Effects of traffic density on communication requirements for cooperative intersection collision avoidance systems (CICAS)

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ABSTRACT

Cooperative Intersection Collision Avoidance Systems (CICAS) are likely to be among the first and most quality-of-service-critical users of wireless DSRC communications. Vehicle and infrastructure systems need to exchange data about the state of the intersection with high reliability and low latency. This paper estimates the number of vehicles that would need to share the DSRC safety communication channel at an intersection under worst-case conditions in rural, suburban and urban environments, to provide a starting point for defining the capacity that wireless channel needs to provide in order to support CICAS services.

KEYWORDS

Intersection collision avoidance, vehicle-infrastructure cooperation, wireless communications

INTRODUCTION

Intersection collisions are difficult to mitigate or eliminate by use of ITS technologies for a variety of reasons. These include the complexity of the driving environment and of the driver decision making process at intersections, but also the difficulty of accurately detecting the movements of all potentially conflicting vehicles. Prior research by Calspan-Veridian Engineering (now part of General Dynamics) (1) showed the near impossibility of detecting the relevant information using vehicle-mounted sensor systems. Current research under the IDS program is revealing the challenges associated with detection using infrastructure-based sensor systems (2,3).

As our understanding of intersection crashes and the performance needs of intersection collision avoidance systems have been improving, so has the interest in cooperative system implementations. In these Cooperative Intersection Collision Avoidance Systems (CICAS), information detected by both vehicle- based and infrastructure-based sensors can be combined to produce better real-time knowledge of the dynamic “state map” of an intersection. Wireless DSRC communication between the vehicles and the infrastructure and among the vehicles makes it possible for each entity (every vehicle, as well as the intersection’s traffic controller) to have complete intersection state map information, so that it can then use its own intelligence and threat assessment logic to determine whether to alert a driver to an impending hazardous condition.

DYNAMIC STATE MAP INFORMATION

The dynamic state map information can be subdivided into three broad categories:

(a) State of the traffic signal system (obviously, only relevant for signalized intersections): the current traffic signal phase (red, green, amber) and the time remaining until the change to the next phase. This becomes complicated when considering the complexity of phases for a large intersection, which may include left and right turn phases, which could occur before, after, or simultaneously with the through phases, and these phases could be pre-scheduled, actuated or semi-actuated.

(b) State of all vehicles approaching the intersection within a relevant distance and/or time: primarily the location, orientation and speed of each vehicle, but it would also be useful to know its acceleration and several other key parameters if possible.

(c) Local environmental conditions (weather, visibility, pavement surface condition): Although this changes much more slowly than the previous two categories, it is still time-varying and has an influence on intersection safety. This includes data such as:

- Ambient lighting conditions (bright sun, cloudy, dawn/dusk, night, low sun angle,…)
- Visibility (clear, foggy, dusty)
- Precipitation (rain, snow, sleet, hail, etc. and how hard)
- Pavement surface condition (above, below or at freezing temperature, dry, wet, standing water, snow, slush, ice, etc.).

Each vehicle collects data from its onboard sensors and the intersection collects data from its infrastructure-based detectors. Each vehicle broadcasts its sensor data so that it can be picked up by the intersection, as well as by the other vehicles. The intersection broadcasts its infrastructure-based detector data, as well as the data that it receives from all N vehicles in its vicinity. This makes it possible for each vehicle to receive information from every other vehicle, even when they are not within line of sight of each other (blocked by buildings near intersection), since all approaching vehicles are within line of sight of the center of the intersection.

GENERAL ARCHITECTURE FOR INTERSECTION INFORMATION SHARING

In most cases, it is relatively straightforward to identify whether a particular kind of information is more readily detected by vehicle-based or infrastructure-based sensor systems. In some cases, it is beneficial to combine both infrastructure-based and vehicle-based data in order for each to be able to compensate for errors in the other, and to enhance confidence in the measurements.

The general architecture for information sharing at the intersection is expected to be as shown in Figure 1. This architecture is sufficiently general that it can accommodate a wide range of driver alert strategies, for a full range of intersection conflict scenarios, and with threat assessments computed and displayed to drivers by the intersection, the vehicle, or both.

In this figure, the solid arrows generally represent wireline communications, while the open arrows are wireless, and the width of the arrows connotes the volume of information exchanged. As Figure 1 shows, each vehicle collects data from its onboard sensors and the intersection collects data from its infrastructure-based detectors. Each vehicle broadcasts its sensor data so that it can be picked up by the intersection, as well as by the other vehicles. The intersection broadcasts its infrastructure-based detector data, as well as the data that it receives from all N vehicles. This makes it possible for each vehicle to receive information from every other vehicle, even when they are not within line of sight of each other (blocked by buildings near intersection), since all approaching vehicles are within line of sight of the center of the intersection.

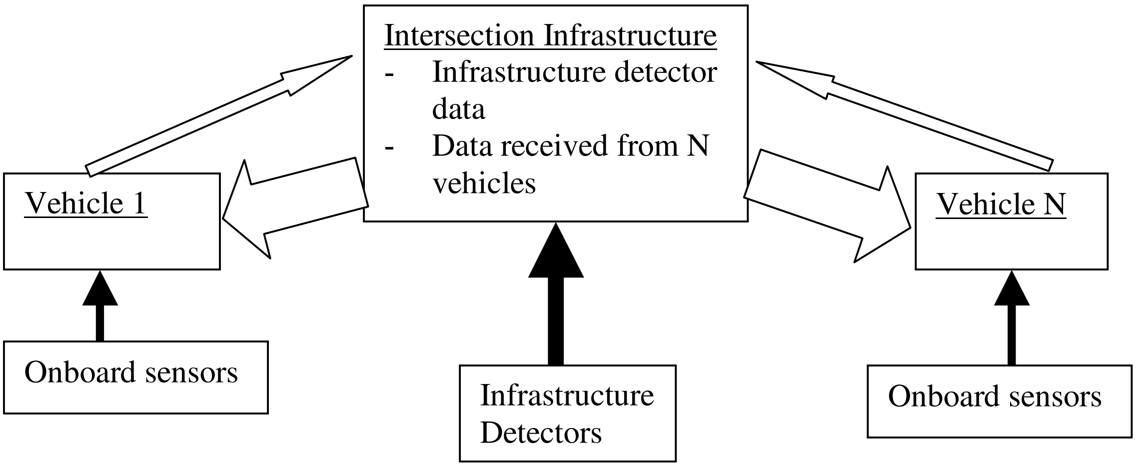

Figure 1: Intersection Information Sharing Architecture

The message sets and needed message update rates are not completely defined yet, although work is progressing on that front. The important factor that needs to be noted here is that the dominant burden on the wireless safety channel is imposed by the vehicles' broadcasts, not by the intersection's broadcasts. This is because each message packet has a significant overhead associated with it, several times larger than the vehicle message payload. For example, the message packet currently under discussion within SAE for vehicle-vehicle communications contains 42 bytes of data. The minimum overhead imposed on this packet by a DSRC-like wireless protocol is likely to be at least 70 bytes, however if serious security protections are incorporated as well, this overhead could be more than doubled. This means that the overhead could be from two to four times larger than the payload. By contrast, the intersection broadcasts its combined data packet once, with one overhead burden. This means that if the combination of the category (a) and (c) dynamic state map data described in the previous section (signal state and environmental conditions) is comparable in size to one vehicle's dynamic state data, which is on the conservative side, the total intersection broadcast data payload is N+1 vehicle payloads, but it only has one overhead burden, while the N vehicle broadcasts have N overhead burdens. The vehicle broadcasts are therefore likely to take almost three times as long as the intersection broadcasts if the overhead per packet is only 70 bytes, but could take as much as five times as long if the overhead per packet is in the range of 160 bytes.

INTERSECTION TRAFFIC SCENARIOS

In order to quantify the communication burden that CICAS could impose on the DSRC safety message channel, we must first estimate the number of vehicles that would be trying to use that channel for safety-critical messages in the vicinity of an intersection. The worst-case burdens on the channel are likely to occur under the heaviest traffic conditions, when we have the highest density of vehicles operating in the vicinity of the intersection. It is not clear *a priori* which conditions will be most demanding, so it is necessary to work through a variety of scenarios representing both high and low speeds, in rural, suburban and urban settings, since these are likely to differ considerably from each other. In each case, we have tried to identify the worst combinations of size of intersection and severity of traffic conditions. Although these conditions are expected to occur very rarely, it is still important to provide some assurances that the DSRC communication channel will not be overwhelmed when they do occur.

High-speed rural signalized intersection

Many rural intersections have such low traffic volumes that they do not warrant signalization, but at the intersections between major, heavily traveled, rural roads (which sometimes occur in or near small towns) it is necessary to have traffic signals. In this kind of environment, the speed limits tend to be high (90 km/h) but the roads are generally no wider than two lanes in each direction. If their traffic volumes were high enough to warrant more lanes, they would probably have been converted to limited-access highways, without signalized intersections.

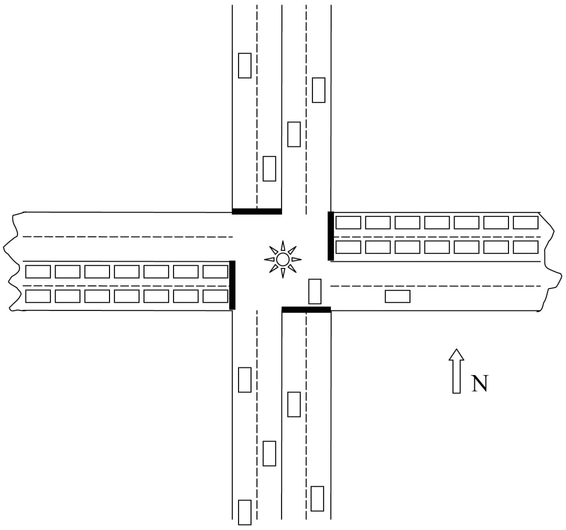

Figure 2: Worst-Case Rural Intersection Scenario (close-up)

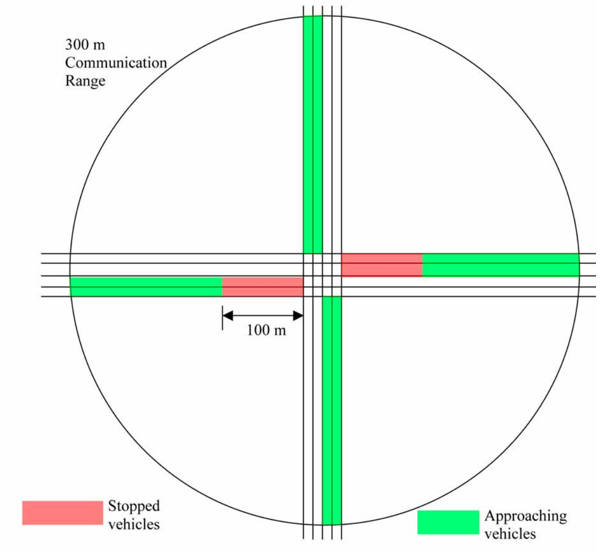

Figure 3: Worst-Case Rural Intersection Scenario (long range)

Schematics of the worst-case rural intersection are shown in Figures 2 and 3. In this scenario, the signal is assumed to be late in the red phase for the East-West traffic, with a long queue buildup, and flowing at maximum speed and volume in the North-South direction. The parameters that have been assumed for the analysis are:

- Widely separated from other intersections, so there is no overlap of communication ranges;
- Departing vehicles are not approaching the next intersection, so they don’t need to broadcast;
- Each crossing road has 2 lanes per direction;
- Maximum approach speed is 30 m/s;
- Stopped direction queues up to 15 vehicles/lane, at 6 m per vehicle, occupying 90 m (twice as long as shown in Figure 2);
- Average free-flow traffic in green (N-S) direction at 22.4 m/s (50 mph), headway of 1.8 s at maximum flow rate (an average of one vehicle for every 40 m of lane);

- 300 m maximum communication range for vehicle communications, permitting communication for 10 s approach time at maximum approach speed.

The number of vehicles sharing the channel is estimated as follows:

- Stopped vehicles:
  - 15 per E-W lane x 4 lanes = 60 (all in first 100 m from intersection)
- Approaching vehicles:
  - Behind stopped vehicles in red (E-W) direction: 5 vehicles per lane (at 40 m average separation) x 4 lanes = 20 (in last 200 m)
  - In green (N-S) direction: 7.5 vehicles average per lane (at 40 m average separation) x 4 lanes = 30 (in 300 m range)
- Total vehicle numbers:
  - 50 approaching
  - 60 stopped.

Suburban intersection at crossing of two major high-speed arterials

Many of the largest and most heavily trafficked intersections are in fast-growing suburban areas, where land was cheap enough at the time the roads were developed to make it possible to accommodate very wide streets (4 lanes in each direction plus turn lanes). With the growth in development, these can become heavily congested, with long queues building up on both the through lanes and the turn lanes. A worst-case example of such a suburban intersection is shown in Figure 4. Because of the number of vehicles involved, it is not practical to show individual vehicles here, but only zones of stopped and approaching vehicles.

The salient characteristics of this intersection are:

- 4 through lanes per direction on each road, plus turn pockets for 15 vehicles on each leg in the stopped (E-W) direction;
- Approaching traffic under free-flowing conditions at up to 25 m/s (55 mph) speed defines needed communication range;
- Each intersection is far enough from adjacent intersections that communication ranges do not overlap, so the full radius of 250 m is assumed here;
- Congested traffic flows at 11.2 m/s (25 mph) in green (N-S) direction (while queued in red direction), with average 2 s headway producing an average density of one vehicle for every 22.4 m of lane length.

The number of stopped and approaching vehicles is estimated as:

- Stopped vehicles:
  - Assume queued for entire range of 250 m, at 6 m per vehicle
  - 8 lanes in red direction, with 41.3 vehicles each = 330 vehicles
  - Queued in 4 turn lanes, 15 vehicles each = 60 vehicles

- Approaching vehicles:
  - Moving at 11.2 m/s, with 2 s headway, provides one vehicle every 22.4 m
  - Each lane in green direction has 12 vehicles in range x 8 lanes = 96 vehicles

- Total vehicle numbers:
    - 390 stopped
    - 96 approaching.

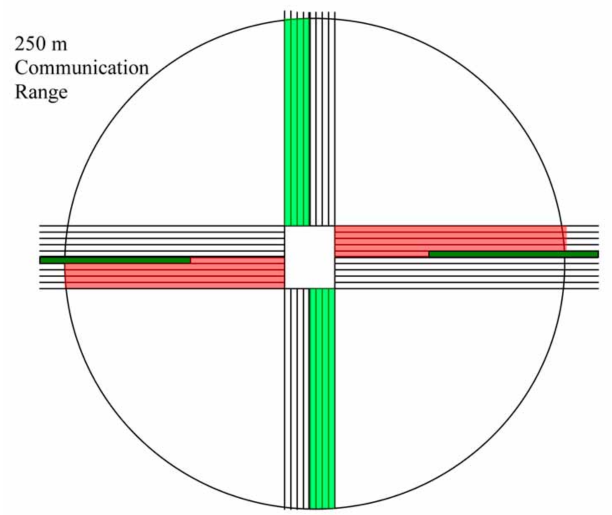

Figure 4: Worst-Case Suburban Intersection

High-density, gridlocked urban (downtown) intersection

The highest-density downtown applications pose a different set of challenges from the other applications. In this case, the signalized intersections are typically only one city block apart from each other, which means that as soon as a vehicle passes through one intersection it is beginning its approach to the next intersection. That, in turn, means that all of the vehicles are likely to have to broadcast their state information all the time, because they are always approaching one intersection or another. The speeds are likely to be lower than in the other applications, but the density of vehicles is also likely to be higher, and indeed could be gridlocked in all directions. This leads to a worst-case scenario in which all vehicles are packed close together but still need to broadcast when they are moving, as shown in Figure 5.

Specific assumptions for the analysis of this case include:

- Each street has 3 lanes per direction (total of 12 lanes approaching and 12 lanes departing intersection in all directions)
- Needed communication range of 150 m is comparable to signalized intersection separation, so each overlaps with neighbors.

The calculations of number of vehicles to accommodate proceed as follows:

- Stopped vehicles:
    - Average 6 m per vehicle in 150 m of lane yields 25 vehicles per lane
    - 12 lanes in red (N-S) direction (on both sides of intersection, pointing in both directions) → 300 vehicles
- Moving vehicles:

- With very slow, gridlocked traffic, assume same vehicle separation and density as for stopped vehicles
- 300 vehicles approaching and departing in green (E-W) direction
- Departing vehicles are approaching next intersection, and therefore need to be heard.

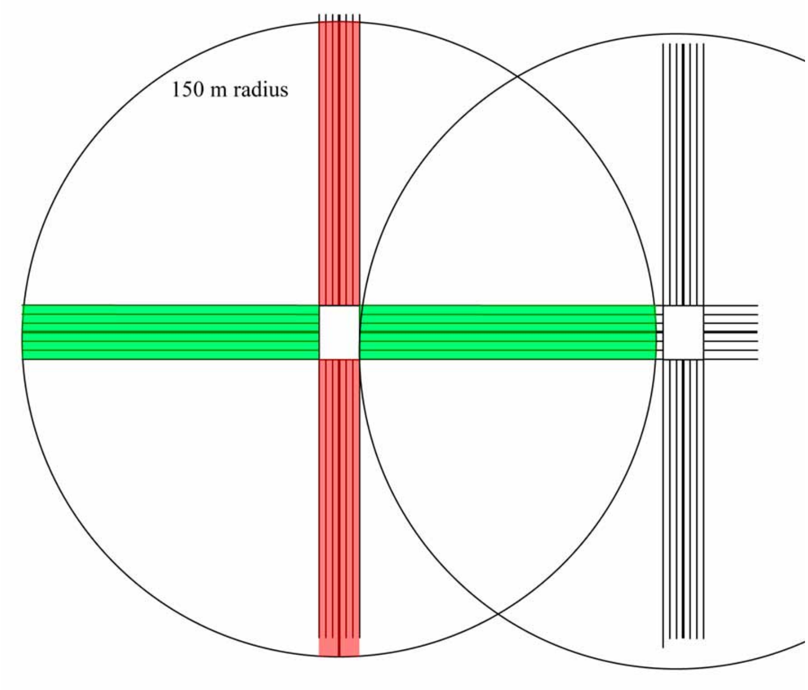

Figure 5: Urban Downtown Worst-case Scenario

SUMMARY OF VEHICLE BROADCAST DENSITY CALCULATIONS

The estimates of burden on the wireless communication channel depend on assumptions about the conditions under which vehicles will be broadcasting their state map information. In particular, if these transmissions are only from vehicles approaching the intersection, fewer vehicles will be broadcasting than if the vehicles departing the intersection and the stopped vehicles are also broadcasting. Table 1 summarizes the numbers of vehicles that would be broadcasting under a variety of assumptions about the conditions for enabling data broadcasts.

The results tabulated here show how much more demanding the urban and suburban scenarios are, as compared to the rural scenario. These indicate a maximum of as many as 600 vehicles if all vehicles are permitted to broadcast. Departing vehicles are not relevant to intersection safety considerations, except in the high-density urban scenario, in which they are approaching the next intersection and therefore probably need to continue broadcasting their data. The boldface numbers in Table 1 are considered to be the most relevant for purposes of defining the worst-case wireless channel capacity needs.

Table 1 – Summary of Numbers of Vehicles Sharing the Wireless Channel

Number of vehicles in range	Rural	Urban	Suburban
Including stopped and departing vehicles	N/A	**600**	582
Including stopped, NOT departing vehicles	**110**	300	**486**
Including half of stopped, NOT departing vehicles	80	450	291
Including approaching and departing vehicles only	80	300	192
Including only approaching, but NO stopped or departing, vehicles	50	150	96

CONCLUSIONS

The analysis presented here provides an initial indication of the demands that could be placed on a wireless channel that needs to support the most time-critical safety services that are likely to be based on use of DSRC. This needs to be coupled with an analysis of the capacity of the communication channel in order to assess the feasibility of implementation.

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