

## LETTER

# A Feasibility Study on Crash Avoidance at Four-Way Stop-Sign-Controlled Intersections Using Wireless Sensor Networks

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**SUMMARY** In this letter, we propose a novel approach using wireless sensor networks (WSNs) to enhance the safety and efficiency of four-way stop-sign-controlled (FWSC) intersections. The proposed algorithm provides right of way (RoW) and crash avoidance information by means of an intelligent WSN system. The system is composed of magnetic sensors, embedded in the center of a lane, with relay nodes and a base station placed on the side of the road. The experimental results show that the vehicle detection accuracy is over 99% and the sensor node battery life expectancy is over 3 years for traffic of 5,800 vehicles per day. For the traffic application we consider, a strong effect is observed as the projected conflict rate was reduced by 72% compared to an FWSC intersection operated with only driver perception.

**key words:** wireless sensor networks, four-way stop-sign-controlled intersection, crash avoidance, magnetic sensors

## 1. Introduction

For four-way stop-sign-controlled (FWSC) intersections, vehicles are required to stop before proceeding through the intersection. In these intersections, the right of way (RoW) is typically given to the vehicle that arrives first at the stop line, or if vehicles arrive simultaneously, to the vehicle on the right. In Korea, most FWSC intersections are based on driver perception without the use of control devices as traffic volume is generally lower at other intersections. However, crashes at FWSC intersections have been steadily increasing because of violators who do not stop at the stop line and confusion about RoW after multiple vehicles stop at an intersection [1].

As a means of enhancing the safety and efficiency of FWSC intersections, crash avoidance systems utilizing intelligent transport system (ITS) technologies can be employed. To this end, current intersection decision support (IDS) [2] and cooperative intersection collision avoidance (CICAS) [3] systems have focused on intersection traffic control configurations in the reduction of accidents. However, device implementation and maintenance costs are relatively high when these systems are deployed in a large number of FWSC intersections, as relatively high-cost sensors such as radar and inductive loops are used, and wires are

needed to either supply power to the sensors or for communication. In addition, INTERSAFE [4], based on vehicle-to-vehicle communication using wireless ad hoc networks, has limitations in that all vehicles must have compatible detection and communication devices. These limitations have led to considerable interest in developing a low-cost and highly reliable system that detects and prevents potential crashes in real-time.

One potential solution is to apply wireless sensor networks (WSNs) technology to ITS; a number of studies have recently been conducted [5], [6], though these works have mainly focused on vehicle detection, speed measurement, and vehicle classification using acoustic and magnetic sensors. Conversely, the proposed system targets more complex ITS applications such as traffic signal control and crash avoidance using WSN. In particular, this letter presents the feasibility of WSN technology for use in FWSC intersections. More specifically, a reliable low-cost system using WSN technology is presented, which provides RoW and crash avoidance information to vehicles to enhance the safety and efficiency of traffic flow at FWSC intersections.

The contribution of this letter can be summarized as follows. First, a novel crash avoidance scheme using WSN for FWSC intersections is presented, which includes the deployment of sensor nodes and a “Start-up Confidence” algorithm to verify the right of one vehicle to cross the intersection before the next vehicle can pass. Second, the feasibility of applying WSNs to ITS for long term use is presented, including a method for calculating battery life and life cycle cost.

## 2. Proposed Crash Avoidance Approach

The proposed crash avoidance approach consists of: 1) the deployment of sensor nodes, including the decision where sensor nodes need to be installed and the number of sensor nodes to be used; 2) how to provide a cautionary warning message; and 3) an algorithm called “Start-up Confidence” that decides RoW and informs drivers of potential accidents.

### 2.1 Deployment of the Sensor Network

Figure 1 illustrates an intersection where sensor nodes are installed in the center of each lane. From the figure, three sensor nodes,  $SN_{ij}$  for  $1 \leq i \leq 4$  and  $1 \leq j \leq 3$ , are required for each road  $i$ .

Sensor nodes  $SN_{i1}$  are used to detect vehicles ap-

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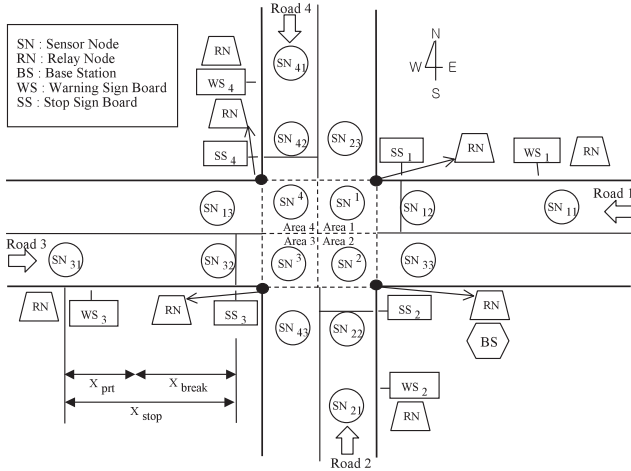


Fig. 1 Planned deployment of sensor nodes.

proaching the intersection and to provide a cautionary warning to drivers; nodes  $SN_{i2}$  are used to detect the existence of a vehicle, which is needed to compute the arrival time at the stop line and control RoW. Sensor nodes  $SN_{i3}$  are then used to confirm that the vehicle with RoW crossed the intersection. There are four additional sensor nodes  $SN^k$  for  $1 \leq k \leq 4$  to detect vehicles inside the intersection;  $SN_{i2}$  and  $SN_{i3}$  are deployed at the entrance and the exit of the intersection, and the position of  $SN_{i1}$  is decided as described in Sect. 2.2.

## 2.2 Cautionary Warning

To prevent crashes from occurring when one or more drivers do not stop at the stop line, a cautionary warning message needs to be sent to a warning board, which then asks the driver to stop or reduce vehicle speed before entering the intersection. To accomplish this task, we define the relations  $X_{STOP}$ ,  $X_{PTR}$ ,  $X_{BREAK}$ , and  $X_{SYSTEM}$  as

$$X_{STOP} = X_{PTR} + X_{BREAK} + X_{SYSTEM}, \quad X_{PTR} = V \times t_{PTR}$$

$$X_{BREAK} = \frac{V^2}{2(d + G \times g)}, \quad X_{SYSTEM} = V \times t_{SYSTEM} \quad (1)$$

where  $X_{PTR}$  denotes the driving distance during the driver's perception response time ( $t_{PTR}$ ) to a collision warning message,  $X_{BREAK}$  is the stopping distance after the driver applies the brake,  $X_{SYSTEM}$  is the driving distance during the delay caused by system processing ( $t_{SYSTEM}$ ),  $X_{STOP}$  is the distance required to stop the vehicle, and  $V$  denotes the speed of the vehicle [7]. Using Eq. (1), the position for deploying  $SN_{i1}$  for the cautionary warning service can be determined; for instance, if the speed limit on the road is  $V_{MAX}$ , sensor nodes must be deployed beyond  $X_{STOP}$  from the intersection to provide a cautionary warning message on time. Thus, the deployment position of  $SN_{i1}$ , i.e.,  $P_{SN_{i1}}$ , can be defined as

$$P_{SN_{i1}} \geq V_{MAX} \times t_{PTR} + X_{BREAK} + V_{MAX} \times t_{SYSTEM} \quad (2)$$

## BEGIN Start-up Confidence

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1. Generate MIN HEAP Q, each node has (road_id, vehicle_arrival_time)
2. Initialize Q. Set SSi to "STOP" for 1 ≤ i ≤ NumOfRoad
3. WHILE
4.   IF SNi2 == ON for 1 ≤ i ≤ NumOfRoad // vehicle detection
5.     Insert (i, vehicle_arrival_time) at Q
// Step 1
6.   sv_road_id = road_id of root node in Q
// Step 2
7.   IF any SNk == ON or all SNk3 == OFF for 1 ≤ k ≤ NumOfRoad
8.     SV waits at the stop line until (all SNk = OFF and any SNk3 = ON)
// Step 3
9.   IF SNm2 == OFF for 1 ≤ m ≤ NumOfRoad, m ≠ sv_road_id
10.    SV waits until any SNn3 == ON for 1 ≤ n ≤ NumOfRoad
// Step 4
11.  Set SSsv_road_id to "PASS", then SV goes through intersection
12.  IF SNsv_road_id 2 == OFF within a predefined time
13.    Delete root node from Q
14.  Set SSsv_road_id to "STOP"
15. END WHILE
END Start-up Confidence

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Fig. 2 Proposed "Start-up Confidence" algorithm.

where  $P_{SN_{i1}}$  denotes the minimum distance from  $SN_{i1}$  to the intersection to provide a cautionary warning.

## 2.3 "Start-Up Confidence" Algorithm

To prevent crashes from occurring when there is confusion about RoW after stopping at an FWSC intersection, we propose the "Start-up Confidence" algorithm shown in Fig. 2. This algorithm illustrates the operational and functional concepts for assigning RoW and preventing crashes using a series of magnetic sensor nodes, relay nodes, and a base station installed on the road. In this design MIN HEAP, a complete binary tree, was used to order vehicle detection events from the sensor nodes; the value of *vehicle\_arrival\_time* in each node in the heap structure is less than the values of its children nodes.

Let a vehicle with RoW be the Subject Vehicle (SV), and a vehicle stopping at the stop line until it is girded with RoW be the Principal Object Vehicle (POV). As a basic requirement of this system, we should prevent conflict by inspecting the movement of POV before SV starts; this procedure can be described as follows:

- Step 1:** Select SV among vehicles waiting at the intersection.
- Step 2:** Confirm that the previous SV has passed through the intersection.
- Step 3:** Verify if any vehicle without RoW is crossing.
- Step 4:** Allow the chosen SV to pass through the intersection and go back to Step 1.

## 3. System Description

The proposed WSN system is composed of three parts: sensor nodes, relay nodes, and a base station.

We developed a sensor node using a ZMY20M magnetic sensor, an MSP-430 microcontroller, an on-board 2.4 GHz CC2420 radio transceiver with data rate of 250 kbps, a Winizen chip antenna, and 4-cell lithium-ion

batteries that can supply 8,800 mAh at 3.6 V. Then, for vehicle detection the magnetic field in the vertical direction is sampled at a frequency of 200 Hz; the sensor node remains in low-power standby mode, and only wakes up when the magnetic signal crosses a given threshold [8].

Relay nodes are used to transmit data packets from a sensor node to the base station within one hop, as depicted in Fig. 1, since the communication range of sensor nodes buried under the ground is too short to directly communicate with the base station. When sensor nodes and relay nodes initialize their parent-child relationship, sensor nodes join the relay node nearest to them. In this design, if one relay node is broken down, affected sensor nodes (child nodes) can search for nearby relay candidates and join the relay node with the highest received signal strength indication (RSSI) among the candidates. Note that the relay nodes have the same H/W specifications as the sensor nodes, but no magnetic sensor; a relay node includes an external antenna, a radio frequency (RF) power amplifier, and a solar cell. Relay nodes are deployed at all corners of the intersection and in close proximity to the sensor nodes  $SN_{il}$ , as depicted in the figure.

The base station computes the state of the intersection in real-time. If an unsafe condition is detected by the threat assessment algorithms described in Sect. 2, the base station controls the movement of vehicles approaching the intersection and/or provides an appropriate warning message to drivers through the warning message board. The base station can be deployed at any corner of the intersection.

With regards to the communication protocol required for transferring the vehicle detection measurements, we adopt the IEEE 802.15.4 standard [9]. In the application of this protocol, time synchronization is an important factor since clock accuracy and precision is stricter than in other WSN applications. Thus, we also adopted the timing-sync protocol for sensor networks (TPSN) [10], which has a hierarchy of lower-level nodes and higher-level nodes, designed for multi-hop networks; a suitable fit for the hierarchy of our proposed system.

#### 4. Experimental Results

To test our system with real-world traffic data, an intersection located in downtown Daejeon, South Korea was selected. The intersection was a single lane FWSC intersection with a posted speed limit (60 km/h). The traffic volume per day, as characterized in Table 1, was categorized as 12 cases, which include: go straight, left turn, and right turn for eastbound (EB), westbound (WB), southbound (SB), and northbound (NB).

**Table 1** Experimental environment.

	NB	SB	EB	WB
Left turn	355	577	1715	104
Go straight	606	1168	680	577
Right turn	177	3135	444	163

#### 4.1 Vehicle Detection and Communication Delay

Table 2 presents the vehicle detection accuracy and time lag statistics of the devices. In the table, the vehicle detection rate compared to manual video counts is seen to be about 99 percent, with most of the undercount caused by motorcycles passing far from the sensor nodes. The average communication delay from sensor node to stop sign board is about 400 ms. The processing time of the sensor node ( $t_{SN}$ ), the delay between a sensor node and the base station ( $t_{SN-BS}$ ), the computation time of the base station ( $t_{BS}$ ), the transmission delay from the base station to warning sign board ( $t_{BS-WS}$ ), and the display time of the warning sign board ( $t_{WS}$ ) are further described in the table.

To calculate the position of  $SN_{il}$ , the values  $t_{PRT} = 1.5$  s, deceleration  $d = 3.0$  m/sec<sup>2</sup>, acceleration of gravity  $g = 9.8$  m/sec<sup>2</sup>, and the vertical slope of the intersection  $G = 0$  were used, respectively. Then, according to Table 2 and Eq. (2),  $P_{SN_{il}}$  was determined to be 80 m.

#### 4.2 Calculating Life Cycle Cost

We defined a model for estimating the battery life of a sensor node as Eq. (3). The current-consuming operations in the sensor nodes considered for each passing vehicle are: sensing with a magnetic sensor ( $C_S$ ), sampling with an analog to digital converter (ADC) in the microprocessor ( $C_{SP}$ ), signal processing ( $C_P$ ), transmission of arrival and departure packets ( $C_T$ ), and listening to the channel ( $C_{CH}$ ).

$$L = \frac{B}{(C_S + C_{SP} + C_P + C_T + C_{CH}) \times V} \quad (3)$$

where  $L$  denotes the battery life (days) of a sensor node,  $B$  is the battery capacity, and  $V$  is the number of vehicles passing the sensor per day. To ensure the accuracy of this simulation, we measured the current consumption profiles for each current-consuming operation performed at a sensor node. The profile for each operation was independently tested by tracking the CPU execution time in each power state, periodically broadcasting a message, and sampling and enabling or disabling the sensor.

In the experiment, we estimated the battery life-expectancy based on a sensor node  $SN^4$  that consumes more current than other sensor nodes (the traffic volume of the

**Table 2** Summary of system performance.

Measurement		Statistics	
Vehicle detection rate		99 % (94undercounts out of 9,700 vehicles)	
Time Delay (ms)		Mean	99 Percentile
	$t_{SN}$	18	25
	$t_{SN-BS}$	75	110
	$t_{BS}$	270	320
	$t_{BS-WS}$	40	60
	$t_{WS}$	10	15

**Table 3** Comparison of measurements.

Measure of Effectiveness (MOE)	Phase 1	Phase 2
MOE 1: Average speed reduction (km/h)	10.4	11.5
MOE 2: Number of projected conflicts	238	67
MOE 3: Average service time (s)	7.4	7.1

right-turn on SB is highest (3135), as shown in Table 1); the battery life expectancy of a sensor node was subsequently determined to be over 3 years at 5,800 vehicle detections per day. To calculate life cycle cost of the proposed system, an equation presented in [5] was used. According to the equation, the annualized life cycle cost of 16 sensor nodes buried on the road was \$2,866, cheaper than conventional loop detector systems.

#### 4.3 Measure of Effectiveness

Three measures of effectiveness (MOEs) were derived from the operational objectives of this study, addressing traffic flow and safety that this system intends to affect.

MOE 1 is the measure of speed reduction as a driver approaches an intersection in the presence of the cautionary warning described in Sect. 2.2. We designated MOE 2 as the number of projected conflicts in Area 1, Area 2, Area 3, and Area 4, as depicted in Fig. 1, because traffic accidents are relatively infrequent events. The number of accidents within an intersection is likely to increase when two or more vehicles are simultaneously located inside the intersection. Thus, the number of events when two or more vehicles were located within an intersection was counted to verify MOE 2 in our experiment. MOE 3 refers to the average service time required by the vehicle to cross the intersection, as a means of evaluating the traffic flow.

Table 3 presents the observed MOE 1–MOE 3 values for Phase 1 (FWSC intersection by driver perception), and Phase 2 (FWSC intersection operated by a WSN system). Data shown in each phase are based on a sample of potentially affected vehicles over 7 days, 6 PM–7 PM.

The strongest effect is shown in MOE 2. In Phase 2 the projected conflict rate was reduced by 72% compared to Phase 1. In the case of MOE 1 and MOE 3, Phase 2 was only slightly improved over Phase 1.

#### 5. Conclusion

In this letter, we presented a reliable and low-cost FWSC

system utilizing WSN technology to provide RoW notification and crash avoidance such that the safety and efficiency of FWSC intersections can be enhanced. More specifically, cautionary warnings and start-up confidence algorithms were presented to prevent crashes. We also specified how to deploy and operate battery-powered sensor and relay nodes and communicate via RF signals and a base station.

Our experimental results show that the proposed system can be effectively applied to prevent crashes at FWSC intersections. For future research, more exhaustive field experiments will be performed to monitor and control the traffic in more complex intersections.

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