEP 6. Analysis of algorithm sensitivity to errors

Two IntelliDrive^{SM} data elements have been used in all the algorithms in this study: the location, and the speed of each vehicle. Different types of errors could creep into both these data elements. Therefore it is desirable to evaluate the sensitivity of an algorithm to these errors, both separately, and together. For this reason, within the simulation test bed, for each vehicle, at each time step, a random error was added to its location attribute, speed attribute, or both, depending on the experiment of interest. For location error, a maximum of 40ft (which is equivalent to 2 average car lengths) was considered. For speed error, a maximum of 40% error (which is equivalent to 2mph at 5mph, and 3.2mph at 8mph) was considered.

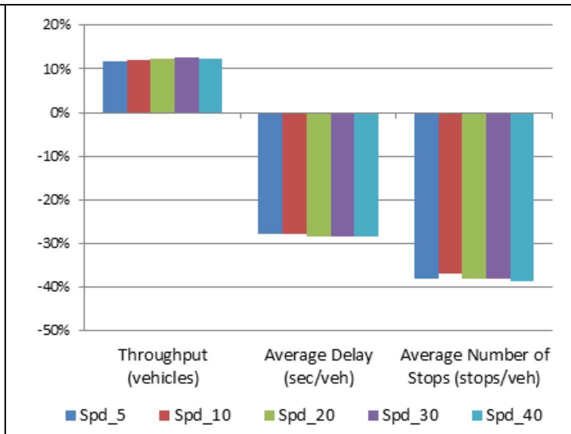
Within these maximum limits, several experiments were conducted:

- 5 levels of maximum location error alone: 5ft, 10ft, 20ft, 30ft, and 40ft;
- 5 levels of maximum speed error: 5%, 10%, 20%, 30%, and 40%.

As mentioned in Step 5 above, the ECG Only algorithm alone was considered for these experiments. The deterioration of benefits was negligible even at 40ft. location error, or 40% speed error (Figure 6 and Tables 6 and 7), illustrating the robustness of the algorithm. Next, both the errors were considered together. Further, since the ECG algorithm was robust for individual errors, the maximum errors were introduced and the algorithm results were studied at different IntelliDrive^{SM} Market Penetrations (20%-100%). As illustrated in Figure 7 and Table 11, the benefits are statistically significant at all IMP levels, and increase linearly with IMP.



(a) ECG Sensitivity to Location Errors 5-40ft.



(b) ECG Sensitivity to Speed Errors 5-40%.

Figure 6: ECG only algorithm sensitivity to individual errors

Table 9: Sensitivity analysis results of ECG only algorithm under maximum 40ft location error

Strategies		Network-Wide Results			Link-Wise Results	
		Throughput (vehicles)	Average Delay (sec/veh)	Average Number of Stops (stops/veh)	Throughput (vehicles)	
					L3	L7
Base	Mean	1720.1	27.9	1.62	204.4	659.3
	StdDev	14.4	0.9	0.16	2.8	8.0
Loc_5	Mean	1935.2	20.4	0.96	191.9	894.3
	StdDev	42.2	1.3	0.10	12.8	50.9
	% Changes	12.5%	-26.9%	-40.4%	-6.1%	35.6%
	p-value	0.00	0.00	0.00	0.01	0.00
Loc_10	Mean	1947.1	20.2	0.95	192.5	903.3
	StdDev	29.9	1.0	0.10	11.1	41.1
	% Changes	13.2%	-27.9%	-41.3%	-5.8%	37.0%
	p-value	0.00	0.00	0.00	0.00	0.00
Loc_20	Mean	1964.3	19.2	0.86	189.9	925.6
	StdDev	33.1	1.3	0.11	9.4	42.5
	% Changes	14.2%	-31.3%	-46.8%	-7.1%	40.4%
	p-value	0.00	0.00	0.00	0.00	0.00
Loc_30	Mean	1945.0	19.6	0.88	191.2	907.9
	StdDev	41.4	1.4	0.12	11.1	49.5
	% Changes	13.1%	-29.9%	-45.6%	-6.4%	37.7%
	p-value	0.00	0.00	0.00	0.00	0.00
Loc_40	Mean	1954.0	19.3	0.87	189.6	918.7
	StdDev	39.4	1.6	0.14	12.4	53.9
	% Changes	13.6%	-30.9%	-46.3%	-7.2%	39.3%
	p-value	0.00	0.00	0.00	0.00	0.00

Table 10: Sensitivity analysis of ECG only algorithm under maximum 40% speed error

Strategies		Network-Wide Results			Link-Wise Results	
		Throughput (vehicles)	Average Delay (sec/veh)	Average Number of Stops (stops/veh)	Throughput (vehicles)	
					L3	L7
Base	Mean	1720.1	27.9	1.62	204.4	659.3
	StdDev	14.4	0.9	0.16	2.8	8.0
Spd_5	Mean	1923.2	20.1	1.00	195.6	886.4
	StdDev	33.9	0.9	0.09	13.3	40.6
	% Changes	11.8%	-27.9%	-38.1%	-4.3%	34.4%
	p-value	0.00	0.00	0.00	0.03	0.00
Spd_10	Mean	1924.8	20.2	1.02	194.9	886.6
	StdDev	30.1	0.9	0.10	10.8	39.7
	% Changes	11.9%	-27.9%	-37.0%	-4.6%	34.5%
	p-value	0.00	0.00	0.00	0.01	0.00
Spd_20	Mean	1933.2	20.0	1.00	191.6	897.0
	StdDev	31.8	1.1	0.10	11.5	38.5
	% Changes	12.4%	-28.3%	-38.2%	-6.2%	36.0%
	p-value	0.00	0.00	0.00	0.00	0.00
Spd_30	Mean	1936.1	20.0	1.00	195.3	890.5
	StdDev	28.8	1.0	0.12	12.7	38.7
	% Changes	12.6%	-28.3%	-38.2%	-4.4%	35.1%
	p-value	0.00	0.00	0.00	0.03	0.00
Spd_40	Mean	1930.7	20.0	0.99	196.4	889.1
	StdDev	23.9	0.8	0.10	9.4	30.4
	% Changes	12.2%	-28.5%	-38.5%	-3.9%	34.8%
	p-value	0.00	0.00	0.00	0.01	0.00

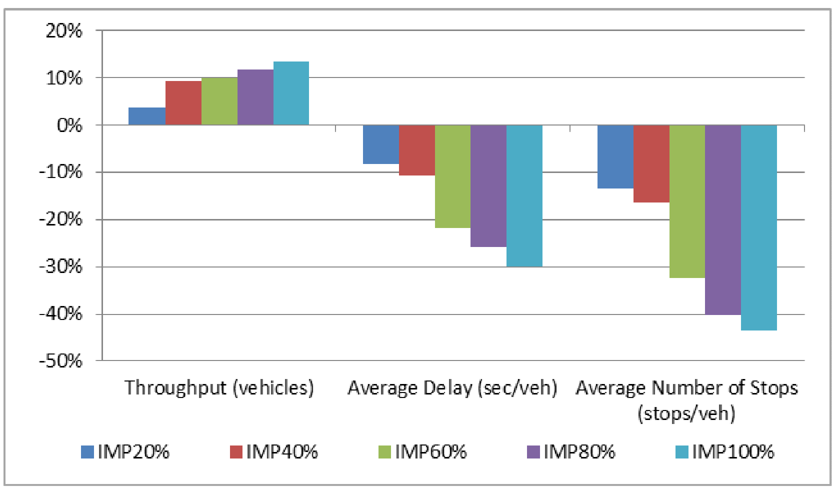


Figure 7: ECG only algorithm sensitivity to maximum 40ft location error and 40% speed error at different IntelliDrive[SM] market penetrations

Table 11: Detailed sensitivity analysis results of ECG only algorithm under both maximum 40ft location error and 40% speed error

Strategies		Network-Wide Results			Link-Wise Results	
		Throughput (vehicles)	Average Delay (sec/veh)	Average Number of Stops (stops/veh)	Throughput (vehicles)	
					L3	L7
Base	Mean	1720.1	27.9	1.62	204.4	659.3
	StdDev	14.4	0.9	0.16	2.8	8.0
IMP20%	Mean	1784.4	25.6	1.40	202.0	726.5
	StdDev	54.8	2.1	0.18	8.6	61.1
	% Changes	3.7%	-8.3%	-13.5%	-1.2%	10.2%
	p-value	0.00	0.00	0.01	0.21	0.00
IMP40%	Mean	1881.6	24.9	1.35	223.2	782.6
	StdDev	274.0	1.5	0.15	111.6	58.8
	% Changes	9.4%	-10.8%	-16.3%	9.2%	18.7%
	p-value	0.05	0.00	0.00	0.30	0.00
IMP60%	Mean	1892.2	21.9	1.09	196.0	848.8
	StdDev	42.4	1.3	0.13	12.1	46.0
	% Changes	10.0%	-21.7%	-32.4%	-4.1%	28.7%
	p-value	0.00	0.00	0.00	0.03	0.00
IMP80%	Mean	1922.1	20.7	0.97	195.5	882.9
	StdDev	44.9	1.6	0.12	11.1	48.1
	% Changes	11.7%	-25.9%	-40.2%	-4.3%	33.9%
	p-value	0.00	0.00	0.00	0.02	0.00
IMP100 %	Mean	1954.2	19.6	0.92	195.1	910.6
	StdDev	27.9	1.1	0.13	12.9	39.8
	% Changes	13.6%	-29.9%	-43.4%	-4.6%	38.1%
	p-value	0.00	0.00	0.00	0.03	0.00

From the above results, it is observed that the ECG Only algorithm provides robust, consistent and statistically significant results for both location and speed errors, and for different market penetration levels.

Concluding Remarks

Based on all the experiments and results presented in this report, the ECG Only algorithm is recommended for any downtown area with one-way traffic streets which experience oversaturation currently. Any minimum green time limits due to pedestrian movement that critically affects the decisions of the ECG algorithm is expected to decrease the benefits, but not worsen the network performance. Even though turning movements were not studied, their presence is expected to improve the network performance, since better knowledge is gained by the algorithms from the field, and spill backs are minimized further.

A follow up study is necessary to evaluate the algorithm benefits on networks with 2-way streets, turning movements, pedestrian movements, and trucks and buses.

PREDICTIVE MICROSCOPIC SIMULATION ALGORITHM

The Predictive Microscopic Simulation Algorithm (PMSA) is discussed in the Task 2 Report. In summary, the PMSA operates by polling all vehicles within the range of an intersection's sensor for vehicles position, speed, and heading. A model of the intersection is then populated with all detected vehicles (all other information about the vehicle, such as desired speed or driver characteristics, are randomized), and the model uses microscopic simulation to evaluate all possible phase change configurations over a period of 15 seconds into the future. The phase configuration with the least cumulative delay is selected as the next phase. The phase remains green for either the minimum green period of five seconds, or the time at which one movement of the phase is predicted to experience no delay, whichever comes later. At that time, the signal then re-polls all vehicles and repeats the process.

The PMSA differs from the one described in Task 2 only in that the maximum allowable red time for a movement has been changed from 150 seconds to 120 seconds to improve level of service for the lowest volume movements.

Methodology

The PMSA was tested using microscopic simulation of a model of four-signal corridor along US Route 50 in Northern Virginia. The model is based on traffic volumes collected in 2004, and the model has been calibrated to reflect conditions along the six-lane arterial. The PMSA was tested in the microscopic simulation software package VISSIM, using the Component Object Model (COM) interface and C# programming language. For the control scenario, the macroscopic traffic simulation tool Synchro was used to develop an optimized coordinated-actuated traffic signal timing plan with identical yellow and red clearance requirements as the PMSA (4 and 2 seconds, respectively). The 120 second cycle length Synchro plan was implemented on the same model in VISSIM and tested for comparison.

Pedestrians were not included in this simulation for several reasons. First, pedestrian volumes at the intersection are very low, generally less than 10 pedestrians per hour per intersection. Second, because of the large geometries of the intersections, pedestrians required almost 50 seconds to cross the intersection, which is well beyond the 15 seconds of horizon time used to calculate the next phase. In its present state, the PMSA is probably better suited for either large, high vehicular volume intersections with rare pedestrian movements, or smaller intersections with pedestrian crossing times of less than 30 seconds.

Each scenario was run between five and thirty repetitions, depending on the amount required to obtain an acceptable error of three seconds of average vehicle delay, and with a significance level of 0.05. All simulation runs were for a period of 30 minutes.

Results

Results from the simulation runs are listed in Table 12. Only the delay and speed of the 25% market penetration scenario can be considered statistically insignificant from the coordinated-actuated base case. The algorithm shows significant improvements in vehicle delay, speeds, and stopped delay, as well as increases in CO_2 emissions. The increase in emissions is likely due to the way the timing plan behaves, as it produces very short green periods. Drivers stop more in the PMSA than with a traditional two-minute cycle length strategy, but the stops are significantly shorter. Although delay is lower, drivers spend more time accelerating and decelerating, which leads to the increase in CO_2 emissions. This may be less of a factor by the time IntelliDrive^{SM}-based control strategies can be implemented, as hybrid vehicles, which produce far lower emissions in start-stop driving than traditional vehicles, may have a larger market share.

Table 12: Results of the Predictive Microscopic Simulation Algorithm (PMSA)

Scenarios	Metric	Average delay time per vehicle [s]	Average speed [mph]	Average stopped delay per vehicle [s]	Emissions CO2 [kg]
Base	Mean	55.15	27.78	31.44	2897367.40
25% Market Penetration	Mean	55.58	27.82	26.02	3115272.28
	% Change	0.8%	0.1%	-17.2%	7.5%
	p-value	0.282	0.894	0.000	0.000
50% Market Penetration	Mean	51.9268	28.4804	24.5456	3044674.012
	% Change	-5.8%	2.5%	-21.9%	5.1%
	p-value	0.003	0.000	0.000	0.001
75% Market Penetration	Mean	50.57	28.72	23.76	3011405.79
	%Change	-8.3%	3.4%	-24.4%	3.9%
	p-value	0.000	0.000	0.000	0.000
100% Market Penetration	Mean	51.41	28.58	24.64	3015184.04
	%Change	-6.8%	2.9%	-21.6%	4.1%
	p-value	0.001	0.000	0.000	0.003

Figure 8 shows percent improvements over the coordinated-actuated base case strategy at various IntelliDrive^{SM} market penetration rates across several metrics. Notice that in many cases, the full benefits of the PMSA were experienced at only 50% market penetration, and that any additional improvements at higher penetration rates were minimal.

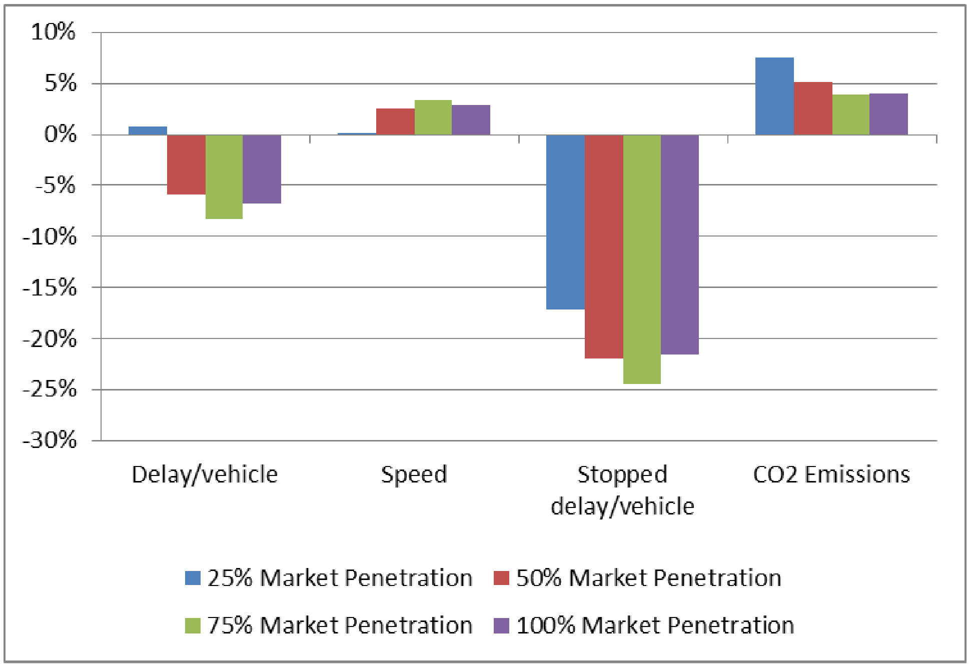


Figure 8: Percent Changes in Performance of PMSA based on Market Penetration Rates

The PMSA was originally developed to be a stand-alone system, basing its signal control strategy only on the immediate present, rather than based on past intersection volumes and turning movements. To test the algorithms ability to handle generally fluctuations in vehicle arrivals, the algorithm at 50% market penetration and base case were evaluated, without any changes to their timing plans, with a 25% increase in vehicle volumes along the main arterial. The results of this evaluation are shown in Table 13. With the unexpected change in volumes, the PMSA was able to substantially outperform the base case timing plan, with a 25% reduction in delay, and a 2% reduction in emissions.

Table 13: Performance of PMSA and Base Case with an Unexpected 25% Increase in Mainline Vehicle Volumes

Scenario (25% Increase in Mainline Volume)	Metric	Average delay time per vehicle [s]	Average speed [mph]	Average stopped delay per vehicle [s]	Emissions CO2 [kg]
Base	Mean	81.75	24.01	41.27	3745067.78
50% Market Penetration	Mean	60.63	27.31	26.71	3675230.96
	% Change	-25.8%	13.7%	-35.3%	-1.9%
	p-value	0.000	0.000	0.000	0.005

Conclusions

Although the results indicate significant improvements at the 50% market penetration, and no improvement at the 25% market penetration, these findings are probably very dependent on the traffic volumes at any particular intersection. After watching simulations, generally individual turning movements are proportionately represented by the IntelliDrive^{SM}-equipped vehicles, although at a rate much lower than is actually present. However, below a certain threshold some movements are not requesting service at all, even though a queue is present, causing the different movements to be unfairly represented. The level of market penetration that can support the PMSA without assistance from traditional loop detectors will likely be a higher percentage of traffic for low volume networks.

The primary benefit of the PMSA is its adaptability to different volume scenarios. Because the PMSA does not favor a particular approach, corridor, or know of any previous volumes, it is able to completely optimize its timing plan to serve the volumes at that moment. Not only should it be able to provide a high level of service to daily and weekly variations in traffic, but also to variations in traffic over several years. This eliminates the need for the signal timing plan to be updated except in cases of geometric improvements, which are very rare.

The PMSA can be recommended as a stand-alone system as-is for low-pedestrian intersection or small intersections with short pedestrian clearance times, simply because of the short time horizon over which the PMSA optimizes timings. Further research is needed to determine the precise threshold at which the PMSA can operate without the assistance of traditional loop detectors. Further research is also needed to better integrate the benefits of the algorithm with loop detector data for serving low market penetration levels. The existing and continuing rolling horizon research (which generally relies on loop detectors only) are an excellent starting point.

VEHICLE CLUSTERING ALGORITHM

Version two of the Vehicle Clustering Algorithm (VCA2) is similar to the VCA presented in the Task 2 Report in that it is decentralized and uses IntelliDrive^{SM} technology to obtain vehicle speeds and locations in order to utilize green times more effectively in urban arterials. There are two key features (discussed later) that allow the VCA2 to take advantage of more capabilities of IntelliDrive^{SM} technology and to make it more robust to different traffic patterns.

The algorithm was tested on a calibrated VISSIM model of a four-intersection segment of Route 50 in Northern Virginia and sensitivity analysis was conducted, examining the algorithm's performance at lower IntelliDrive^{SM} technology market penetration levels and higher volumes. These results were compared to those from an actuated-signal control for the network. The VCA2 outperformed the actuated-signal plan on several measures of effectiveness (MOEs) at varying penetration levels and network volumes, demonstrating the benefits of leveraging IntelliDrive^{SM} technology to improve traffic signal efficacy. Prior to displaying the results, the distinguishing features of the VCA2 will be presented. (See Figure 9 for a flowchart).

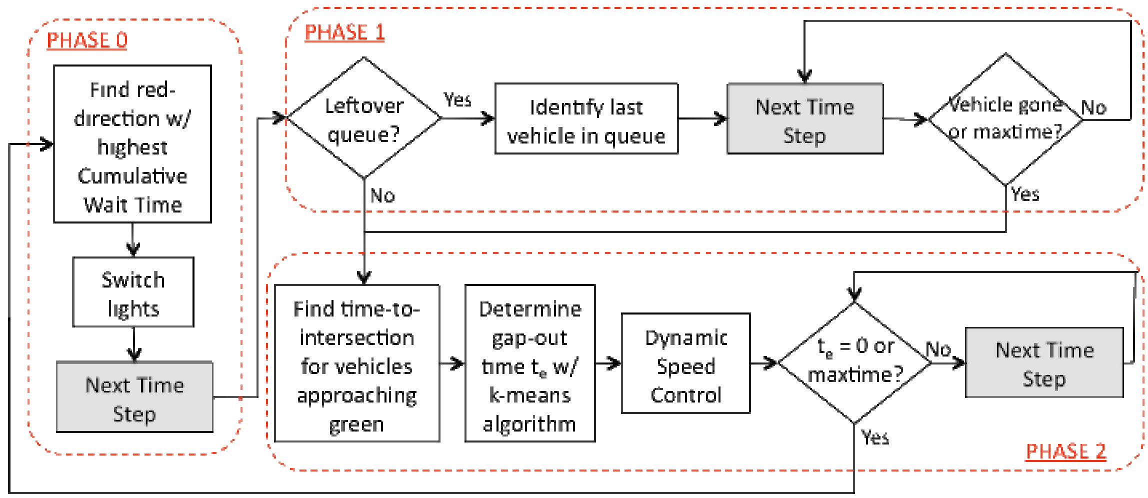


Figure 9: Vehicle Clustering Algorithm (Version 2) Flowchart

First new feature of the VCA2 is that it uses a k-means clustering algorithm to determine the optimal time to end the green phase. After the queues have been cleared, the algorithm calculates the time-to-intersection (distance divided by speed) of all vehicles approaching the intersection and sets the gap-out time where the largest gap in this distribution occurs. Figure 10 displays an example; the red line indicates that the green will end in 11 seconds. The second key feature of the VCA2 is that it provides drivers feedback similar to the dynamic speed control of Abu-Lebdeh & Chen (2010). After using k-means clustering to calculate the gap-out time, the VCA2 assigns suggested speeds to all vehicles approaching the intersection. Vehicles on the approaches with a green are told to increase their speeds provided they can pass through the intersection within the remaining green time, while vehicles that are approaching a red signal are advised to decrease their speeds in order to increase their time-to-light, allowing the red signal to change to green and any queues to clear prior to the vehicle arriving at the intersection. Providing such speed control is not possible with current detectors and should increase throughput and decrease delays. The VCA2 currently assumes a 100% compliance rate, but the effects of lower compliance levels on the algorithm's performance will be explored.

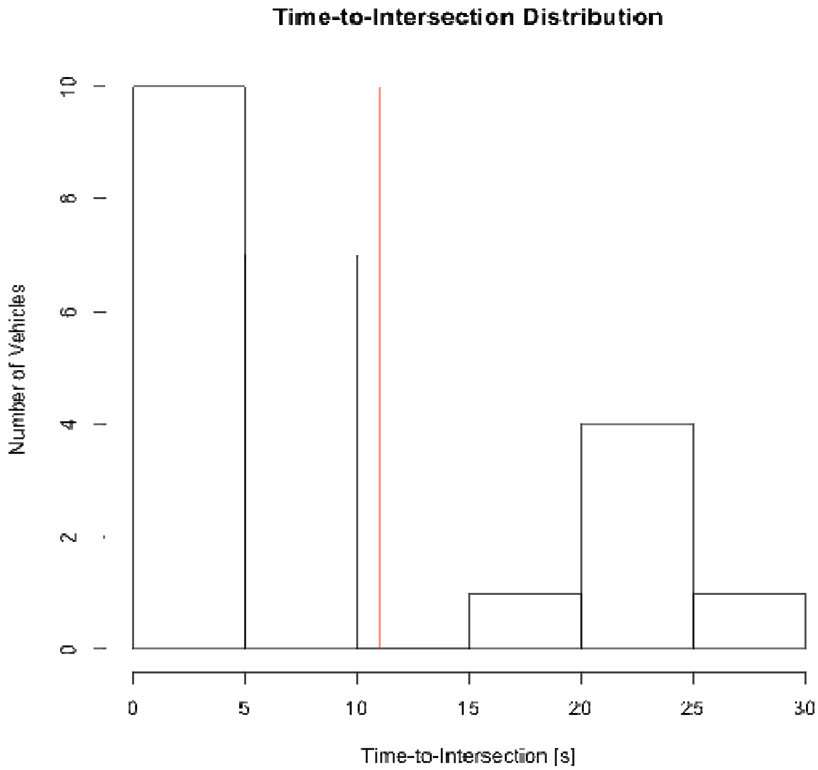


Figure 10: Example Time-to-Intersection Distribution

The VCA2 was evaluated using 10 one-hour simulations on a four-intersection segment of Route 50. Table 14 displays the average MOE values for the actuated control and the VCA2, as well as the percent difference between them, at different IntelliDrive^{SM} market penetration levels. Interestingly, the VCA2 leverages IntelliDrive^{SM} technology to improve, though marginally, the efficacy of signal timing until less than 50% of vehicles are equipped with the technology; the VCA2 performs worse than the actuated plan at market penetration levels lower than 50%. According to a recent study (Chang, 2010), 50% market penetration may be realized within 15 years. For higher levels of market penetration, vehicles are generally stopping for less time, moving faster, and getting to their destinations sooner. However, achieving these benefits comes at the cost of an 11% increase in fuel consumption. Adding more driver feedback to future versions of the VCA should reduce both fuel consumption and overall delay.

Table 14: Market Penetration Levels Results

Penetration	Average Values	Delay [s]	Stopped Delay [s]	Speed [mph]	Fuel Consumption [l]
-	*Actuated*	*58.43*	*33.48*	*27.81*	*2736.72*
100%	VCA2	54.44	22.42	28.61	3016.58
	% Difference	**-6.83%**	**-33.03%**	**2.88%**	**10.23%**
75%	VCA2	54.66	22.99	28.59	3032.74
	% Difference	**-6.45%**	**-31.33%**	**2.80%**	**10.82%**
50%	VCA2	56.12	24.99	28.34	3028.58
	% Difference	**-3.95%**	**-25.36%**	**1.91%**	**10.66%**
25%	VCA2	76.09	46.59	25.33	3058.65
	% Difference	**30.22%**	**39.16%**	**-8.92%**	**11.76%**

The VCA2's signal control led to higher fuel consumption with only minimal decreases in delay under normal conditions. However, when vehicle volumes are increased without an adjustment to the actuated signal control plan, the VCA2 was able to adapt significantly better. Table 15 displays the results from 10 one-hour simulations with various volume increases for the 100% IntelliDrive^{SM} market penetration level. The two signal control schemes performed similarly under a slight increase (10%) in volumes, but the actuated control (which was optimized for the base volumes) began to breakdown at the higher volume levels. A 20% increase in the number of vehicles over the one-hour simulation led to a 59% increase in delay and a 37% increase in fuel consumption. By contrast, the VCA2's performance was not as adversely affected by the increase in volumes. Under the VCA2, a 20% increase in network volumes produced only a 28% increase in delay and a 27% increase in fuel consumption across all vehicles in the network. The VCA2 is much more robust to changes in volumes than the actuated plan, demonstrating the advantages of IntelliDrive^{SM}-informed signal control schemes.

Table 15: Increased Network Volumes Results

Volume Increase	Measure of Effectiveness	Actuated Average	VCA2 Average	Percent Difference
10%	Delay [s]	66.53	62.68	**-5.79%**
	Stopped Delay [s]	37.23	26.55	**-28.68%**
	Speed [mph]	26.53	27.24	**2.67%**
	Fuel Consump. [l]	3159.53	3454.09	**9.32%**
15%	Delay [s]	74.62	64.74	**-13.24%**
	Stopped Delay [s]	41.10	27.32	**-33.52%**
	Speed [mph]	25.37	26.91	**6.07%**
	Fuel Consump. [l]	3392.36	3602.56	**6.20%**
20%	Delay [s]	92.74	69.95	**-24.57%**
	Stopped Delay [s]	47.03	30.10	**-36.00%**
	Speed [mph]	23.11	26.15	**13.14%**
	Fuel Consump. [l]	3749.22	3831.57	**2.20%**

Looking beyond the fact that the VCA2 led to increased fuel consumption while achieving only minor improvements in delay, these results are encouraging because they illustrate the potential benefits of traffic signal control algorithms that utilize IntelliDrive^{SM} technology. Actuated control schemes are the product of decades of traffic research and when optimized for specific conditions, they perform well. However, traffic patterns are dynamic, both daily variations and long-term trends in traffic can produce major delays. Not only would IntelliDrive^{SM} technology-informed algorithms, like the VCA2, be more robust to varying traffic patterns and volumes – benefits felt on the road – such algorithms would obviate, or at least reduce, the need for traffic studies to re-optimize signals and remove the need for inductive loop detector maintenance – benefits felt in the budget. These results do not prove that algorithms that utilize IntelliDrive^{SM} would be more cost effective than traditional timing plans, but certainly demonstrate potential.

Future research will focus on developing new versions of the VCA2 that further improve the efficacy of traffic lights, the ultimate goal being an algorithm that produces improved control across MOEs and displays robustness to both volumes and market penetration levels. As mentioned previously, additional driver feedback will be incorporated into the algorithm. Also, the benefits of adding more coordination between intersections will be explored. Forcing coordination between the intersections should result in reduced fuel consumption and delays, but will require more computing power and the increased complexity may reduce the algorithm's robustness to market penetration levels or traffic volumes.

COMPATIBILITY WITH INTELLIDRIVE^{SM}

All algorithms evaluated in this document are fully compatible with IntelliDrive^{SM} as outlined in the Society of Automotive Engineers (SAE) J2735 Dedicated Short Range Communications (DSRC) Message Set Dictionary (SAE, 2009). All algorithms require vehicle speed, position, and heading. This data are required at most once per second. In the SAE J2735 standard, this data are transmitted from the vehicle at least every second, and sometimes as often as 10 times per second, as part of the Basic Safety Message. The following are the data elements required by all algorithms:

SAE J2735 Basic Safety Message Part I Data Elements

- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading

The VCA2 provides speed advisories for vehicle approaching an intersection to encourage platoon formation and discourage unnecessary accelerations and decelerations. While there is no direct data element in SAE J2735 for speed advisories, one can be developed by processing other data elements. The required data elements involve the Map Data (MAP) and Signal Phase and Timing (SPAT) messages.

MAP messages contain information about the intersection, and along with vehicle location information can determine a vehicle's approach movement. SPAT messages contain information about signal timing and phasing including a vehicle's current movement state (red, amber, or green) and the amount of time until the signal changes. By combining time until red and time until green based on a vehicle's approach with the vehicle's speed, trajectory, and distance from the intersection, the recommended speed for the vehicle can be quickly calculated. The required data elements are for speed advisory include, but may not be limited to:

SAE J2735 Map Data Message Data Elements
- DF_Intersection

SAE J2735 Signal Phasing and Timing Data Elements
- DF_MovementState
- DF_IntersectionState
- DE_SignalState
- DE_SignalLightState

SAE J2735 Basic Safety Message Part I Data Elements
- DE_TemporaryID
- DE_DSec
- DE_Latitude
- DE_Longitude
- DF_PositionalAccuracy
- DF_TransmissionAndSpeed
- DE_Heading

The SAE J2735 standard may be subject to further revisions, at which point a speed advisory data element may be added. Because it would only involve processing existing data rather than collecting entirely new data, adding the data element would not be difficult.

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Abu-Lebdeh, G., and Chen, H., Exploring the Potential Benefits of IntelliDrive^{SM}- Enabled Dynamic Speed Control in Signalized Networks, Paper: 10-3031, TRB Annual Meeting CD-ROM, 2010.

Chang, James. Market Penetration Analysis for VSC-A Safety Benefit Opportunities Estimation. Prepared for the Intelligent Transportation Systems Joint Program Office, Research and Innovative Technology Administration, and the National Highway Traffic Safety Administration. Contract DTFH61-05-D-00002. June 8, 2010.

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Task 5: Deployment Analysis of Traffic Signal Control Algorithms in an IntelliDrive[SM] Environment

OBJECTIVE AND SCOPE OF THE DOCUMENT

This task report investigates the potential implications of a large-scale real-world implementation of IntelliDrive[SM]-enabled at signal systems. The cost of transitioning from a detector-focused system to an IntelliDrive[SM]-focused system is discussed first. Then, each of the three algorithms (oversaturated conditions, vehicle clustering, and predictive microscopic simulation) is considered in separate sections, with a more general discussion of signalization issues included in the conclusion.

For background information on IntelliDrive[SM], traffic signal control, and each of the three algorithms, see the Task 2 report *Development of New Traffic Signal Control Strategies under IntelliDrive[SM]*, available at: http://cts.virginia.edu/PFS_SIG03_Task2.pdf.

COST-BENEFIT ANALYSIS

Most traffic signals along high volume arterials use actuated, traffic-responsive, or adaptive signal control strategies, where the traffic signal responds to vehicle volumes as reported by video or loop detection, and selects or changes the timing plan accordingly. Costs and performance can vary dramatically depending on the utilized equipment. In order to evaluate an IntelliDrive[SM] deployment using dedicated short-range communications (DSRC), its installation and maintenance costs must be compared to an alternative detection technology. The following sections estimate the costs of deployment for each type of detection (loop, video, and DSRC) and list several advantages and disadvantages for each. The costs are in 2008 US dollars, and are based on an a single eight-phase intersection, with a six-lane mainline and four-lane side streets, over a ten year horizon.

Loop Detection

Inductive-loop detection, referred to in this document as "loop detection," senses the presence of a conductive object, such as a vehicle, by inducing a current in the object (Klein et al.). Loop detectors have the disadvantage of being laid into cuts made in the pavement, which are then sealed. Although loop detectors provide reliable presence detection when working, maintenance and replacement of defective loop detectors is very difficult, and requires closing lanes and cutting the pavement. These cuts in the pavement allow moisture to penetrate the pavement, accelerating deterioration.

Loop Detection Costs

- Loop detector: $900 (20) = $18,000
- Installation and 10 year maintenance: $796 (20) = $15,920
- **Total: $33,920 per intersection (Klein et al.)**

Video Detection

Many signalized intersection use video processing to detect presence. A video camera views each approach to the intersection, and software interprets the changing colors or shades of pixilation in the image to detect the presence of vehicles in several predefined detection zones (Klein et al.). While video detection costs significantly less than loop detection, it has been shown to have significantly more false and missed detections (Rhodes et al.), and is subject to error due to adverse weather conditions (Medina et al.) and shadows (Chituri et al.).

Video Detection Costs

- Video detection: $6,400
- Installation and 10 year maintenance: $7,430
- **Total: $13,830 per intersection (Klein et al.)**

DSRC

In order to use a wireless communication system as described in the Task 1 report, and applying the system to the traffic signal control algorithms described in the Task 2 report, a signalized intersection would need a road-side unit (RSE) mounted on or near a mast arm to allow line-of-sight communications with approaching vehicles. The costs for on-board equipment (OBE) are not estimated, as the signal control algorithms are expected to be a value-added application that "listens" to existing safety messages, and controls traffic with the speed and location data within these messages.

Unlike loop or video detection, DSRC has the added benefit of being able to collect individual vehicle system data, such as brake pressure and acceleration rates. These data can then be used to create the advanced performance measures introduced in the Task 3 report, such as sudden decelerations and aggregate regulation compliance.

Although the IntelliDrive^{SM}-enabled traffic signal control algorithms would not require loop or video detection when IntelliDrive^{SM} market penetration is high, they will all benefit from additional detection sources when market penetration is low, particularly in late-night, low-volume scenarios.

DSRC Costs

- Basic RSE Unit: $1,000
- RSE Incidentals: $1,000
- Signal "Sniffer" (detects signals from OBEs): $2,000
- Labor: $2,400
- Installation Rental Equipment: $3600
- 10-year maintenance: $4,000
- **Total: $14,000 per signalized intersection (Volpe, 2008).**

Traffic Control Algorithm Benefits

Each of the three traffic signal control algorithms presented in the Tasks 2 and 4 reports showed significant improvements in delay with as few as 25% of vehicles participating. The benefits of these algorithms are described in terms of travel time savings, using a conservative time-value of money of $11.20 per hour (2008 dollars) from the Office of the Secretary of Transportation

(Frankel, 2003). Over the 10-year horizon, volumes are expected to increase 1.65% annually, and a discount rate of 7% is used. Both figures are consistent with a previous VII cost benefit analysis (Volpe, 2008).

The travel time savings from the predictive microscopic simulation and vehicle clustering were measured based on expected afternoon traffic volumes from 3:00 PM to 4:00 PM. The travel time savings are assumed to be experienced for eight hours each day, Monday to Friday, allowing four hours during morning and evening peak periods. Assuming the savings are experienced for 50 weeks per year, then the algorithms will yield travel time savings during 2000 hours of operation each year. This is a conservative estimate, as these algorithms will likely generated substantial travel time savings during off-peak periods, especially with high market penetrations.

The oversaturated conditions algorithm is expected to be used only during periods of extreme oversaturation. An intersection is assumed to experience oversaturation for 50 hours per year, at an average of approximately 1 hour per week.

The total benefits over a 10-year horizon are shown in for each of the three algorithms at various market penetrations are shown in Table 16.

Table 16: IntelliDrive[SM] Traffic Signal Control Algorithm Benefits

Traffic Signal Control Algorithm	Market Penetration (%)	Hours of Operation Per Year	Time Saved Per Hour of Operation (h)	Value of Time ($/hour)	One-Year Benefits	10-year Benefits
Oversaturated	25	50	1.6	$11.20	$899	**$6,743**
	50	50	2.0	$11.20	$1,124	**$8,428**
	75	50	2.7	$11.20	$1,498	**$11,238**
	100	50	3.7	$11.20	$2,098	**$15,733**
Vehicle Clustering	25	2000	NA	$11.20	NA	**NA**
	50	2000	5.6	$11.20	$125,440	**$940,831**
	75	2000	8.4	$11.20	$188,160	**$1,411,246**
	100	2000	9.8	$11.20	$219,520	**$1,646,454**
Predictive Microscopic	25	2000	0.3	$11.20	$5,716	**$42,875**
	50	2000	9.7	$11.20	$217,719	**$1,632,946**
	75	2000	13.3	$11.20	$296,899	**$2,226,812**
	100	2000	10.9	$11.20	$243,578	**$1,826,891**

Benefit-Cost Ratio

As was previously shown, an intersection using loop detectors requires $33,930 in construction and maintenance costs over ten years, and an intersection using video detection requires $13,830 over ten years. Installing and maintaining DSRC would cost $14,000 per intersection. In estimating the total deployment costs, the oversaturated algorithm was evaluated using two intersections, and the vehicle clustering and predictive microscopic algorithms using four intersections.

These additional costs and benefits were included in the final benefit-cost values provided in Table 17. Depending on the algorithm chosen, the market penetration, and the detection method being replaced, the B/C ratio over ten years may range from 1.1 to 42.2. The 2008 VII benefit-cost analysis found a ratio of 1.6, however this estimate included the cost of outfitting vehicles with OBEs.

Table 17: Benefit-Cost Ratios for IntelliDrive^{SM} Signal Control Algorithms

Traffic Signal Control Algorithm	Market Penetration (%)	Benefit/Cost Ratio	
		Previous Detection System	
		Loop	Video
Oversaturated	25	**2.5**	**1.1**
	50	**2.6**	**1.1**
	75	**2.6**	**1.2**
	100	**2.7**	**1.3**
Vehicle Clustering	25	**NA**	**NA**
	50	**19.2**	**17.8**
	75	**27.6**	**26.2**
	100	**31.8**	**30.4**
Predictive Microscopic	25	**3.2**	**1.8**
	50	**31.6**	**30.1**
	75	**42.2**	**40.8**
	100	**35.0**	**33.6**

In the following sections, each of the three traffic signal control algorithms described in the Task 2 and 4 reports are discussed. Each algorithm is described individually, along with its benefits, constraints, deployment risks, and additional cost considerations.

OVERSATURATED CONDITIONS

The oversaturated conditions algorithm was developed to showcase the unique capabilities of a signal using data available with IntelliDrive^{SM}. With precise vehicle locations and speeds, the signal control scheme can recognize queues and intersection blockages instantly, and enact strategies to minimize queues and eliminate blockages.

Benefits

The algorithm has two major benefits. First, it is an add-on module that works on top of the controller's existing timing plan. A malfunction in the add-on module will at worst have no effect on the previously developed signal timings, leaving the signal to operate at its natural efficiency. Second, because the algorithm's goal is to limit zero-flow green times, all road users accumulate benefits such as increased safety and improved traffic flow when the algorithm is activated.

Constraints

The oversaturated conditions algorithm also has several constraints. In order to provide the intended benefits, microscopic simulations indicated a minimum IntelliDrive^{SM} market penetration of 20% of vehicles was required, with benefits increasing with higher market penetrations.

In order to better understand the behavior of the algorithm, it was tested only at vehicle-only intersections with one-way streets and no turning movements. Real world multi-directional streets and multi-phase intersections would undoubtedly complicate the algorithm. The presence of pedestrians, trucks, bus stops, and parking would also need to be considered in refining the algorithm. Some potential refinements include the following:

- **For bi-directional movements,** if one direction is oversaturated and the minimum green time for the opposite direction is not yet met, the oversaturated direction may be stopped, while the opposite direction is allowed to continue to use the intersection. This is not a typical method of signal control.
- **For pedestrian movements**, if the minimum time is not yet satisfied, the vehicular traffic alone may be stopped, to avoid further aggravating the intersection blockage problem.
- **For turning movements,** there are several possible solutions. Fair allocation of green times to the right turns and left turns may not be always possible, if protected left-turns do not exist. Further, lane blockages may occur due to overflowing queue from a turn lane. In such situations, significant fine tuning of the times may be ideal, but not possible. In all such situations, the progression of through lane traffic is recommended to be the primary objective.
- **For trucks, bus stops, and parking,** the effects of these elements were not studied in this project, and are not expected to pose major constraints in the field.

Further study is required to determine what if any benefits the algorithm could provide more complicated networks.

Deployment Risks

The main risk of implementing this algorithm is not getting any benefits, i.e., the add-on module will never come into functional status. However, oversaturation conditions can be expected at any intersection, owing to road closures for maintenance, or due to incidents or special events. Excess traffic demand due to special events will also cause oversaturation.

No additional dis-benefits are expected due to this algorithm.

Additional Cost Considerations

As an add-on module, with additive benefits, the oversaturation algorithm does not present a fixed benefit. The actual benefits observed in the field depend on individual circumstances. The main qualitative benefit is reduced intersection blockages, thereby providing improved traffic flow and safety, and reduced driver frustration.

The direct costs to the agency are firmware development and maintenance, which are expected to be negligible, in comparison to the development and maintenance costs of the entire controller hardware and firmware.

VEHICLE CLUSTERING

The vehicle clustering algorithm uses the same principals as an actuated signal controller, but uses the data available with IntelliDrive^{SM} to make sophisticated next-phase decisions. The algorithm uses clustering to find a suitable gap in approaching vehicles for each phase's green end.

Benefits

The vehicle clustering has several advantages over traditional signal control. The algorithm has been developed to obviate the need for traditional detector installation and maintenance. The algorithm was written to be completely decentralized, therefore eliminating the need for communications equipment to link several controllers. This also eliminates the occasional communications failures that affect signal operations. The algorithm also seamlessly reacts to changes in vehicle volumes, without the need for time-of-day timing plan changes.

Constraints

The algorithm has several issues that may discourage implementation in certain cases. First, to maintain simplicity in model development, no pedestrian movements were included in the algorithm. Additional development and testing would be required to allow pedestrian movements.

Based on tests of the algorithm on the Route 50 network in Chantilly, Virginia, it requires approximately 50% IntelliDrive^{SM} market penetration to begin to see benefits over an actuated-coordinated timing plan. However, this percentage is likely a function of the volumes at the intersection. Below a certain market penetration, there is no longer a representative sample of vehicles represented at each approach, and benefits sharply decrease. It is possible that at low volumes, much higher market penetration may be needed to experience benefits.

Deployment Risks

The greatest risk for deployment is low market penetration rates. Without incorporating detectors, the algorithm runs of the risk of poor behavior due to vehicles that are never detected. It is likely that the algorithm could be refined for near-term deployment by incorporating more traditional coordinated-actuated control, and using IntelliDrive^{SM} data to complement signal control. Also, the controller could continuously measure the number of vehicles with communications equipment and the number of vehicles measured by detectors; when a high percentage of equipped vehicles are detected, the controller could activate the vehicle clustering algorithm.

Another risk of near-term deployment is the speed advisory component, where vehicles are told the appropriate speed to remain in the green band. The safety ramifications of providing speed advisories to some vehicles and not others is not well understood, and requires further study before it can be implemented.

Additional Cost Considerations

specific costs of a field implementation are discussed in the conclusions. This algorithm would require updates to the existing controller software, which if deployed on a large scale, would be a negligible cost compared to the entire IntelliDrive^{SM} investment of in-vehicle and roadside equipment.

PREDICTIVE MICROSCOPIC SIMULATION

The predictive microscopic simulation algorithm collects the speeds and positions of all equipped vehicles near a traffic signal, and uses microscopic simulation to predict the delays of all vehicles over the next fifteen seconds. The fifteen second simulation is repeated for all potential phases. The phase with the lowest cumulative vehicle delay is given the next green. This process is also known as rolling horizon.

Benefits

The algorithm has several benefits. First is the reduction in delay and stopped delay along the corridor. Also, the algorithm does not require any input volumes other than approximate turning ratios. Therefore, the algorithm self-corrects at different volumes throughout the day. With a high enough IntelliDrive^{SM} market penetration, the algorithm could eliminate the need for turning movement counts, as the controller simply considers the immediate conditions.

The algorithm also has the benefit of, at high market penetrations, to virtually eliminate delay during low volume late-night and weekend conditions. Because the algorithm *predicts* vehicle delay, it can anticipate vehicle arrivals and provide green phases, assuming there are no conflicting vehicles.

The algorithm can potentially accommodate transit and emergency vehicles seamlessly, by weighting each vehicle's measured delay by an appropriate factor. For example, a transit vehicle could be treated like five passenger vehicles, and an emergency vehicle like 1,000. This would allow preemption and priority, with only a minor (less than 20 second) disruption to coordination.

The predictive microscopic simulation algorithm, although it relies on delay as its objective function, can be quickly altered to try and minimize any performance measure or combination of performance measures chosen. By altering the objective function, the traffic engineer may quickly alter the signal's behavior to produce the desired level-of-service. However, more testing is needed to fully understand how changes to the objective function impact behavior.

Finally, because it relies solely on DSRC communications, the algorithm would eliminate the need for detectors, at a substantial cost savings.

Constraints

Pedestrians were not included in the simulation or the algorithm. The Route 50 model used in testing, although it had very low pedestrian volumes, required over 60 seconds for some pedestrian phases. The time required for pedestrian phases was well beyond the 15 second horizon used by the algorithm, and predictably the algorithm made poor decisions when trying to accommodate pedestrians. However, if the algorithm were applied to a small intersection with short pedestrian crossing times, the short phases produced by the algorithm would most likely improve pedestrian delay substantially. Until the algorithm can be refined and tested, it cannot be recommended for large intersections with pedestrian crossings.

Communications latency, dropped messages, and incorrect vehicle position and speed measurements, although possible in a real world deployment, were not tested. These would need to be considered to determine their effect on signal behavior.

Deployment Risks

The predictive microscopic simulation algorithm uses a non-cyclic timing plan, meaning that the signal does not serve each phase in a specific order, but may skip phases as needed. In this algorithm, a vehicle may be waiting and see another phase served two or three times before his/her own phase is served. It is unclear how drivers will react to this behavior in the early stages of implementation, but driver's may assume that they have been "skipped" and that their vehicle has not been recognized by the controller, and may attempt to enter the intersection illegally. To avoid this, a 120 second maximum red time has been built into the control strategy. However, more testing is encouraged to ensure that this is an appropriate maximum red time to ensure safe driver behavior.

The algorithm as it stands requires a fairly high IntelliDrive^{SM} market penetration. On the Route 50 model tested, 25% market penetration was needed to match the performance of a coordinated-actuated system. At lower market penetrations, or on a low-volume network, there is considerable risk of worse performance. The algorithm could possibly be altered to include detector data, either at the signal or upstream, to help validate the wireless communications data. Most rolling horizon schemes use detector data, so the incorporation of detector data should serve to compliment the IntelliDrive^{SM} data. If the signal controller determines that there are too few connected vehicles, it may switch to a more traditional adaptive system.

Additional Cost Considerations

The costs are mostly in the deployment of new controller software than can perform the microscopic simulation quickly enough. Although there are only a few thousand calculations required per second, the microscopic simulation tool used in this study collected performed a lot of unnecessary tasks and took much more time than needed. A customized software solution would be needed.

CONCLUSIONS

This task report considered the implications of a real-world deployment of IntelliDrive^{SM}-enabled traffic signal control. The cost of deployment is substantially less expensive than a similar adaptive traffic signal control strategy using loop detectors, and slightly more expensive than adaptive traffic signal control using video detection. However, DSRC has the advantage of high-reliability communication in inclement weather, whereas video detection has been shown to miss vehicles in the presence of adverse weather or shadows. By installing RSEs at signalized intersections, the traffic management agency gains the additional benefit of the collection more detailed measures-of-effectiveness, as explained in the Task 3 report on arterial MOEs.

In terms of communications costs, the algorithms presented in this task report are expected to piggy-back onto the vehicle-to-vehicle DSRC safety applications. Therefore, the applications would not require any dedicated communications equipment be installed in vehicles specifically for signal timing. Instead, the signal controller would "listen" to other ***Here I Am*** messages.

Although each algorithm comes with its own restrictions and limitations, the study was able to show substantial potential provided certain conditions are met, most notably adequate market penetration. The algorithms are all still relatively new, and will require more extensive testing and refinement before a large-scale deployment is feasible.

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