

Article

An Adaptive ADAS Support Framework Based on Microwave Signal Conversion to Address Radar Perception Limitations

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Abstract

Advanced Driver Assistance Systems (ADAS) can exhibit perception limitations involving large or stationary vehicles, occluded downstream hazards, and the finite detection range of onboard radar. This study proposes a microwave signal conversion based support framework comprising a vehicle-mounted V2V–V2V system and a roadside I2I–I2V system. The algorithms convert and retransmit radar signals according to vehicle speed and spacing states or downstream congestion, while longitudinal responses were behaviorally represented in VISSIM-COM through conditional Desired Speed modification for equipped trucks and buses. A calibrated 12-km Seoul Tollgate corridor was evaluated using V2V–V2V market penetration rates of 0–100%, a binary I2I–I2V condition, and a combined full-deployment scenario. Run-level TTC and conflict frequency were summarized using means, standard deviations, and 95% confidence intervals, and both measures were compared using two-sided paired *t*-tests. Increasing V2V–V2V penetration was associated with higher TTC and fewer conflicts. Within the tollgate influence area, combined deployment increased mean TTC from 0.72 to 1.27 s and reduced mean conflict frequency from 1486 to 764; both paired comparisons were statistically significant ($p < 0.001$). These findings suggest potential surrogate-safety benefits from coordinating vehicle- and infrastructure-based recognition support and advance speed adjustment.

Keywords: Advanced Driver Assistance Systems (ADAS); Cooperative Intelligent Transportation Systems (C-ITS); microwave signal conversion; traffic safety; Vehicle-to-Vehicle communication



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1. Introduction

According to the World Health Organization (WHO), approximately 1.34 million road accidents occur globally each year, resulting in 1 million fatalities and 50 million injuries [1]. Human error constitutes a significant proportion of these traffic accidents that cause such severe casualties [2]. Consequently, various companies and research teams worldwide are striving to develop systems that address these causative factors. Among these solutions, Advanced Driver Assistance Systems (ADAS) and Intelligent Transportation Systems (ITS) have garnered attention as technologies that enhance traffic safety. ADAS technology contributes significantly to accident prevention and driving convenience by recognizing surrounding conditions and providing warnings to drivers or directly controlling vehicles [3].

Examples of ADAS include Forward Collision Warning (FCW), Autonomous Emergency Braking (AEB), Lane Keeping Assist (LKA), and Adaptive Cruise Control (ACC), all of which aim to substitute driver tasks and compensate for human errors [4]. Therefore, when ADAS is properly implemented and utilized, it offers substantial safety benefits by significantly reducing human errors, economic costs, and environmental impacts [5]. Previous studies on ADAS safety improvements have demonstrated that all ADAS features, including FCW, ACC, and AEB, show significant accident reduction effects [6–9]. Furthermore, ADAS corresponds to levels 1–2 of autonomous driving as defined by the Society of Automotive Engineers (SAE). Consequently, it represents a fundamental technology for future Autonomous Vehicles, possessing considerable research and practical value.

However, current ADAS still face several limitations, particularly those associated with sensor-based perception. ADAS-equipped vehicles use cameras, LiDAR, and radar to perceive their surroundings. Cameras primarily identify visual information, such as traffic signs, lane markings, and obstacles, whereas LiDAR estimates the three-dimensional position and distance of objects using reflected laser signals. Radar measures the distance and relative velocity of surrounding objects by analyzing reflected microwave signals based on the Doppler effect [10]. These sensors are used individually or through sensor-fusion architectures to improve the reliability of environmental perception.

Nevertheless, even sensor-fusion systems remain subject to physical perception-range limitations and object-recognition uncertainty. Their performance may vary depending on sensor configuration, operating mode, target characteristics, occlusion, roadway geometry, weather conditions, and manufacturer-specific perception processes. In particular, large commercial vehicles and stationary objects may be misdetected or tracked inconsistently because of their body structures, radar-reflection characteristics, and errors occurring during object detection, classification, and tracking [11–14]. Such limitations can delay the operation of FCW, ACC, or AEB, thereby reducing the time available for stable vehicle responses under high-speed driving conditions.

To mitigate these perception-related safety risks and improve subsequent vehicle responses, previous studies have generally followed three complementary directions: improving onboard perception and object-tracking performance, enhancing vehicle-control algorithms, and extending situational awareness through external information.

In the first direction, deep-learning, sensor-fusion, and state-estimation approaches have been proposed to improve object detection, classification, and tracking. Rawlley et al. [15] applied cross-domain modeling to enhance the robustness of object detection under dynamic driving environments. Feng et al. [16] reviewed deep multimodal object-detection and semantic-segmentation methods that combine information from multiple sensors to improve autonomous-driving perception. Chandrashekaraiah and Raju [17] proposed a modified Kalman-filter-based radar- and sensor-aware framework to improve multi-object tracking under low signal-to-noise ratios, nonlinear object motion, occlusion, and sensor uncertainty. Their study demonstrated the importance of incorporating sensor-noise characteristics and dynamic-state estimation into radar object-tracking processes. These approaches can improve the robustness of onboard perception; however, their implementation generally requires modification, retraining, or additional processing within vehicle perception systems and may remain dependent on training data, computing resources, sensor configurations, and noise-model assumptions.

In the second direction, vehicle-control studies have focused on improving how ADAS translates detected information into longitudinal and lateral vehicle responses. Prastiyanto et al. [18] developed an ACC model for curved roads by integrating longitudinal speed and following-distance control with lateral steering control. They applied an Archived Crow Search Algorithm to optimize the ACC and steering-control parameters, thereby improving

the stability of speed, following-distance, and steering responses. This study highlights that the safety performance of ADAS depends not only on the accuracy of object perception but also on the control algorithms that convert detected information into vehicle responses. However, these approaches generally require vehicle-specific controller design, parameter calibration, and integration with existing onboard control architectures.

In the third direction, V2X communication and cooperative-perception technologies have been investigated to extend situational awareness beyond the direct sensing range of individual vehicles. Thandavarayan et al. [19] evaluated cooperative perception in connected and automated vehicles and examined how communication congestion affects the exchange of locally detected object information. Their subsequent study [20] proposed a cooperative-perception-message-generation method that enables vehicles to share information on objects detected by onboard sensors. Yusuf et al. [21] reviewed V2X technologies integrating communication, sensing, and artificial intelligence and highlighted their potential to improve situational awareness and road-user safety. However, these approaches generally require compatible communication units, roadside or network infrastructure, and standardized message-exchange protocols.

In parallel with these perception-, control-, and communication-oriented approaches, various C-ITS traffic-management strategies have been proposed to provide advance information on downstream hazards and support proactive speed adjustment. Khazraeian et al. [22] evaluated a connected-vehicle-based queue-warning system that identified the back of a queue using vehicle data and delivered warning messages to approaching drivers. Their simulation and surrogate-safety analyses indicated that earlier queue detection and sufficient driver compliance could reduce rear-end conflicts. Strömberg and Lind [23] investigated a motorway traffic-management system combining variable-speed-limit-based speed harmonization, queue warning, and variable message signs. The system reduced speed variation and delayed traffic-flow breakdown, demonstrating the potential of upstream speed management before vehicles entered congested conditions. Raddaoui et al. [24] evaluated connected-vehicle-based weather and work-zone warnings using a driving simulator and found that the information promoted earlier driver responses and improved merging behavior, although multiple simultaneous warnings could also introduce driver-distraction concerns.

These studies demonstrate that existing approaches mitigate perception-related safety risks at different technical and operational levels. Deep-learning, sensor-fusion, and state-estimation methods aim to improve onboard perception and object-tracking processes, whereas vehicle-control studies focus on translating detected information into stable speed, following-distance, and steering responses. V2X and cooperative-perception technologies extend situational awareness by sharing externally detected information, while queue-warning, speed-harmonization, and work-zone warning systems adopt an operational approach by providing advance warnings or advisory speeds before vehicles encounter downstream hazards. However, each approach has practical constraints. Onboard perception enhancement generally requires modifications to vehicle sensors or algorithms, vehicle-control approaches require controller redesign and calibration, V2X-based systems depend on compatible communication equipment and standardized data exchange, and C-ITS warning strategies rely on roadside displays, onboard interfaces, or driver and vehicle compliance with advisory information. More importantly, most external warning and traffic-management strategies do not directly intervene in the perception input of existing radar-based ADAS. Consequently, a research gap remains for a support approach that can utilize the perception functions of existing ADAS, support an earlier longitudinal vehicle response, and provide advance hazard information without requiring the receiving vehicle

to replace its onboard sensors, modify its perception algorithms, or decode an additional V2X warning message.

Accordingly, this study proposes a speed-control-based support framework to address major ADAS limitations encountered in real-world highway environments, including recognition errors associated with large vehicles, failures to detect stationary vehicles in crash and congestion zones, and the limited perception range of onboard radar sensors. The proposed framework aims to support earlier responses to potential hazards and improve traffic safety by enabling proactive speed adjustment before vehicles encounter potential hazards. The proposed system operates by receiving microwave signals emitted by ADAS-equipped vehicles and converting them into modified radar responses corresponding to a slower-moving or decelerating lead vehicle before retransmission.

The device can be installed either on the rear of large commercial vehicles, such as buses and trucks, or along roadside infrastructure. Based on the surrounding traffic conditions, the system generates and retransmits converted radar responses that allow the receiving ADAS to interpret the presence of a slower-moving or decelerating lead vehicle and initiate an earlier longitudinal response. This mechanism encourages proactive speed reduction before reaching the actual hazard location, thereby mitigating sudden braking events and reducing potential rear-end collision risks caused by large-vehicle recognition errors, stationary-vehicle detection failures, and limited radar perception ranges.

To evaluate the potential surrogate safety effects of the proposed framework, microscopic traffic simulation was conducted under various traffic conditions. Furthermore, this study presents a cooperative vehicle–infrastructure support framework designed to utilize the existing radar-based ADAS functions of the receiving vehicle without requiring replacement of its onboard radar sensor, modification of its perception algorithms, or decoding of an additional V2X warning message. Therefore, the proposed approach provides a potential support pathway toward future Cooperative Intelligent Transportation Systems (C-ITS) and connected autonomous driving environments.

2. Methods

2.1. ADAS Support System Development

Practical limitations exist in approaches that attempt to upgrade ADAS performance for all commercial vehicles, deploy new V2X technologies across the entire vehicle fleet, or fundamentally improve object-recognition and decision-making algorithms. In particular, the large-scale implementation of new sensors and communication devices in vehicles already in operation would require substantial technical and economic investment. Therefore, this study proposes an ADAS support framework that integrates additional signal-conversion devices installed on selected vehicles or roadside infrastructure with existing radar-based ADAS functions while addressing limitations associated with perception range and object-recognition errors. The framework is designed to utilize the receiving vehicle's existing onboard radar sensor and perception algorithms without requiring modification of those algorithms.

The technical concept of the proposed framework was derived from a work-zone rear-end collision prevention device that had been validated through full-scale vehicle testing [25] (Figure 1). The device operates as an active microwave signal conversion and retransmission unit. When the forward radar signal emitted by an approaching ADAS-equipped vehicle reaches the device, the signal is received and frequency-converted to correspond to a predefined apparent target speed. The modified signal is then retransmitted toward the approaching vehicle. Consequently, the receiving ACC or AEB system interprets the stationary device as a slow-moving target and initiates an earlier longitudinal response. In the previous evaluation, the apparent target speed was set to 12 km/h to induce gradual

deceleration before the vehicle reached the stationary work-zone protection vehicle. The device was evaluated at the Korea Intelligent Automotive Parts Promotion Institute proving ground under 40 full-scale vehicle test scenarios. The scenarios combined four approach speeds of 80, 90, 100, and 110 km/h, five production vehicle models from three vehicle brands, and same-lane and adjacent-lane approaches. The evaluation considered the effective response distance, estimated collision speed, and unintended responses of ADAS-equipped vehicles traveling in the adjacent lane. The device received evaluation scores of 4.86 out of 5 for effective response distance, 4.70 for collision-speed reduction, and 5.00 for non-response of adjacent-lane vehicles. These findings provide initial empirical evidence that the microwave-signal-conversion mechanism can induce appropriate longitudinal responses across multiple commercially available vehicle models.

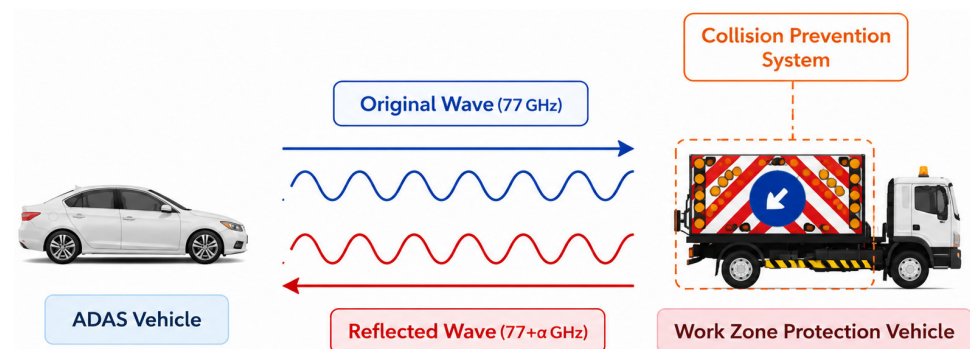


Figure 1. ADAS support system conceptual diagram.

Building on this experimentally evaluated mechanism, the present study extends the original work-zone application in two directions. The first is a vehicle-mounted system installed on the rear of large commercial vehicles, and the second is an infrastructure-based system connected to roadway traffic information. The ADAS support device, highlighted in blue in Figure 2, operates through different mechanisms depending on its installation location. The present study evaluates the potential surrogate safety effects of these extended applications under highway operating conditions. Figure 2 presents an overview of the proposed framework.

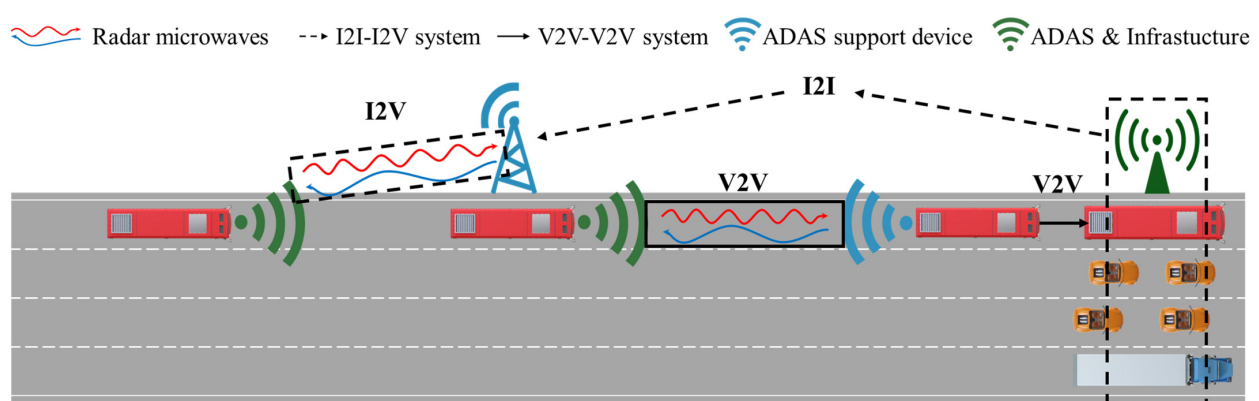


Figure 2. ADAS support system overview diagram.

When installed along roadside infrastructure, the device operates according to an Infrastructure-to-Infrastructure-Infrastructure-to-Vehicle (I2I-I2V) architecture. In this study, I2I-I2V denotes a sequential two-stage process: roadway monitoring infrastructure first transfers traffic-state information, including traffic speed, traffic volume, and congestion status, to the roadside device through I2I communication, after which the roadside device supports approaching ADAS-equipped vehicles through an I2V-based radar

signal-conversion and retransmission process. Based on the collected information, the system evaluates the current traffic condition and determines an advisory speed suitable for traffic-flow stabilization. When congestion is detected, the device receives radar microwave signals emitted by approaching ADAS-equipped vehicles and converts them into modified retransmission signals corresponding to the determined advisory speed. Through this process, the receiving ADAS interprets the presence of a slower-moving lead vehicle before reaching the actual congestion area. Consequently, vehicles perform gradual speed reductions in advance rather than entering the back of the queue at high speed, thereby reducing sudden braking events and mitigating rear-end collision risks associated with recurrent congestion.

When installed on the rear of large commercial vehicles, such as trucks and buses, the device operates according to a Vehicle-to-Vehicle–Vehicle-to-Vehicle (V2V–V2V) architecture. In this study, V2V–V2V denotes a two-stage vehicle-based signal process: the radar microwave signal emitted by a following ADAS-equipped vehicle is first received by the device mounted on the large vehicle, and the signal is then converted based on the driving state of the equipped vehicle and retransmitted to the following vehicle. In this configuration, the system continuously collects information regarding vehicle speed, acceleration or deceleration behavior, spacing to the lead vehicle, and relative speed from the equipped vehicle and its surrounding traffic environment. Based on these data, the system evaluates the current driving condition, identifies potential hazards, and determines an appropriate advisory speed for the following vehicle. If the large vehicle is approaching its lead vehicle or is expected to decelerate, the system retransmits modified microwave signals that allow the following ADAS-equipped vehicle to interpret the large vehicle as traveling at a lower speed than its actual speed. As a result, the following vehicle initiates speed reduction earlier and maintains safer longitudinal spacing. Furthermore, when the large vehicle is stationary, the system converts and retransmits the signal so that the receiving ADAS interprets the stationary vehicle as a slow-moving vehicle. This mechanism is intended to compensate for ADAS recognition failures associated with stationary and large vehicles, thereby improving hazard recognition and reducing potential collision risks.

By incorporating both the I2I–I2V and V2V–V2V concepts, the proposed system broadens its applicability across various traffic environments. The framework utilizes infrastructure- and vehicle-derived information to support existing radar-based ADAS functions and address perception limitations associated with detection range, large vehicles, and stationary vehicles. Consequently, the proposed system provides a cooperative vehicle–infrastructure support approach that integrates vehicle- and infrastructure-based information with existing ADAS functions. A key advantage of the framework is that the receiving vehicle can retain its onboard radar sensor and perception algorithms without requiring sensor replacement or algorithm modification.

2.2. ADAS Support System Algorithm

Figure 3 presents the operational logic of the proposed V2V–V2V and I2I–I2V support systems. This section describes the intended functional algorithm of the physical signal-conversion device. The behavioral representation adopted in VISSIM-COM, including the modification of the following vehicle's Desired Speed and the simulation-specific activation criteria, is described separately in Section 2.3. In the physical system, the signal-conversion device determines whether the received radar signal should be retransmitted without conversion or converted into a signal corresponding to a virtual lower-speed target. The receiving vehicle subsequently interprets the retransmitted signal and responds through its existing radar-based ADAS functions.

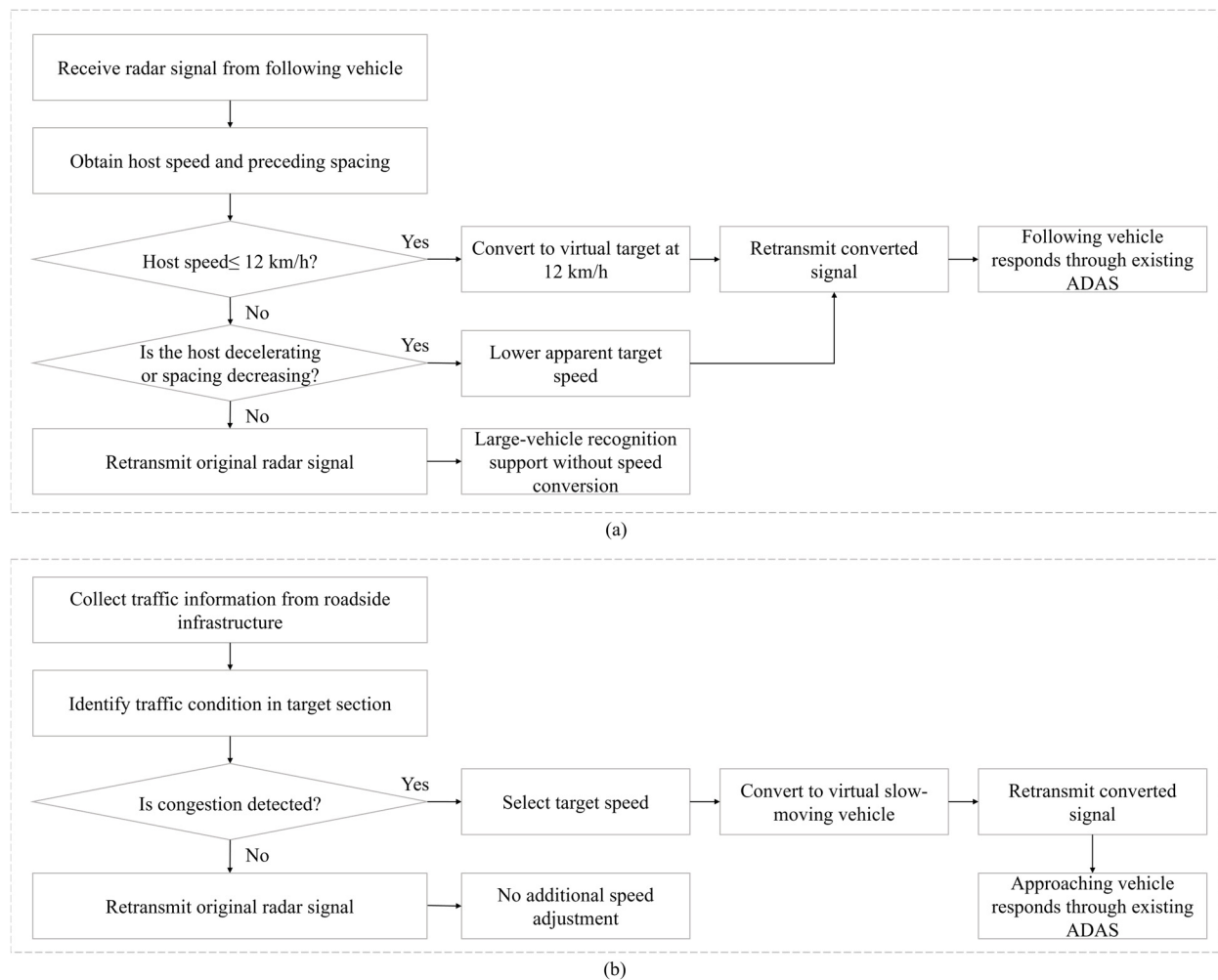


Figure 3. ADAS support system algorithm ((a) V2V–V2V system, (b) I2I–I2V system).

The V2V–V2V algorithm begins when the signal-conversion device mounted on a large commercial vehicle receives the radar signal emitted by a following ADAS-equipped vehicle. The device obtains the current speed of the equipped large vehicle and its spacing from the vehicle immediately ahead. Let $v_H(t)$ denote the speed of the device-equipped host vehicle at control-update time t , and let $d_H(t)$ denote its spacing from the preceding vehicle. The changes in speed and spacing are defined as follows:

$$\Delta v_H(t) = v_H(t) - v_H(t - \Delta t) \quad (1)$$

$$\Delta d_H(t) = d_H(t) - d_H(t - \Delta t) \quad (2)$$

The host vehicle is classified as decelerating when $\Delta v_H(t) < 0$ and as stationary when $v_H(t) = 0$. The spacing is classified as decreasing, maintained, or increasing when $\Delta d_H(t) < 0$, $\Delta d_H(t) = 0$, or $\Delta d_H(t) > 0$, respectively. These states are determined by directly comparing the current and immediately preceding observations. The device continuously updates the vehicle state and determines whether signal conversion is required; however, the specific update interval and numerical activation constraints used in the VISSIM-COM evaluation are described in Section 2.3. When the device-equipped large vehicle is moving and the spacing from its preceding vehicle is maintained or increasing, the interaction is classified as normal driving. In this case, the received radar signal is retransmitted without speed conversion, and the device primarily supports the recognition of the large vehicle by the following ADAS-equipped vehicle. When the host vehicle is

decelerating or its spacing from the preceding vehicle is decreasing, the algorithm determines that additional longitudinal adjustment may be required by the following vehicle. The received radar signal is then converted into a signal corresponding to a lower apparent target speed and retransmitted toward the following vehicle. The receiving ADAS consequently interprets the equipped large vehicle as traveling at a lower speed than its actual speed and may initiate an earlier longitudinal response. When the speed of the device-equipped vehicle is 12 km/h or lower, the received signal is converted into a signal corresponding to a virtual slow-moving target with an apparent speed of 12 km/h. This operating condition was adopted from the preceding full-scale evaluation of the work-zone rear-end collision prevention device [25]. It was intended to compensate for possible recognition failures involving stationary or very-low-speed large vehicles and to induce a longitudinal response from the following ADAS-equipped vehicle. When the host vehicle returns to a normal driving state or no relevant preceding vehicle is present, the conversion condition is released and the original radar signal is retransmitted. The objective of the signal-conversion process is not to bring the following vehicle to a complete stop solely through the proposed device. Instead, it is intended to improve the recognition of a large, stationary, or very-low-speed hazard and induce speed reduction before full emergency braking becomes necessary. In the preceding full-scale tests, the approaching vehicles did not necessarily stop completely but passed the test object at a reduced speed, thereby decreasing the potential collision speed [25]. In actual driving conditions, the driver may additionally intervene after an FCW or partial-braking response. However, such driver intervention was not considered in the present simulation evaluation.

The I2I–I2V algorithm begins with traffic-state monitoring through roadside infrastructure. The system continuously collects traffic information from upstream and downstream detectors, including traffic volume, average speed, and congestion status. Based on the collected information, the algorithm determines whether congestion is present within the target section. The detailed congestion criteria may vary according to the traffic-monitoring system and operational agency and are therefore not fixed as universal thresholds within the conceptual device algorithm. When congestion is not detected, the received radar signal is retransmitted without conversion, and no additional speed-adjustment response is induced by the signal-conversion system. When congestion is detected, the roadside device selects and retransmits a signal corresponding to an appropriate target speed to induce advance deceleration in approaching ADAS-equipped vehicles. The predefined target speed is intended to prevent vehicles from approaching the back of a queue at an excessive speed and to facilitate gradual speed adjustment before reaching the congested section. Accordingly, the receiving ADAS interprets the presence of a virtual slow-moving lead vehicle before directly detecting the actual queue and can initiate a longitudinal response in advance.

The target speed and the roadside-device location can be configured according to the posted speed limit, downstream operating conditions, available deceleration distance, and site-specific operational requirements. In the present study, the fixed target speed, installation location, and behavioral activation conditions used for the simulation represent one selected implementation of this general device concept. These simulation-specific assumptions are described in Section 2.3 and are not presented as universally optimal operating values.

The main distinction between the proposed framework and conventional standalone ADAS is that conventional ADAS initiates a response after directly detecting and classifying a physical target, whereas the proposed system modifies the radar input received by the existing ADAS based on vehicle- or infrastructure-derived information. The physical signal-conversion device therefore determines and retransmits the virtual target signal,

while the receiving vehicle's existing ADAS remains responsible for interpreting the signal and generating the subsequent longitudinal vehicle response.

2.3. Simulation Experiment and Validation

To evaluate the effectiveness of the proposed ADAS support system, microscopic traffic simulation was conducted using PTV VISSIM 2021 (PTV Planung Transport Verkehr GmbH, Karlsruhe, Germany). The study site consisted of a 12-km section of the Gyeongbu Expressway (Seoul-bound direction) between Singal Junction and Pangyo Junction (Figure 4). This section experiences recurrent congestion due to speed restrictions near the Seoul Tollgate and frequent lane-changing maneuvers associated with Hi-Pass access movements. Furthermore, among the four mainline lanes, Lane 1 operates as an exclusive bus lane, Lanes 2 and 3 are primarily used by passenger vehicles, and Lane 4 accommodates a relatively high proportion of freight traffic. Because the proposed system aims to mitigate large-vehicle recognition errors and congestion-related rear-end collision risks, this section was considered an appropriate study site due to its high commercial vehicle volume and recurring congestion patterns.

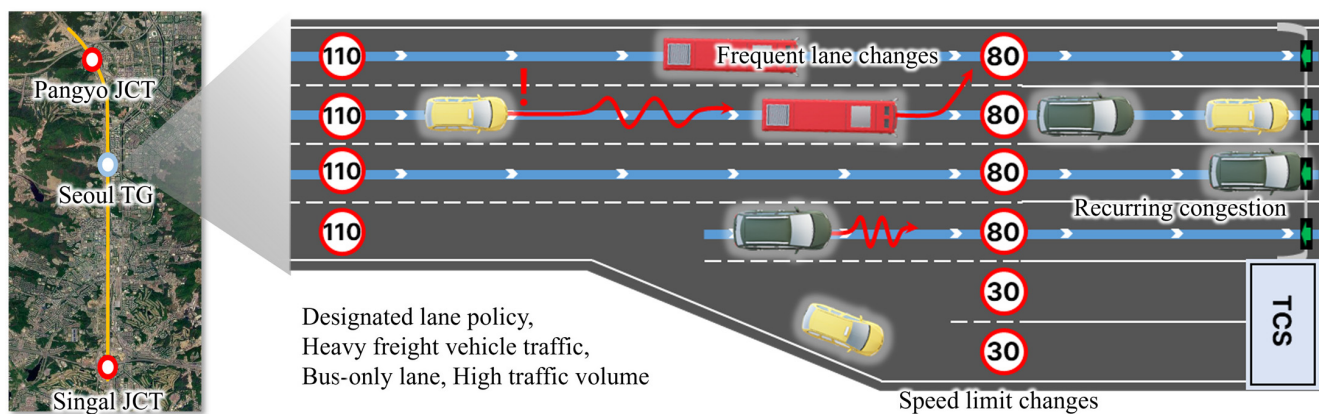


Figure 4. Traffic characteristics of the Seoul tollgate section.

The simulation network was developed to replicate the actual roadway geometry, lane operation characteristics, and traffic conditions of the Seoul-bound section between Singal JCT and Pangyo JCT on the Gyeongbu Expressway. The network incorporated key operational features of the study corridor, including lane configurations, speed limits, dedicated bus lanes, Hi-Pass tolling facilities, and toll plaza operations near Seoul Tollgate. Vehicle interactions were modeled using the Wiedemann 99 car-following model embedded in VISSIM, with parameter adjustments based on guidelines from VDOT, WisDOT, and relevant Korean traffic regulations to better represent realistic driving behavior. In addition, Static Vehicle Routing Decision Points were established 1–2 km upstream of Seoul Tollgate, and Lane Change Distance parameters were adjusted between 1000 and 2000 m to reproduce observed lane-changing behavior associated with toll collection and Hi-Pass lane access. Traffic demand was generated using Vehicle Detection System (VDS) data collected during the afternoon peak period (15:00–17:00) along the study corridor. Vehicle composition reflected observed traffic conditions and consisted of 76.13% passenger cars, 8.35% buses, and 15.52% trucks based on Korea's official vehicle classification system. Toll payment methods at Seoul Tollgate were also considered, including 87.29% multi-lane Hi-Pass, 6.24% single-lane Hi-Pass, and 6.47% manual Toll Collection System (TCS) users. To facilitate calibration and validation, Data Collection Points were installed at locations corresponding to actual VDS stations, and simulated traffic volumes and speeds were compared with observed data on a lane-by-lane basis. The calibration results produced an average U-value of 0.08 and a GEH statistic of 4.99 (Equations (3) and (4)), indicating that

the simulation network reasonably reproduced actual traffic conditions and was suitable for evaluating the proposed ADAS support system [26,27].

$$U = \frac{\sqrt{\sum_{i=1}^N (V_i - \hat{V}_i)^2}}{\sqrt{\sum_{i=1}^N V_i^2} + \sqrt{\sum_{i=1}^N \hat{V}_i^2}}, \quad (3)$$

$$GEH = \sqrt{\frac{2(E - O)^2}{E + O}}, \quad (4)$$

Three experimental scenarios were established to evaluate the effects of the proposed system (Figure 5). The first scenario was designed to evaluate the performance of the infrastructure-based I2I–I2V system and its effects in compensating for the detection-range limitations of ADAS and reducing risks associated with the back of congestion queues. The second scenario was designed to evaluate the performance of the V2V–V2V system installed on the rear of large commercial vehicles. This system was configured to compensate for recognition errors involving large and stationary vehicles, and the overall safety effects of large-vehicle recognition support were evaluated. The third scenario considered the simultaneous deployment of the I2I–I2V and V2V–V2V systems. In this scenario, deceleration support before entering the congested section was provided through roadside infrastructure, while recognition support was provided through devices installed on large vehicles, allowing the combined safety effects of the two systems to be evaluated.

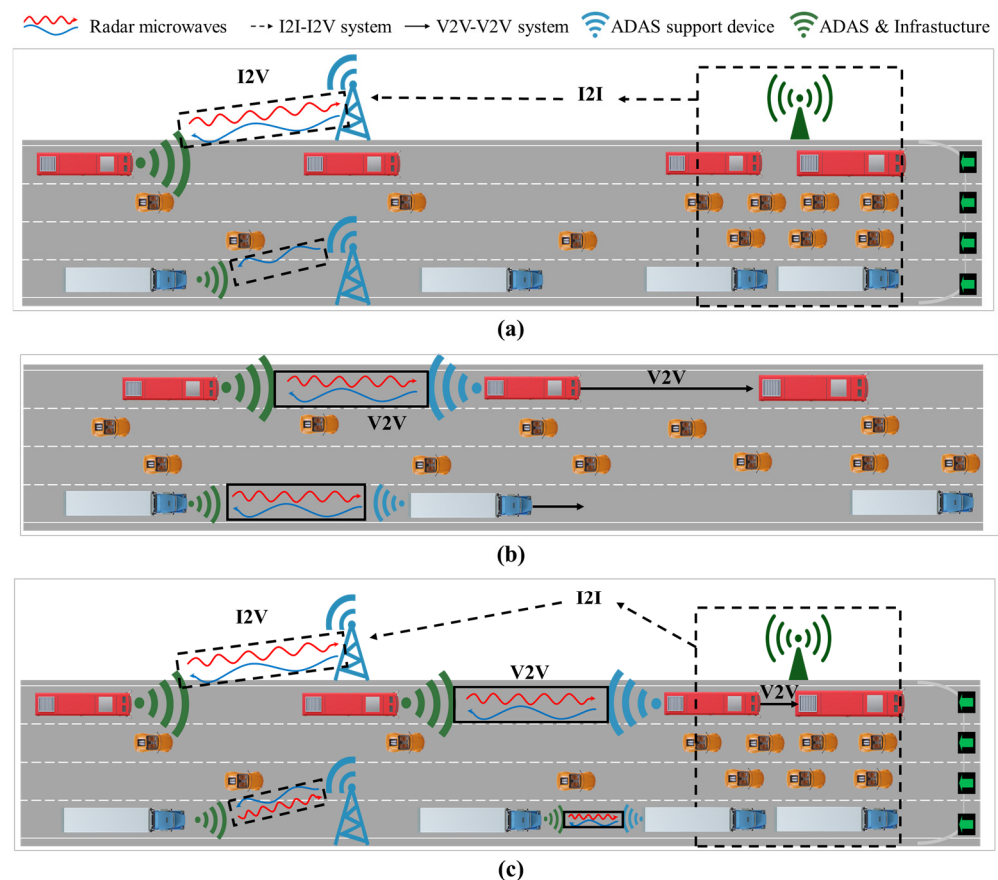


Figure 5. Simulation scenarios ((a) I2I–I2V system, (b) V2V–V2V system, (c) Both systems).

Market Penetration Rate (MPR) scenarios were established to examine the effects of different deployment levels of the proposed systems. For the V2V–V2V system, MPR was defined as the proportion of trucks and buses equipped with both ADAS and the

vehicle-mounted support device, and was varied at 0%, 25%, 50%, 75%, and 100%. The 0% condition represented a baseline in which no trucks or buses were equipped with the V2V–V2V system, whereas the remaining conditions represented progressively increasing equipment rates among these vehicle types. This vehicle-type configuration was established in consideration of recent regulatory trends toward the mandatory installation of AEB and lane-departure warning systems in passenger vans and in trucks and special-purpose vehicles with a gross vehicle weight exceeding 3.5 tons. In contrast, the I2I–I2V system was represented as a binary infrastructure condition because the roadside support device was either installed or not installed within the target section. Accordingly, intermediate MPR levels were not assigned to the I2I–I2V system. The combined scenario was evaluated under the full-deployment condition, consisting of the installed I2I–I2V system and a 100% MPR of the V2V–V2V system. Therefore, comparisons among the V2V–V2V, I2I–I2V, and combined deployment strategies were limited to the common baseline and full-deployment conditions, whereas the effects of intermediate MPR levels were examined only for the V2V–V2V system.

In the simulation, trucks and buses were classified as either equipped or unequipped with ADAS and the proposed support device, whereas passenger cars were not equipped with these devices. All ADAS-equipped trucks and buses were assumed to be equipped with the V2V–V2V support device. Vehicles without ADAS or support devices, as well as vehicles that did not satisfy the system activation conditions, were modeled using the calibrated Wiedemann 99 car-following model and the VISSIM lane-changing model. The proposed behavioral logic was implemented using Python through the Component Object Model (COM) interface of PTV VISSIM 2021. This implementation did not physically reproduce microwave-signal reception, conversion, retransmission, or the internal control logic of production ADAS. Instead, it represented the expected longitudinal response of the receiving vehicle by modifying the Desired Speed of the following equipped vehicle. Thus, Section 2.2 describes the decision and signal-transmission logic of the physical device, whereas this section describes its behavioral abstraction in the simulation.

For the V2V–V2V condition, the operating state of each equipped large vehicle was reassessed at every simulation step using its current and previous speed and spacing values. A negative speed change indicated deceleration, while spacing was classified as decreasing, maintained, or increasing according to the sign of the difference between the current and previous spacing to the immediately preceding vehicle. The behavioral adjustment was applicable only when both the device-equipped large vehicle and the following vehicle were equipped with the proposed system. When the speed of the device-equipped large vehicle was 12 km/h or lower, the Desired Speed of the following equipped vehicle was set to 12 km/h to represent its response to the virtual slow-moving target described in Section 2.2. The value of 12 km/h was adopted from the preceding full-scale evaluation [25]. For the general risk-responsive condition, the Desired Speed of the following equipped vehicle was adjusted when the spacing between the equipped large vehicle and its preceding vehicle was decreasing, the spacing was within 100 m, and the corresponding TTC was 1.5 s or less. The 100 m condition represented the maximum spatial activation range, while the TTC threshold of 1.5 s was selected within the partial-braking activation range of approximately 1.3–1.7 s identified in the preceding ADAS evaluation [25]. While these activation conditions remained satisfied, the following vehicle's Desired Speed was updated at every simulation step to 90% of its current speed. This proportional adjustment was intended to represent a temporary and gradual risk-responsive deceleration rather than a complete stop or full emergency-braking maneuver. When any activation condition was no longer satisfied, when the spacing was no longer decreasing, or when no relevant preceding vehicle was present, the vehicle returned to the default Desired Speed assigned to the corresponding

VISSIM link. Vehicle deceleration, acceleration, car-following, and lane-changing behavior following the Desired Speed adjustment were governed by the calibrated VISSIM models. The maximum deceleration was limited to 3.27 m/s^2 , whereas no separate jerk constraint or manufacturer-specific ADAS response was applied. Equipped trucks and buses were assumed to exhibit the same longitudinal response.

For the I2I–I2V condition, the conceptual congestion-detection and target-speed-selection processes presented in Section 2.2 were simplified to represent a recurrently congested tollgate scenario. Because the network geometry and traffic demand were designed to generate and maintain congestion throughout the analysis period, no separate downstream detector, real-time congestion threshold, or detector-based activation logic was implemented. Instead, the roadside support device was treated as active under the predefined congested condition. The roadside activation point was located 200 m upstream of the beginning of the tollgate influence area, defined by the location at which the number of lanes increased. When an equipped truck or bus reached this point, its Desired Speed was set to 40 km/h to represent advance speed adjustment before entering the congested area. The 200 m location was based on the maximum ADAS recognition distance adopted in the preceding device evaluation [25]. In addition, reducing speed from 80 km/h to 40 km/h over 200 m requires an average deceleration of approximately 0.93 m/s^2 , which is substantially lower than the maximum simulated deceleration of 3.27 m/s^2 . When the vehicle left the applicable control condition, the default link-specific Desired Speed was restored.

When the V2V–V2V and I2I–I2V conditions were simultaneously active, the V2V–V2V adjustment was prioritized because it represented the more immediate vehicle-level interaction. The 90% proportional adjustment and the fixed target speed of 40 km/h were selected as scenario-specific operating parameters to evaluate the feasibility and potential effects of the proposed framework. They were not intended to represent universally optimal control values. A systematic sensitivity and optimization analysis of the proportional factor, target speed, activation thresholds, and device location is therefore identified as a subject for future research.

Following the Desired Speed adjustment, all actual vehicle responses remained subject to the calibrated Wiedemann 99 and VISSIM lane-changing models. Subsequent driver intervention after a warning or partial-braking response, radar-processing delay, actuator dynamics, and manufacturer-specific ACC/AEB control differences were not modeled. The key characteristics of the simulation network, traffic demand, vehicle composition, driving-behavior settings, and calibration and validation results are summarized in Table 1.

Table 1. Summary of simulation network establishment and validation.

Category	Description
Study Corridor	Seoul-bound Gyeongbu Expressway (Singal JCT–Pangyo JCT, 12 km)
Roadway Features	Dedicated bus lane, Seoul TG, Multi-Lane Hi-Pass, Single-Lane Hi-Pass, TCS facilities
Traffic Demand Source	VDS data collected during the 15:00–17:00 peak period
Vehicle Composition	Passenger Cars (76.13%), Buses (8.35%), Trucks (15.52%)
Toll Payment Distribution	Multi-Lane Hi-Pass (87.29%), Single-Lane Hi-Pass (6.24%), TCS (6.47%)
Driving Behavior Model	Wiedemann 99
Lane-Changing Settings	Static Routing Points (1–2 km upstream), Lane Change Distance (1000–2000 m)
Calibration Data	Lane-specific traffic volume and speed collected from VDS locations
Validation Measures and Results	U-value = 0.08, GEH = 4.99

Each scenario was simulated ten times using ten different random seeds. The same set of random seeds was consistently applied across the scenarios and MPR conditions to control stochastic differences in traffic conditions and ensure consistent and reproducible comparisons. The mean value of each evaluation measure was calculated from the repeated simulation results.

2.4. Surrogate Safety Evaluation and Statistical Analysis

The effectiveness of the proposed system was evaluated using two surrogate safety measures: Time-to-Collision (TTC) and the number of traffic conflicts [28]. TTC represents the remaining time until a collision would occur if two vehicles maintain their current speeds and trajectories and is widely used as an indicator of potential collision risk [29,30]. TTC is calculated as:

$$TTC = \frac{D}{V_f - V_l} \quad (5)$$

where D is the distance between the lead and following vehicles (m), V_f is the speed of the following vehicle (m/s), and V_l is the speed of the lead vehicle (m/s). Smaller TTC values indicate higher collision risk, and TTC values below 1.5 s are generally considered critical safety conditions.

A conflict refers to a hazardous interaction between vehicles that could potentially result in a collision, even if an actual crash does not occur. In this study, vehicle trajectory data generated from VISSIM were processed using the Surrogate Safety Assessment Model (SSAM) version 3.0 developed by the Federal Highway Administration (FHWA) to identify traffic conflicts [31]. The TTC and Post-Encroachment Time (PET) thresholds were set to 1.5 s and 5.0 s, respectively. Based on these thresholds, SSAM extracted hazardous vehicle-interaction events and calculated the minimum TTC observed for each identified conflict. Therefore, the average TTC reported in this study represents the mean of the minimum TTC values obtained from the conflict events identified by SSAM, rather than an independent TTC measure calculated from all vehicle interactions. Conflict frequency represents the total number of conflict events extracted under the specified thresholds. Accordingly, average TTC describes the temporal proximity of the identified conflicts, whereas conflict frequency indicates how often hazardous vehicle interactions occurred.

The individual simulation run was treated as the statistical analysis unit. For each scenario, roadway section, and random-seed run, run-level TTC was calculated as the arithmetic mean of the minimum TTC values associated with all conflict events identified within that run. Run-level conflict frequency was defined as the total number of SSAM-identified conflict events in each simulation run.

TTC and conflict frequency were first calculated for each simulation run, and scenario-level results were derived using the ten run-level observations obtained from the ten simulation replications. The mean, standard deviation, and 95% confidence interval were calculated for each surrogate safety measure. The 95% confidence interval was estimated using Student's t distribution as follows:

$$CI = \bar{x} \pm t_{0.975, n-1} \frac{s}{\sqrt{n}} \quad (6)$$

where $\bar{x}$ is the mean of the run-level values, s is the corresponding standard deviation, and $n = 10$ is the number of simulation replications.

Because identical random seeds were applied to the baseline and deployment scenarios, statistical comparisons were conducted using matched run-level observations. Paired t -tests were used to compare both TTC and conflict frequency. All statistical tests were two-sided, with a significance level of 0.05. The potential surrogate safety effects of the

proposed system were evaluated by comparing run-level TTC and conflict frequency across the simulation scenarios.

3. Results and Discussion

To examine the spatial variation in the effects of the proposed ADAS support system, the analysis area was divided into three sections: the upstream section located more than 400 m before the Seoul Tollgate, the Seoul Tollgate influence area, and the downstream section after passing the tollgate. In each section, the baseline condition was compared with the V2V–V2V system at MPR levels of 25%, 50%, 75%, and 100%, the fully deployed I2I–I2V system, and the combined full-deployment condition. For the ten simulation replications, TTC and conflict frequency were summarized using the mean, standard deviation, and 95% confidence interval. Because the same random seeds were applied across all experimental conditions, the results were matched by simulation run. Although conflict frequency was measured as a run-level count variable, the paired differences consisted of relatively large aggregate counts and showed no substantial departure from normality or influential extreme outliers. Therefore, two-sided paired *t*-tests were conducted for both TTC and conflict frequency to compare each system-applied condition with the corresponding baseline. These section-based comparisons were used to identify where the proposed systems produced the greatest changes in surrogate safety performance and whether the observed effects were primarily reflected in TTC, conflict frequency, or both.

3.1. Safety Performance Before the Seoul Tollgate

Table 2 presents the surrogate safety performance of the proposed ADAS support system in the upstream section located more than 400 m before the Seoul Tollgate. This section is located before vehicles directly enter the tollgate influence area; therefore, the direct effect of the I2I–I2V system is expected to be relatively limited compared with the tollgate section. Under the baseline condition, the mean TTC was 1.23 ± 0.03 s, and the mean conflict frequency was 297.0 ± 16.90 . Overall, the system-applied conditions showed higher mean TTC values and lower mean conflict frequencies than the baseline, although the magnitude and statistical significance of these changes varied according to the system and MPR.

Table 2. Safety performance before the Seoul Tollgate.

System	MPR (%)	TTC			# of Conflicts		
		Mean $\pm$ SD	95% CI	Paired <i>t</i> -Test <i>p</i>	Mean $\pm$ SD	95% CI	Paired <i>t</i> -Test <i>p</i>
Baseline	0	1.23 ± 0.03	1.21–1.25	–	297.0 ± 16.90	284.9–309.1	–
V2V–V2V	25	1.24 ± 0.04	1.21–1.27	0.557	289.0 ± 18.68	275.6–302.4	0.347
V2V–V2V	50	1.27 ± 0.05	1.24–1.30	0.028	274.0 ± 14.41	263.7–284.3	0.008
V2V–V2V	75	1.32 ± 0.03	1.30–1.34	<0.001	250.0 ± 12.88	240.8–259.2	<0.001
V2V–V2V	100	1.34 ± 0.04	1.31–1.37	<0.001	243.0 ± 13.47	233.4–252.6	<0.001
I2I–I2V	100	1.32 ± 0.05	1.29–1.35	<0.001	251.0 ± 15.65	239.8–262.2	<0.001
Both systems	100	1.37 ± 0.03	1.35–1.39	<0.001	221.0 ± 10.61	213.4–228.6	<0.001

For the V2V–V2V system, the changes observed at 25% MPR were relatively small. The mean TTC increased to 1.24 ± 0.04 s, while the mean conflict frequency decreased to 289.0 ± 18.68 ; however, neither difference was statistically significant compared with the baseline condition ($p = 0.557$ and $p = 0.347$, respectively). At 50% MPR, the mean TTC increased to 1.27 ± 0.05 s ($p = 0.028$), and the mean conflict frequency decreased to 274.0 ± 14.41 ($p = 0.008$). More pronounced changes were observed at MPR levels of 75% and 100%, at which both TTC and conflict frequency differed significantly from the baseline condition (all $p < 0.001$). At 100% MPR, TTC increased to 1.34 ± 0.04 s, while conflict

frequency decreased to 243.0 ± 13.47 . This result indicates that the vehicle-mounted system may improve upstream surrogate safety performance by supporting more stable following behavior, with the observed effects becoming clearer as the proportion of equipped trucks and buses increased.

In the I2I–I2V scenario, TTC increased to 1.32 ± 0.05 s, and conflicts decreased to 251.0 ± 15.65 , with both differences being statistically significant relative to the baseline condition (both $p < 0.001$). Although the roadside system does not directly operate within the analyzed upstream section, the improvement suggests that smoother speed adjustment near the tollgate may indirectly reduce unstable vehicle interactions propagating upstream. Because the roadside device was installed 200 m upstream of the Seoul Tollgate, whereas the upstream analysis section was located more than 400 m before the tollgate, the changes observed in this section are likely to reflect an indirect traffic-flow stabilization effect rather than a direct response to the device.

The largest improvement was observed when both systems were simultaneously deployed. In this scenario, TTC increased to 1.37 ± 0.03 s, and conflicts decreased to 221.0 ± 10.61 , corresponding to a 25.6% reduction compared with the baseline condition. Both changes were statistically significant (both $p < 0.001$). Under the specific full-deployment condition evaluated in this study, the combined system produced the highest mean TTC and the lowest mean conflict frequency among the evaluated conditions. This numerical pattern suggests that the vehicle-based recognition-support function and the infrastructure-based speed-adjustment function may provide complementary effects.

Overall, both individual systems improved upstream surrogate safety performance, while the combined full-deployment condition produced the greatest improvement; for the V2V–V2V system, the effects became more evident at MPR levels of 50% and above. This implies that early speed harmonization and improved large-vehicle recognition can reduce abrupt speed changes before vehicles reach the bottleneck, thereby contributing to safer and more stable traffic operations across the broader corridor [32]. From a traffic engineering perspective, these results suggest that the proposed framework can function as a proactive traffic management tool by suppressing the formation and propagation of traffic disturbances before congestion fully develops [33]. The results therefore provide simulation-based evidence that the proposed vehicle- and infrastructure-based support functions can contribute to earlier speed adjustment and more stable vehicle interactions under the evaluated traffic conditions. Accordingly, the proposed framework showed the potential to improve surrogate safety performance and traffic-flow stability on freeway approaches to recurrent bottlenecks and toll facilities.

3.2. Safety Performance Within the Seoul Tollgate Influence Area

Table 3 presents the surrogate safety performance of the proposed ADAS support system within the Seoul Tollgate influence area. This section represents the primary bottleneck location within the study corridor, where recurrent congestion frequently occurs due to toll collection operations, speed-limit transitions, and intensive lane-changing maneuvers associated with Hi-Pass access movements. Consequently, this section exhibited the highest level of simulated conflict risk among the analyzed sections. Under the baseline condition, the mean TTC was 0.72 ± 0.04 s, while the mean conflict frequency was 1486.0 ± 69.56 . The relatively low TTC and high conflict frequency indicate that the identified vehicle interactions occurred with greater temporal proximity and frequency than those in the upstream and downstream sections. Overall, the system-applied conditions showed higher TTC values and lower conflict frequencies than the baseline, although the statistical significance of the changes at low MPR differed between the two measures.

Table 3. Safety performance within the Seoul Tollgate influence area.

System	MPR (%)	TTC			# of Conflicts		
		Mean $\pm$ SD	95% CI	Paired <i>t</i> -Test <i>p</i>	Mean $\pm$ SD	95% CI	Paired <i>t</i> -Test <i>p</i>
Baseline	0	0.72 $\pm$ 0.04	0.69–0.75	–	1486.0 $\pm$ 69.56	1436.2–1535.8	–
V2V–V2V	25	0.77 $\pm$ 0.04	0.74–0.80	0.06	1370.0 $\pm$ 84.16	1309.8–1430.2	0.008
V2V–V2V	50	0.85 $\pm$ 0.04	0.82–0.88	<0.001	1261.0 $\pm$ 87.69	1198.3–1323.7	<0.001
V2V–V2V	75	0.95 $\pm$ 0.04	0.93–0.98	<0.001	1204.0 $\pm$ 56.82	1163.4–1244.6	<0.001
V2V–V2V	100	1.13 $\pm$ 0.04	1.10–1.16	<0.001	976.0 $\pm$ 71.72	924.7–1027.3	<0.001
I2I–I2V	100	1.11 $\pm$ 0.04	1.08–1.14	<0.001	1014.0 $\pm$ 57.18	973.1–1054.9	<0.001
Both systems	100	1.27 $\pm$ 0.02	1.25–1.29	<0.001	764.0 $\pm$ 49.95	728.3–799.7	<0.001

For the V2V–V2V system, at 25% MPR, the mean TTC increased to 0.77 ± 0.04 s, but the difference from the baseline was not statistically significant ($p = 0.060$). In contrast, the mean conflict frequency decreased to 1370.0 ± 84.16 , representing a statistically significant reduction ($p = 0.008$). At MPR levels of 50%, 75%, and 100%, both TTC and conflict frequency differed significantly from the baseline condition (all $p < 0.001$). At 100% MPR, TTC increased to 1.13 ± 0.04 s, while conflict frequency decreased to 976.0 ± 71.72 . The progressively larger changes with increasing MPR suggest that a greater proportion of equipped trucks and buses supported earlier speed adjustment and more stable following behavior within the bottleneck influence area.

For the I2I–I2V system, TTC increased to 1.11 ± 0.04 s, and conflict frequency decreased to 1014.0 ± 57.18 , with both differences being statistically significant relative to the baseline condition (both $p < 0.001$). Since this system operates near the location where congestion directly develops, the observed changes suggest that advance speed adjustment before vehicles entered the queue contributed to reducing the frequency and temporal proximity of simulated conflicts.

The largest improvement was observed when both systems were simultaneously deployed. Under the specific full-deployment condition evaluated in this study, TTC increased from 0.72 ± 0.04 s to 1.27 ± 0.02 s, representing an increase of approximately 76%, while conflict frequency decreased from 1486.0 ± 69.56 to 764.0 ± 49.95 , corresponding to a reduction of approximately 49%. Both changes were statistically significant (both $p < 0.001$). The combined condition produced the highest mean TTC and the lowest mean conflict frequency among the conditions evaluated in this section. These results suggest that the two systems may provide complementary surrogate safety benefits under full deployment. While the I2I–I2V system supports advance speed adjustment based on downstream congestion conditions, the V2V–V2V system provides vehicle-level recognition and driving-state support. The combination of these functions was associated with earlier and smoother speed adaptation within the most unstable portion of the study corridor.

From a traffic-flow perspective, the proposed system may also contribute to mitigating traffic disturbances and shockwave propagation [34]. Vehicles receiving speed-adjustment support gradually adapted their speeds before encountering congestion, thereby reducing traffic instability and the likelihood of chain-reaction rear-end conflicts. Considering that rear-end crashes frequently occur at the back of highway queues, the simulation results provide evidence that vehicle- and infrastructure-based support functions can reduce surrogate conflict risk at recurrent bottlenecks characterized by simultaneous queue formation, speed transitions, and intensive lane-changing activity [35]. From a broader traffic-engineering perspective, the proposed framework therefore shows potential as a cooperative safety-support strategy for congestion-prone tollgate influence areas and similar freeway bottlenecks.

3.3. Safety Performance After Passing the Seoul Tollgate

Table 4 presents the surrogate safety performance of the proposed ADAS support system in the downstream section after passing the Seoul Tollgate. Because most queue-end approaches, merging maneuvers, and major speed adjustments had already occurred within the tollgate influence area before vehicles entered the downstream section, the direct effects of the proposed systems were relatively limited in this section compared with those in the tollgate influence area. Under the baseline condition, the mean TTC was 1.31 ± 0.04 s, and the mean conflict frequency was 314.0 ± 15.25 .

Table 4. Safety performance after passing the Seoul Tollgate.

System	MPR (%)	TTC			# of Conflicts		
		Mean $\pm$ SD	95% CI	Paired <i>t</i> -Test <i>p</i>	Mean $\pm$ SD	95% CI	Paired <i>t</i> -Test <i>p</i>
Baseline	0	1.31 ± 0.04	1.28–1.34	–	314.0 ± 15.25	303.1–324.9	–
V2V–V2V	25	1.32 ± 0.04	1.29–1.35	0.669	277.0 ± 17.06	264.8–289.2	<0.001
V2V–V2V	50	1.33 ± 0.04	1.30–1.36	0.34	247.0 ± 10.96	239.2–254.8	<0.001
V2V–V2V	75	1.33 ± 0.03	1.31–1.35	0.315	234.0 ± 13.40	224.4–243.6	<0.001
V2V–V2V	100	1.33 ± 0.03	1.31–1.35	0.306	224.0 ± 12.16	215.3–232.7	<0.001
I2I–I2V	100	1.32 ± 0.03	1.30–1.34	0.562	241.0 ± 11.76	232.6–249.4	<0.001
Both systems	100	1.35 ± 0.04	1.32–1.38	0.033	189.0 ± 10.31	181.6–196.4	<0.001

For the V2V–V2V system, the mean TTC was 1.32 ± 0.04 s at 25% MPR and 1.33 ± 0.03 s at 100% MPR, with no statistically significant differences from the baseline at any MPR level ($p = 0.306$ – 0.669). This result can be interpreted as indicating that most merging and speed-adjustment processes requiring vehicle-level support had already occurred within the tollgate influence area, thereby limiting additional TTC improvements in the downstream section. In contrast, mean conflict frequency decreased significantly at all MPR levels, from 277.0 ± 17.06 at 25% MPR to 224.0 ± 12.16 at 100% MPR (all $p < 0.001$). For the I2I–I2V system, mean TTC increased slightly to 1.32 ± 0.03 s, but the difference from the baseline was not statistically significant ($p = 0.562$), whereas mean conflict frequency decreased significantly to 241.0 ± 11.76 ($p < 0.001$). Under the combined full-deployment condition, mean TTC increased to 1.35 ± 0.04 s ($p = 0.033$), while mean conflict frequency decreased to 189.0 ± 10.31 , representing a 39.8% reduction relative to the baseline ($p < 0.001$).

The absence of a statistically significant TTC change under the I2I–I2V condition is consistent with the spatial operating characteristics of the roadside system, which was designed to support advance speed adjustment upstream of the tollgate rather than directly affect downstream vehicle behavior. In addition, the significant reductions in conflict frequency across all system-applied conditions suggest that the stable speed and vehicle-following conditions established in the upstream section and the tollgate influence area may have been partially maintained after vehicles passed the tollgate. Therefore, the downstream results can be interpreted as reflecting the residual effects of traffic-flow stabilization achieved in the preceding sections rather than a strong direct system effect within the downstream section.

3.4. Deployment Strategies and Operational Implications

The results suggest that the two proposed systems may support different aspects of radar-based ADAS perception limitations under the evaluated conditions (Figure 6). The V2V–V2V system provides vehicle-level support by improving the recognition of large vehicles and their driving states, whereas the I2I–I2V system provides advance information on congestion conditions beyond the immediate perception range of onboard sensors. Accordingly, the former primarily supports local vehicle-following interactions, while the

latter support anticipatory speed adjustment before vehicles encounter a bottleneck. These functional differences explain why the effectiveness of each system varied according to the location and characteristics of the traffic disturbance.

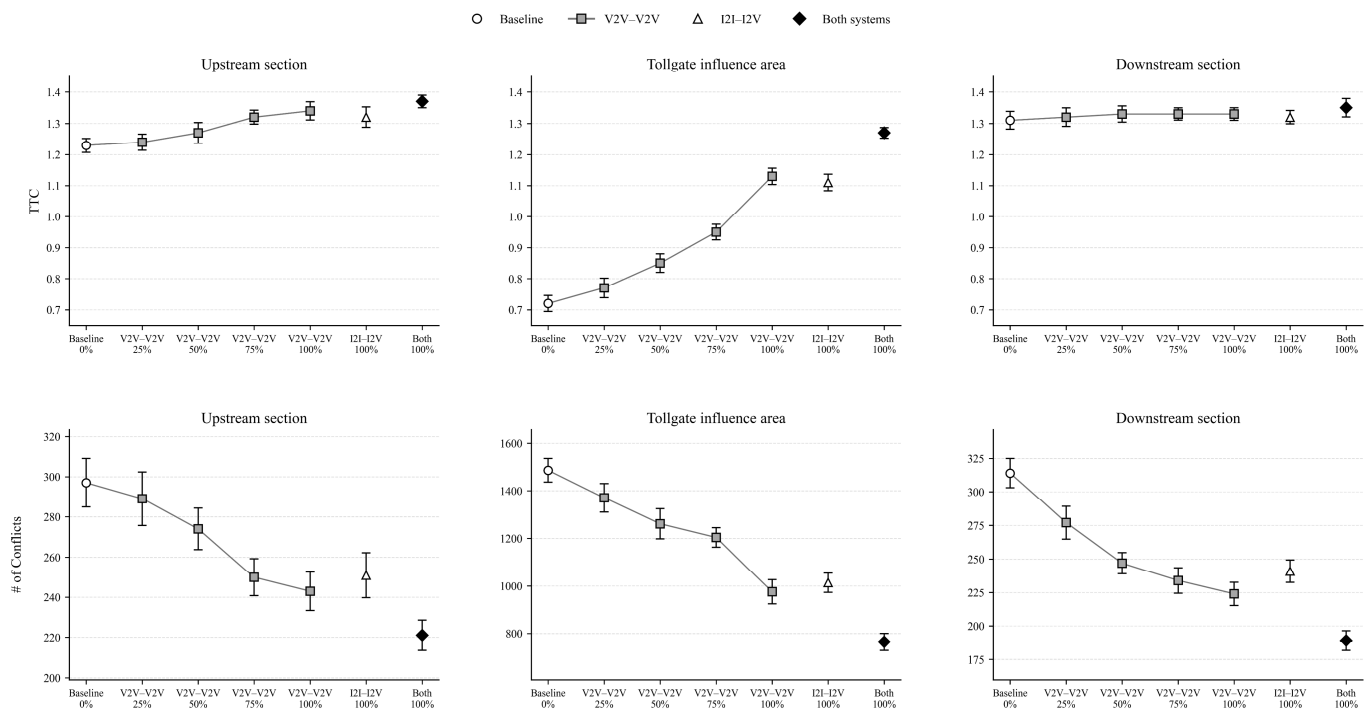


Figure 6. Comparison of TTC and Conflict Frequency.

The MPR analysis also provides an important operational implication for the deployment of the V2V-V2V system. At a low MPR, only a limited proportion of large vehicles transmitted converted signals, and the resulting changes in TTC were not consistently significant. In contrast, the effects became clearer at MPR levels of 50% and above, particularly in the upstream section and the tollgate influence area. This finding suggests that the traffic-level benefits of the vehicle-mounted system depend not only on the performance of individual devices but also on whether a sufficient proportion of relevant vehicles are equipped.

The I2I-I2V system showed a different deployment advantage. Because a roadside device can provide traffic-condition-based speed support at a fixed location, it is particularly suitable for recurrent and spatially concentrated bottlenecks, such as tollgate approaches. Its application can complement the gradual penetration of vehicle-mounted devices by providing infrastructure-based support at locations where advance speed adjustment is most necessary. This indicates that the two systems should not be regarded as competing alternatives, but rather as deployment options that can be selected or combined according to the spatial extent and causes of traffic risk.

Among the evaluated conditions, the combined full-deployment strategy produced the most favorable surrogate safety performance. This result suggests that the simultaneous provision of local vehicle-recognition support and advance traffic-condition information may provide complementary support for immediate and downstream perception limitations. From an operational perspective, the findings indicate the potential for a phased deployment approach in which roadside systems are first introduced at high-risk bottlenecks and vehicle-mounted systems are progressively deployed among large commercial vehicles. The roadside system also showed potential surrogate-safety improvements through increased TTC and reduced conflict frequency. In particular, under the evaluated full-deployment condition, the integration of the two functions produced more favorable

TTC and conflict-frequency outcomes than either individual system. Overall, these findings highlight the potential value of coordinating vehicle- and infrastructure-based technologies rather than relying on a single support mechanism in complex freeway environments.

4. Conclusions

This study proposed a microwave-signal-conversion-based ADAS support system to address key limitations of current ADAS technologies, including limited radar detection range, large-vehicle recognition failures, and stationary-vehicle recognition errors in congestion and crash-related situations. Although ADAS has demonstrated significant potential for improving traffic safety and driving convenience, its effectiveness remains constrained by sensor-based perception limitations. To overcome these challenges, this study proposed a cooperative support framework that integrates vehicle-mounted and roadside signal-conversion devices with existing radar-based ADAS functions. The framework is designed to utilize the receiving vehicle's existing onboard radar sensor and perception algorithms without requiring sensor replacement or algorithm modification.

The proposed framework consists of two complementary systems. The first is a vehicle-based V2V–V2V system mounted on the rear of large commercial vehicles, which converts and retransmits microwave signals to support the recognition of large or low-speed vehicles and convey their operating states to following ADAS-equipped vehicles. The second is an infrastructure-based I2I–I2V system installed along the roadside, which utilizes traffic-condition information collected from infrastructure to support advance speed adjustment before vehicles reach downstream congestion. The potential surrogate-safety effects of the proposed systems were evaluated using a calibrated VISSIM microscopic traffic simulation model representing a 12-km section of the Gyeongbu Expressway, including the Seoul Tollgate bottleneck area. The physical processes of microwave-signal reception, conversion, and retransmission were not directly simulated. Instead, the expected longitudinal responses were behaviorally represented through conditional modification of the Desired Speed of equipped trucks and buses using VISSIM-COM. V2V–V2V Market Penetration Rate (MPR) scenarios of 0%, 25%, 50%, 75%, and 100% were evaluated, whereas the I2I–I2V system was represented as a binary installation condition. The combined system was evaluated under the full-deployment conditions. Each scenario was simulated ten times using matched random seeds and run-level TTC and conflict frequency were analyzed using 95% confidence intervals and paired statistical comparisons.

The simulation results indicated that the V2V–V2V and I2I–I2V systems have the potential to improve surrogate safety performance under the evaluated conditions. Increasing V2V–V2V penetration was associated with higher TTC and lower simulated conflict frequency across the analyzed sections. The most substantial improvements were observed within the Seoul Tollgate influence area, where recurrent congestion frequently occurs. In this section, under the evaluated full-deployment condition, the combined system increased mean TTC from 0.72 s to 1.27 s and reduced mean conflict frequency from 1486 to 764, corresponding to a 48.6% reduction. Paired comparisons showed statistically significant differences in both TTC and conflict frequency. These findings suggest that coordinating local vehicle-recognition support with advanced infrastructure-based speed adjustment may provide complementary surrogate-safety benefits in congested freeway environments.

Despite these promising simulation-based findings, several limitations should be acknowledged. First, although the underlying radar signal-conversion device was previously evaluated through full-scale vehicle testing, the vehicle-mounted V2V–V2V and infrastructure-based I2I–I2V applications proposed in this study were assessed using microscopic traffic simulation for a specific freeway section. In VISSIM-COM, the expected longitudinal responses of equipped vehicles were represented behaviorally through con-

ditional Desired Speed modification. The simulation did not physically reproduce radar propagation, microwave-signal reception, conversion and retransmission, virtual-target recognition, or the internal control processes of production ACC and AEB systems. Therefore, the previous tests provide an initial empirical basis for the practical applicability of the microwave signal-conversion mechanism, whereas the present results should be interpreted within the scope of the selected road section, traffic demand, vehicle composition, MPR scenarios, and simulation assumptions. Fixed assumptions were also applied to ADAS penetration rates, recognition-error conditions, and traffic demand. Second, the potential safety effects of the proposed framework were evaluated using surrogate safety measures, including TTC and traffic-conflict frequency, rather than actual crash data. Consequently, the direct relationship between the proposed framework and crash reduction could not be verified. Third, the fixed target speed of 40 km/h for the I2I–I2V system, the iterative Desired Speed adjustment to 90% of the current speed for the V2V–V2V system, the 12 km/h virtual-target setting, the 100 m spatial activation range, the TTC threshold of 1.5 s, and the 200 m roadside-device location were applied as scenario-specific operating parameters. Although some settings were informed by the preceding device evaluation and reported ADAS operating characteristics, they were not optimized in the present study. Further research should therefore examine the sensitivity and optimization of target speeds, proportional adjustment factors, activation and release thresholds, infrastructure locations, and operational coverage ranges.

Additional technical and institutional considerations must be addressed before practical implementation. Although previous full-scale vehicle tests examined the applicability of the underlying signal conversion mechanism across multiple vehicle models and manufacturers, the extended vehicle-mounted and infrastructure-connected configurations require further hardware level integration and validation. Detailed information on the operating frequency bands, modulation formats, sensor configurations, object-tracking algorithms, and longitudinal-control architectures of commercial automotive radar systems is generally inaccessible because such information is proprietary. Therefore, compatibility with heterogeneous radar and ADAS platforms should be evaluated across a broader range of vehicle models and manufacturers. Future hardware evaluations should characterize supported radar frequency bands and FMCW waveform compatibility, the relationship between signal conversion and apparent target speed, processing and retransmission latency, retransmission power, synchronization requirements, and electromagnetic compatibility. Signal-processing latency, simultaneous transmissions, electromagnetic interference, the generation of false or conflicting virtual targets, and interactions among multiple vehicle- and infrastructure-based devices should also be investigated. In addition, activation and release conditions, signal-prioritization rules, and fail-safe mechanisms should be established to prevent unnecessary or unintended braking. Practical deployment should also address vehicle-mounted and roadside hardware integration, power supply, access to vehicle- and infrastructure-state data, and the required communication and signal processing interfaces. Cybersecurity, device authentication, liability allocation, radio-spectrum requirements, technical certification, and regulatory approval should also be considered before deployment in open-road environments. Future research should integrate traffic simulation with radar bench testing, Hardware-in-the-Loop experiments, closed-course vehicle testing, pilot applications, and field operational testing. These evaluations should examine radar-system compatibility, driver and vehicle responses, signal-processing latency, simultaneous-signal handling, interference and false-target suppression, and operational reliability under diverse traffic conditions. Furthermore, analyses based on actual crash and operational data, together with sensitivity and optimization studies of target speeds, decision thresholds,

device locations, and operational coverage, are required to further validate and improve the proposed framework.

Overall, under the evaluated road, deployment, and behavioral conditions, the coordination of vehicle-based and infrastructure-based support was associated with higher TTC and lower simulated conflict frequency, particularly within the Seoul Tollgate influence area. These findings suggest the potential value of combining local vehicle recognition support with advance traffic condition-based speed adaptation to improve surrogate safety performance in complex freeway environments. The results provide a basis for further parameter refinement, hardware level validation, and phased evaluation of cooperative vehicle infrastructure support systems.

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Abbreviations

The following abbreviations are used in this manuscript:

WHO	World Health Organization
ADAS	Advanced Driver Assistance Systems
ITS	Intelligent Transportation Systems
FCW	Forward Collision Warning
AEB	Autonomous Emergency Braking
LKA	Lane Keeping Assist
ACC	Adaptive Cruise Control
SAE	Society of Automotive Engineers
C-ITS	Cooperative Intelligent Transportation Systems
I2I	Infrastructure-to-Infrastructure
I2V	Infrastructure-to-Vehicle
V2V	Vehicle-to-Vehicle
VDS	Vehicle Detection System
TCS	Toll Collection System
MPR	Market Penetration Rate
TTC	Time-to-Collision
SSAM	Surrogate Safety Assessment Model
FHWA	Federal Highway Administration
PET	Post-Encroachment Time

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