COMPARISON AND EVALUATION OF COOPERATIVE INTELLIGENT TRANSPORT SYSTEMS (C-ITS) SCENARIOS IN TERMS OF TRAFFIC SAFETY AND EFFICIENCY

by

Ertan Yalçın

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ABSTRACT

COMPARISON AND EVALUATION OF COOPERATIVE INTELLIGENT TRANSPORT SYSTEMS (C-ITS) SCENARIOS IN TERMS OF TRAFFIC SAFETYAND EFFICIENCY

Cooperative Intelligent Transport Systems (C-ITS) represent a significant advancement in transportation technology where communication between various sub-systems occurs in real-time. The C-ITS connects vehicles, infrastructure, and other road users in real-time using vehicles (V2V), vehicles and infrastructure (V2I), and various entities (V2X). Despite widespread implementation, comprehensive research summarizing the overall benefits of C-ITS on traffic safety and efficiency is limited. This study utilized the available literature to fill that gap.

The evaluation shows that C-ITS significantly improves traffic safety and efficiency. Real-time communication enables timely actions to avoid incidents, enhances traffic flow, and reduces congestion through improved coordination. However, the reviewed literature indicated that although the C-ITS implementation is widespread around the globe, most of the evaluation reports are geographically biased towards developed countries, with Europeancountries, the United States, China, Korea, and Japan, being the leaders, necessitating morestudies in other regions for global validation. Future research should focus on studies insideand outside Europe, the U.S., China, Korea, and Japan to develop standardized methodologies for assessing C-ITS impacts, exploring emerging communication technologies, and investigating supportive policy frameworks.

In conclusion, C-ITS holds significant promise for improving traffic safety and efficiency. This study synthesizes existing research, providing valuable insights into the benefits and challenges of C-ITS, and paving the way for future advancements in intelligenttransportation systems.

ÖZET

K-AUS SENERYOLARININ TRAFİK GÜVENLİĞİ VE VERİMLİLİĞİ AÇISINDAN KARŞILAŞTIRILMASI VE DEĞERLENDİRİLMESİ

Kooperatif Akıllı Ulaşım Sistemleri (K-AUS), ulaşım teknolojisinde önemli bir ilerleme olarak, çeşitli alt sistemler arasındaki gerçek zamanlı iletişimi temsil eder. K-AUS, araçlar arası (V2V), araç altyapı (V2I) ve araç her şey haberleşmesi (V2X) kullanarak araçları, altyapıyı ve yol kullanıcılarını gerçek zamanlı olarak birbirine bağlar. K-AUS'un trafik güvenliği ve verimliliği üzerindeki etkilerini özetleyen kapsamlı araştırmalar sınırlıdır. Bu çalışma, K-AUS senaryolarını özetlemek ve karşılaştırmak için mevcut literatürden yararlanılarak farklı bölgelerdeki standartları inceleyerek K-AUS uygulamalarına ilişkin değerlendirmeler sunmaktadır.

Değerlendirmeler, K-AUS'un trafik güvenliğini ve verimliliğini artırdığını göstermektedir. Gerçek zamanlı iletişim, kazaları önlemek için hızlı müdahalelere oalanak tanır, trafik akışını iyileştirir tıkanıklığı azaltır. Ancak K-AUS yaygın olmasına rağmen, araştırmalar Avrupa, ABD, Çin, Kore ve Japonya gibi gelişmiş ülkelere odaklanmıştır. Gelecekteki araştırmalar, K-AUS'un etkilerini değerlendirmek için standart metodolojiler geliştirmek, gelişmekte olan iletişim teknolojilerini ilerletmek ve destekleyici politika çerçevelerini araştırmak için bu ülkelerdeki çalışmaları standartlaştırmaya ve diğer bölgelerde de çalışmalara odaklanmalıdır.

Sonuç olarak, K-AUS trafik güvenliğini ve verimliliğini iyileştirmek için önemli bir araştırma alanıdır. Bu çalışma mevcut araştırmaları sentezleyerek K-AUS'un avantajları ve dezavantajları hakkında değerli içgörüler sunmakta ve akıllı ulaşım sistemlerinde gelecekteki çalışmalar için kaynak oluşturmaktadır.

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LIST OF ACRONYMS/ABBREVIATIONS

5GAA	The 5G Automotive Association
CACC	Cooperative Adaptive Cruise Control
CAV	Connected and Automated Vehicle
C-ITS	Cooperative Intelligent Transportation System
CVIS	Cooperative Vehicle-Infrastructure Systems
DSRC	Dedicated Short-Range Communications
EU	European Union
GIS	Global Information System
GPS	Global Positioning System
IVP	Infrastructure-to-Pedestrian
NHTSA	National Highway Traffic Safety Administration
OBUs	On-Board Units
PET	Post-encroachment time
RSU	Road-Side Unit
SSAM	Surrogate Safety Assessment Model
TTC	Time to collision
V2I	Vehicle to infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle to vehicle
V2X	Vehicle to everything

1. INTRODUCTION

Cooperative intelligent transportation system (C-ITS) technology represents a significant advancement in transportation technology whereby real-time communication between various system participants occurs. The C-ITS is made possible by the presence of the vehicle-to-vehicle (V2V), vehicle to infrastructure (V2I), and vehicle-to-everything (V2X) communication [1]. In turn, such communication can enable safer and more efficient trafficflow. The communication between the leading vehicle and the following vehicles can improve safety by disseminating the incident and traffic flow message to the following vehicles. Similarly, in the V2I-enabled environment, the communication between vehicles and infrastructure can facilitate smooth traffic; a typical example is flow-changing traffic coordination due to the communicated message from a connected vehicle to infrastructure, such as a traffic signal. The C-ITS technology is relatively new. It started being implementedin Europe in the 2000s [2]. Thereafter, it spread to the United States and Asian countries. Currently, this technology has spread across the globe, especially in developed countries.

1.1.Purpose and Scope of the Thesis

Although the technology is widespread, and several studies have been performed to understand its impact on traffic safety and efficiency, studies documenting such benefits are relatively scarce. Individual studies have presented varying magnitudes of the impact, which provide no conclusive evidence. Thus, there is a need for a study that can summarize such benefits.

Therefore, this thesis aims to review, compare, and evaluate various C-ITS scenariosto improve traffic safety and efficiency. It covers a wide range of applications from various countries across the globe, and the standards of the countries are also evaluated. The study provided valuable insight into the effectiveness of C-ITS based on

the types of communications such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) in improving safety and efficiency of the transportation systems.

The study intends to use the literature review to attain this objective. To do so, severalstudies were searched through various databases using proper keywords; the list of studies obtained will then be filtered to obtain relevant studies. The relevant studies were then reviewed and summarized to compile the C-ITS's safety and efficiency benefits.

The rest of the thesis is as follows. The remainder of this chapter presents background information on the importance of C-ITS, followed by an overview of traffic safety and efficiency. The next chapter presents the literature review, which covers the development and historical background of C-ITS scenarios, C-ITS applications in Europe, Asia, and America, and the review of studies on traffic safety and efficiency in the existing literature.

1.2.Description and Importance of C-ITS Scenarios (V2V, V2I, V2X)

Emerging vehicle technologies play important roles in the communication infrastructure of C-ITS. Vehicle communication plays a significant role in C-ITS [3] as it is the center point of communication. It facilitates communication between vehicle and everything (V2X), which includes different types of communication such as Vehicle-to-Infrastructure (V2I), Vehicle-to-Vehicle (V2V), and Vehicle-to-Pedestrian (V2P) [4], [5], [6].

The V2X enables the system to capture safety-related information for road users by enabling real-time communication between vehicles and infrastructures [7]. C-ITS scenarios enable advanced features like traffic signal optimization, hazard warnings,

and dynamic route planning. That led to the enhancement of traffic flow, congestion reduction, and efficiency in the transportation system.

Vehicle-to-vehicle (V2V) communication enables vehicles to communicate with each other over Dedicated Short-Range Communications (DSRC) technology or cellular networks, such as LTE or 5G, to enable low-latency communication between vehicles [8]. V2V is just a part of the V2X category. Communication between vehicles allows informationsharing about their current location, speed, and movement direction to increase road safety.Additionally, V2V warns drivers about potential hazards, such as an approaching vehicle atan intersection or a car braking suddenly ahead. This system can also support automated driving functions, such as cooperative adaptive cruise control (CACC) and coordinated maneuvers at intersections [4]. National Highway Traffic Safety Administration (NHTSA) in the United States has been actively involved in assessing the real-world deployment of V2V technology and has reported the potential to prevent a significant percentage of non-impaired, light vehicle crashes [9].

Similarly, V2I communication is crucial in improving the safety and operation of connected vehicles. Information from one vehicle is disseminated to other infrastructure elements, such as coordinated traffic signals, to change signal timing to improve traffic flowand safety.

2. LITERATURE REVIEW

Recently, there has been a growing interest in Cooperative Intelligent Transport Systems (C-ITS), which are intended to revolutionize the efficiency and safety of road transport. Similar to a well-conducted orchestra where every instrument plays in harmony with others, C-ITS aims to facilitate seamless communication and collaboration between vehicles and infrastructure. This collaboration of technology aims to minimize road accidents and streamline traffic flow, making journeys more predictable and less stressful.

This review provides an in-depth exploration of C-ITS, its evolution, and its variousapplications worldwide. It's like tracing the growth rings of a centuries-old tree, where eachring represents a milestone in the development of C-ITS and offers insights into its growing complexity and impact. The review also highlights unique ways different regions have implemented C-ITS to suit their transportation needs.

This section presents a comprehensive view of the C-ITS domain, showcasing its evolution from an emerging concept to a global movement with the potential to significantlytransform our transportation ecosystems.

2.1.Development and Historical Background of C-ITS Scenarios (EU, 5GAA)

The pioneers of C-ITS encompass a diverse array of stakeholders who have collectively advanced the development and deployment of C-ITS technologies [10], [11], [12]. Research institutions like MIT and Stanford University, alongside government agencies such as USDOT and EC, have driven research, funding, and policy initiatives [11].Automobile manufacturers like General Motors and Toyota, as well as technology companies including Qualcomm and Bosch, have spearheaded the integration of C-ITS features into vehicles. International organizations like ISO and

IEEE have played pivotal roles in establishing common standards and protocols. Through collaboration and innovation, these pioneers have laid the groundwork for safer, more efficient, and interconnected transportation systems, shaping the future of mobility.

Several countries and regions have taken significant steps in implementing C-ITS. The Netherlands, for instance, has been a pioneer in deploying C-ITS applications, with successful trials and pilot projects in cities like Amsterdam and Eindhoven. Similarly, Singapore has proactively adopted C-ITS, leveraging its Smart Nation initiative to integrateadvanced technologies into its transport infrastructure.

2.2.C-ITS Applications in Different Geographical Regions

The application of C-ITS across the globe presents a rich tapestry of regional variations shaped by infrastructure development, regulatory landscapes, and technological adoption rates. Insightful research conducted across Europe, Asia, and the Americas unveilsthe complex character of C-ITS deployments. These studies examine diverse applications, such as traffic management systems and vehicle-to-vehicle communication protocols. Irrespective of the region, C-ITS is in its initial stages in most countries. They highlight regional differences and best practices.

Among the studies that provide a better geographical perspective of the C-ITS applications is a review study by Kotsi et al. [13] and the C-Roads Platform report [19], which is Co-financed by the Connecting Europe Facility of the European Union. Kotsi et al. [13] study compared the status of cooperative intelligent transport systems (C-ITS) deployment projects in Europe and the USA. The data used included information on ongoingC-ITS activities, strategies, and funding sources in both regions collected from reports, publications, and official documents from government agencies, industry organizations, andresearch institutions. The methodology involved a comparative analysis of C-ITS deployment strategies, technical specifications, interoperability

testing, regulatory frameworks, and policy development. Their study revealed that Europe has a robust C-ITSdeployment strategy focused on joint activities, technical specifications, and interoperabilitytesting, supported by various funded projects. In contrast, the USA has made significant progress in developing regulatory frameworks and policies to foster connected vehicle (CV)growth, emphasizing improving roadway safety. However, Europe is still addressing technical challenges related to C-ITS interoperability, while the USA has established clear guidelines and a national architecture framework for C-ITS deployment. Both regions are actively shaping the future of C-ITS technologies and autonomous mobility [13]. On the other hand, the C-Roads Platform report [14] provided updated information on the status ofthe C-ITS projects in eighteen European countries.

In the United States, several C-ITS initiatives have been established by various organizations since 2008. Notably, the USDOT, Arizona State University, the Maricopa County DOT, the Michigan DOT, FHWA, and Auburn University are among the organizations that have implemented C-ITS projects. For instance, a two-phase project, namely “Arizona Emergency Vehicle Infrastructure Integration (E-VII),” [15] funded jointly by the Arizona Transportation Research Center, the Arizona State University, the MaricopaCounty DOT, and the Michigan DOT focused on developing and testing advanced technologies for emergency vehicles. Another project was the "Multipath Signal Phase and Timing (SPaT) Broadcast project," [16] which provided speed advice to drivers to safely passthrough green phases at signalized intersections. It was funded by the Michigan DOT, the University of Michigan Transportation Research Institute (UMTRI), and the Institute for Information Industry. The project also included a down counter on the vehicle's interface, indicating the remaining seconds of the green phase. The down counter enhances driver safety and traffic efficiency through advanced signal broadcasting technologies. In 2011, atleast two major projects were implemented in the United States. One is funded by UMTRI and USDOT, titled “Connected Vehicle Safety Pilot Model Deployment (SPMD),” [17] andthe other is “Integrated Mobile Observations 2.0 (IMO)” [18]. The first aimed to assess the effectiveness of Connected Vehicles (CV) safety technologies, while the second

focused ongathering weather-road data from a fleet of 60 vehicles on the I-94 corridor and providing itto weather analysts.

The number of deployed C-ITS-based projects has grown significantly in recent years. The "Heavy Truck Cooperative Adaptive Cruise Control" project, sponsored by FHWA and Auburn University, was to implement Driver Assistive Truck Platooning (DATP), a type of Cooperative Adaptive Cruise Control (CACC) for heavy trucks. The project utilized radars, dedicated short-range communications (DSRC) based on Vehicle-to-Vehicle (V2V) communications, and satellite positioning technologies [19]. The "ConnectedVehicle Pilot Deployment Program," launched by USDOT, aimed to combine innovative CV technologies and mobile applications to enhance traveler mobility and safety and reduce environmental impacts. The program's first phase, completed in September 2016, involved developing operational concepts, system requirements, safety plans, and benefits evaluationplans. The second phase focused on detailed design, field equipment development, softwareintegration, and installation of in-vehicle devices and roadside infrastructure. The final phaseincluded activating New York City (NYC), Tampa, and Wyoming applications [20]. The NYC pilot focused on safety applications using V2V, I2V, and Infrastructure-to-Pedestrian (IVP) communications in three corridors, covering 300 Road Side Units (RSUs) and 8000 CVs [21]. The Tampa pilot aimed to reduce congestion and collisions, enhance pedestrian safety, speed bus operations, and reduce conflicts using CV technology with 1600 cars, 10 buses, 10 trolleys, 500 pedestrians, and 40 RSUs [22]. The Wyoming pilot targeted safety improvements and incident-related delay reduction with 400 vehicles, including heavy trucks and fleet vehicles, along with 75 RSUs [23]. In addition, USDOT's "Smart City Challenge" project led to the "Columbus Smart City demonstration" project in Ohio, focusing on CV deployment, infrastructure upgrades, and integrated data platforms to improve safety, mobility, and environmental sustainability [24]. The project involved variousCV applications and equipment across different vehicle types and intersections. Other projects like TPIMS, Ohio Smart Mobility Corridor, and the 5.9 GHz DSRC Vehicle-basedRoad and Weather Condition Application also contributed to advancing CV technologies and real-time information

provision for transportation efficiency and safety [25].

Similar to the United States, various activities have taken place in European countries. Under the Sixth Framework Programme (FP6) and the Seventh Framework Programme for Research and Technological Development (FP7), the European Commission(EC) funded several projects focused on cooperative systems and real-time safety-related traffic/information provision for drivers. Projects under FP6 included SAFESPOT, COOPERS, and CVIS, while FP7 initiatives included SAFERIDER, euroFOT, SISCOGA, PRESERVE, COMeSafety2, FOTsis, ITSSv6, MOBiNET, P4ITS, VRUITS, COMPANION, HeERO2, TeleFOT, DRIVE C2X, eCoMove, interactIVe, and OVERSEE [13]. Further, the CIP funded five projects for advancing cooperative intelligent transportation systems (C-ITS). FREILOT is aimed at energy-efficient road goods transportvia C-ITS services, optimizing freight routes for reduced fuel consumption. COSMO showcased energy efficiency from cooperative traffic management, enhancing urban trafficflow. HeERO prepared Europe for eCall, a standardized in-vehicle emergency call system, improving response times and road safety. These projects were pivotal in C-ITS technology advancement, promoting energy savings and enhancing safety measures like automatic emergency calls [13].

Furthermore, the Compass4D project implemented three cooperative services (Road Hazard Warning, Red Light Violation Warning, and Energy Efficient Intersection service) in seven European cities: Bordeaux, Copenhagen, Eindhoven-Helmond, Newcastle, Thessaloniki, Verona, and Vigo. These services aim to enhance road safety and energy efficiency through advanced communication technologies [13]. Similarly, the CO-GISTICS project focused on implementing C-ITS services to increase energy efficiency and reduce CO2 emissions in seven European cities/logistics hubs: Bordeaux, Frankfurt, Thessaloniki, Trieste, Arad, Bilbao, and Vigo. The project aimed to optimize logistics operations and traffic management using cooperative systems. Under the Connecting Europe Facility (CEF)funding instrument (2014-2020), several projects were supported to promote wide-scale C- ITS deployment in Europe.

Projects such as SCOOP@F, Repsol Security Parking, I_HeERO, NordicWay, CITRUS, SolC-ITS, InterCor, and CRoads aimed to establish harmonized specifications and strategic rollout plans for C-ITS implementation across EU members. Additionally, under the Horizon 2020 programme (2014-2020), projects like PROSPECT, CIMEC, CODECS, XCYCLE, and C-MobILE were launched to support strategic and technical policy solutions for the C-ITS rollout. These projects focused on deploying C-ITS services in urban environments to ensure safe and efficient road transport for Vulnerable Road Users (VRUs). At the national and international levels, various projectswere initiated to advance C-ITS technologies and implementation. These projects included CoCarX, simTD, Ko-FAS, UR:BAN in Germany; SPITS, Brabant InCar II: ParckR, Beter Benutten programme, DITCM in the Netherlands; Testfeld Telematik and ECo-AT in Austria; SCORE@F in France; A2/M2 Connected Vehicle Corridor in the UK; and Cooperative ITS Corridor involving German, Dutch, and Austrian road operators for European-wide C-ITS implementation. These initiatives aimed to create living laboratories,develop standardized C-ITS applications, and improve traffic management and road safety through cooperative systems [13].

The most recent C-ITS projects in Europe include the C-Road project implemented in 53 cities in eighteen European countries [11]. The project has over 20,000 km covered with ITS-G5, 100,000 km with cellular/long-range, and 2,300 fixed and mobile operating RSUs. In Austria, C-Roads Austria, following the European C-ITS Corridor project, aims to establish an operational C-ITS system on Austrian motorways. Starting with a 2018 tender,hundreds of roadside stations were planned, including ITS-G5 technology and various use cases. In late 2019, pilot installations of 25 ITS-G5 roadside stations began around Vienna,Graz, and Linz. Siemens Mobility Austria was contracted for national deployment, coveringcentral C-ITS stations and 175 ITS-G5 stations. The second phase of C-Roads Austria expanded roadside stations, focusing on multimodal traffic management and public transportintegration [11]. In Belgium, The C-Roads Flemish pilot utilized cellular-based mobile networks, HERE Location Cloud, and the Traffic Management Centre to provide Safety Related Traffic Information (SRTI) to approximately 650 test drivers, following EU regulations.

Partners included the Flemish Department of Mobility, HERE, ITS.be, and Tractebel Engineering, covering motorways in Flanders, focusing on E313/E34 segments for evaluation. Use cases included accidents, road obstacles, and extreme weather. The pilot aimed to assess a cloud-based infrastructure for effective C-ITS deployment, connecting road users with the Traffic Management Centre via a smartphone app called Hermes [11]. The Czech Republic, a founding member of the C-Roads Platform, leverages its C-ITS experience across cities, public transport, railways, and motorways. Cities like Brno, Ostrava, and Pilsen showcase fully implemented C-ITS, even on trams and railway crossings. C-ITS services on Czech motorways offer vital hazard warnings, aiding driver adjustments. Urban projects in Brno foster complex C-ITS networks with public-private cooperation, ensuring interoperability. Challenges in equipping public transport vehicles highlight coordination needs with railway regulations. Further, pilots in Pardubice address level crossing safety, while data protection remains a critical focus for C-ITS credibility andlegislative changes [11]. Other countries where the C-Roads project has expanded include Finland, France, Greece, Ireland, Spain, Hungary, and Slovenia [11].

In Asia, Cooperate Intelligent Transportation Systems have been developed since the1970s, starting with policy formulations and the establishment of research institutions. Research has been conducted to investigate the technology to suit the country's needs. Pioneers of C-ITS technology in Asia have been Japan from the early days, followed by China, South Korea, India, Singapore, and Thailand [26].

Several initiatives have been established in Japan that have a compounding effect onthe development of C-ITS systems. The promotion of ITS as a government policy of the 1996 Comprehensive Plan for Intelligent Transport System (ITS) master plan and 1999 Systems Architecture for ITS positioned guidelines for the work that follows the years to come. In 2005, the Electronic Toll Collection (ETC) service started and has since grown to adopt international standard certifications (ISO 15628, ISO 14906, and ISO 17574) [12]. In 2014, Due to the progression of technology and

research, Japan shifted to ETC 2.0, which integrates 5G technology, AI, cameras, Vehicle performance information sensors, VICS technology, and other information combinations to achieve safety-related improvements in their transportation systems. The goals and objectives of the Japanese are to reduce crashesand fatalities and are not constrained by current knowledge, practices, or technology. Thesegoals are seen to be sufficiently important to drive researchers toward eventual encompassing solutions [27].

The development of ITS in Singapore came after the poor performance of the Singaporean Traction Company (STC), which led to the birth of the Singapore Mass RapidTransit Corporation (SMRT) in 2001 and was renamed SMRT Buses Ltd in 2004 [26]. By 2010, ITS systems had worked with information and control technologies, which provided core ITS functionalities such as loop detectors, traffic identification systems, bus route identification systems, and the use of IoT in ITS [28]. Singapore's experience in utilizing smart technologies to achieve a sustainable transport system shows that the technologies have enhanced the overall safety and efficiency of the transport system [29].

In the 1970s, China began a policy of reform and opening; the policy led to the development of road transport, which accelerated the urbanization and motorization of citiesin China [30]. From the 1980s, research on highway toll collection systems, driver behavior,and intelligent vehicles started in universities such as Wuhan University of Technology, Shanghai Jia Tong University, and Tsinghua University [31]. The Republic of China initiated the C-ITS to elevate the connected communication system of vehicle-to-any. In theshort term, the expressway information for safety and traffic management is disseminated while encouraging roadside and in-vehicle equipment collaboration is set for the long-term [26]. China now has new national strategies and interests, such as active vehicle safety and intelligent vehicles, vehicle road network synergy, integrated traffic management and emergency systems, Cooperative Driving for Platoons, and Intelligent Transportation Management [31].

The success of nations like Japan, China, South Korea, and the US-led Thailand to startthe process of adopting ITS to its transportation policy. In 2019, they succeeded in setting up a master plan to achieve smart transport by 2027. Main ITS areas are traffic control systems, commercial vehicle operations, travel information systems, advanced public transportation systems, automation traffic enforcement, and toll collection. Thailand's model aims to replicate the benefits of countries that pioneered the technology in their transportation systems by 2027 [26].

2.3.Review of Traffic Safety and Efficiency in the Existing Literature

Cooperative Intelligent Transport Systems (C-ITS) have gained significant attentionin recent research due to their potential to improve traffic safety and enhance the efficiencyof transportation networks. Various studies have evaluated the potential of C-ITS to improvesafety and traffic flow efficiency.

Regarding the safety aspect of C-ITS, rigorous studies have evaluated C-ITS's contribution to minimizing accidents, optimizing traffic flow, and bolstering the resilience of transportation systems. These investigations have highlighted the potential of C-ITS to reduce road hazards and streamlinevehicle movements significantly.

The innovative metrics Javed and Ben Hamida [32] introduced in 2016 have helpedevaluate vehicle safety awareness in C-ITS environments. The objective of their study was to evaluate and analyze the reliability of various applications supported by Cooperative Intelligent Transportation Systems (C-ITS) by proposing two novel safety awareness metrics(SAM) that consider factors such as age and weight of received cooperative awareness messages (CAMs). The study aimed to enhance vehicle safety awareness and provide accurate information about vehicles in the vicinity through regular sharing of CAMs. The methodology involved using simulation results in NS-3 to compare the proposed SAMs withexisting metrics like packet delivery ratio, which do not consider the accuracy of received information. The data source was simulation

data from NS-3, and the data type included metrics related to vehicle safety awareness. The key findings indicate that the proposed SAMs offer a more realistic view of vehicle safety awareness compared to current metrics, highlighting their importance in analyzing the reliability of applications in C-ITS and tuning wireless transmission parameters for maintaining the required quality of service. This is a significant step forward in understanding and enhancing safety protocols within these systems. Additionally, Elhenawy et al [33] evaluated the safety benefits of Cooperative Intelligent Transportation Systems (C-ITS) deployed in various cities, particularly focusingon Field Operational Tests (FOT) to demonstrate these benefits and enhance public awareness and uptake. The study introduced safety hypotheses for seven driver safety use cases being tested in the Ipswich Connected Vehicle Pilot by the Queensland Department ofTransport and Main Roads in Australia. Safety performance indicators were also introducedto test these hypotheses. The methodology involved evaluating C-ITS algorithms triggeringsafety events and Human-Machine Interface (HMI) messages to induce expected driver behavior changes. Data collection relied solely on information from C-ITS units without additional sensor augmentation. An experiment conducted at the Mt Cotton training facility near Brisbane involved collecting Cooperative Awareness Message (CAM) messages to analyze speed and acceleration data for detecting speed changes and braking behavior. The analysis revealed successful detection of speed changes but identified noisy acceleration/braking patterns requiring careful manipulation for accurate braking behavior retrieval. Biral et al. [34] highlighted the contribution of the SAFESTRIP EU project's technology to implementing Dynamic Local Maps used by Cooperative Intelligent Transportation Systems (C-ITS) safety applications. The road strips developed in SAFESTRIP can detect and estimate the longitudinal and lateral positions of vehicles at thelane level, a feature utilized by various C-ITS applications. The study focused on describing a Cooperative Intersection Support application as an example to illustrate this concept and emphasize the benefits offered by the road strip information. The SAFESTRIP technology was shown to enhance the performance of existing C-ITS applications by providing accuratelocalization at the lane level for both equipped and unequipped vehicles. While the study presented simulation results regarding the performance of the

Cooperative Intersection application with three approaching vehicles at a T-shaped intersection, it noted that factors such as communication latency, localization accuracy, and the number of vehicles were notthoroughly investigated. Biral et al. [34] proposed that the next steps should include evaluating the technology's performance through extensive and more accurate simulations using traffic generator software and experimental testing, including user trials, to assess its effectiveness in real-world scenarios further. A study by Erick [35] focused on addressing the potential errors in disseminated velocity accuracy within Cooperative Intelligent Transport Systems (C-ITS), particularly concerning automated and autonomous driving contexts where such errors can lead to accidents. The study emphasized the importance of detecting and warning vehicles about inaccuracies in the speed reported by vehicles in C- ITS Cooperative Awareness Messages (CAM). To showcase their solution's potential, the study presented two use cases: platooning green light priority and cyclist safety in scenarioswhere a cyclist unexpectedly enters a vehicle's lane. Their solution integrates a Roadside Unit (RSU) with a velocity detection device to ensure the accuracy of disseminated velocities in C-ITS messages. The methodology involved comparing disseminated velocities in CAMswith velocities obtained from standard speed detection devices. Emulating a vehicle sendingand receiving C-ITS messages in a virtualized environment, the RSU receives and processesC-ITS messages to detect inaccuracies in disseminated velocities, if any, and issues warningsaccordingly. The study reported that their solution can process information and report inaccuracies in less than 500 μs, highlighting its feasibility for real-time applications and introducing a data calibration warning beneficial for autonomous vehicles. Pirkko Rämä and Satu Innamaa [36] evaluated the impact of Cooperative Intelligent Transport Systems (C- ITS) on traffic safety and reassessed assumptions from previous studies while updating safety estimates. Seven C-ITS services warning about various hazards were selected, and expert estimates were grounded on new evidence about driver behavior, crash categories inthe European Risk Calculation tool (ERiC), and literature. The study found that C-ITS services significantly reduce fatalities and injury crashes, with the largest drop in fatalities observed for 'In-vehicle signage, speed limit' and 'Weather warning' being the second most effective. Other effective services included 'Warning of

emergency braking ahead' and 'Roadworks warning', while 'Traffic jam ahead warning', 'Car breakdown warning', and 'In-vehiclesignage, child and pedestrian crossing ahead' had smaller but still positive impacts. Generally, the effectiveness was slightly lower for injury crashes compared to fatalities. The authors concluded that these results support the implementation of C-ITS services as both standalone measures and as support for more intervening Intelligent Transport Systems (ITS)and automated driving technologies. Lara et al., [37] focused on the challenges and trade- offs involved in integrating vulnerable road users (VRUs) such as pedestrians, cyclists, and motorcyclists into Cooperative Intelligent Transportation Systems (C-ITS). While C-ITS advancements aim to improve VRU safety, concerns arise regarding increased channel congestion due to VRU-generated messages. Existing studies primarily concentrate on network-related metrics, overlooking VRU safety metrics. The study addressed this gap by evaluating motion-based message generation rules for VRU transmissions and analyzing them through theoretical and simulation-based assessments. In addition to traditional channel load metrics like channel busy ratio (CBR) and packet delivery ratio (PDR), a new metric called VRU Awareness Probability (VAP) was introduced. VAP measures the probability of VRU detection by nearby vehicles by exchanging messages from active VRUs. The results indicated that while fixed message-filtering mechanisms reduce channelload, they may hinder VRU detection. The study emphasized the importance of quantifyingVRU awareness for C-ITS analysis due to its direct impact on VRU safety. It also discussedstrategies involving VRU context and dynamism to enhance message generation rules, highlighting the need for a balanced approach considering both network efficiency and VRUsafety.

Apart from traffic safety, overall traffic flow, delays, and congestion have been the key focuses of studies that evaluated the implications of C-ITS on traffic efficiency. Chalkiadakis et al. [38] assessed the operational performance of transportation networks during Extreme Weather Events (EWEs) and the effectiveness of Cooperative Intelligent Transportation Systems (C-ITS) in mitigating their impacts. The study emphasized the importance of quantifying network behavior under

disturbances like EWEs and highlighted the need for proper Traffic Management Strategies to maintain road network efficiency. By implementing Cooperative Awareness Messages and In-Vehicle Information C-ITS services, the research investigated their impact on two urban transportation networks during EWEs. The findings indicated that integrating c-ITS strategies with other Traffic Management Strategies resulted in improved operational performance of the transportation network, leading to more efficient management during EWEs. This highlights the potential of c-ITS in enhancing network resilience and ensuring smooth operations under challenging conditions like Extreme Weather Events. Lu et al., [39] study explored the impact of Connected Automated Vehicles (CAVs) on urban road networks, a crucial aspect of the Cooperative Intelligent Transportation System (C-ITS). Using Simulation of Urban MObility (SUMO), a microscopic traffic simulator, the study assesses various factors such as network maximum flow, critical density, average speed, congestion duration, and roadway over-saturation degree with different penetration levels of CAVs. The MacroscopicFundamental Diagram (MFD) is employed to estimate maximum flow and critical density, revealing that a road network can exhibit less scattered MFDs even with heterogeneous traffic flow distribution. Analysis of congestion duration and over-saturation degree aids inevaluating traffic congestion. Simulation results demonstrate that a 100% CAV deploymentcan lead to a 13.55% increase in maximum flow and a similar trend in critical density improvement. Moreover, the network with 100% CAVs can handle over 130% of the original travel demand under comparable congestion scenarios, showcasing the significant enhancement in traffic conditions even with low CAV penetration rates. Hapner et al [40] examined the optimization of traffic flow using Cooperative Intelligent Transportation Systems (C-ITS) in conjunction with public transport. A novel traffic signal control model based on the C-ITS framework was developed to enhance traffic speed and reduce emissions from public transport vehicles by minimizing unnecessary stops at signalized intersections. The study conducted simulations and tests in the C-ITS test area in Kassel. Results from both simulation and real-world testing demonstrate that public transport vehicles equipped with C-ITS experience higher speeds and fewer unnecessary stops before intersections. This indicates more efficient traffic flow control with the inclusion of prediction and

drive strategies. The simulation model revealed that early coordination between the traffic signal system and vehicles can influence driving strategies. Implementing C-ITS in the test area positively impacted public transport efficiency by dynamically adjusting green phase releasetimes based on the vehicles' movement states, thereby reducing energy loss and exhaust emissions from braking and stopping at traffic lights. Overall, prioritizing public transport with C-ITS offers additional avenues to achieve environmental and traffic management goals.

In summary, the investigation into Cooperative Intelligent Transport Systems (C- ITS) in terms of their development, application, and impact on traffic safety and efficiency emphasizes the transformative potential of these technologies in redefining road safety and transportation efficiency. By carefully examining technological advancements, policy initiatives, and regional implementations and conducting rigorous assessments of their effectiveness in improving traffic management, the collective body of research highlights afuture where C-ITS will play a central role in promoting safer, more efficient, and resilient transportation networks. The practical application and scalability of C-ITS are exemplified by innovative solutions and methodologies developed by companies such as Jumpdrive, paving the way for broader adoption and realizing its full potential in enhancing global transportation systems.

3. C-ITS SCENARIOS AND TRAFFIC SAFETY

The C-ITS Scenarios in Traffic Safety can be grouped into three parts: the effects of V2V,V2I, and V2X scenarios on traffic safety, the effects on preventing accidents and reducing damages, and the comparative analysis and evaluation of different scenarios. The next section presents the effects of V2V, V2I, and V2X scenarios on traffic safety.

3.1.Effects of V2V, V2I, V2X Scenarios on Traffic Safety

Overall, the V2V, V2I, and V2X scenarios have the potential to improve safety as indicated by various studies. The available studies can be divided into survey-based and simulation-based, and the actual data can be used. While a few studies present the actual scenarios of the V2V, V2I, and V2X scenarios in action, numerous studies are based on thesimulations and surveys. In most cases, the simulation-based approach was utilized due to the unavailability of the actual C-ITS data or the high cost of acquiring the data.

Karkhanis et al., [41] explored the application of Agent-Based Modelling and Simulation (ABMS) to assess the impact of Cooperative Intelligent Transport Systems (C- ITS) on safety and efficiency at the Neckerspoel intersection in Eindhoven, the Netherlands.The primary objective was to overcome the challenges associated with evaluating C-ITS without relevant data and established traffic systems, aiming to prevent unnecessary costs. By employing simulations that encompassed various scenarios at both unsignalised and signalized intersections, the study sought to understand how different types of road users, including attentive, distracted, and reckless individuals, interacted with C-ITS technologies.The methodology involved developing an ABMS framework to model and simulate the traffic scenarios at the Neckerspoel intersection. Data sources included traffic flow patterns, road user behavior, and the performance of C-ITS agents such as the On-Board Unit (OBU)and Central Warning Light (CWL). The simulation experiments were conducted using these

models to observe and analyze the impact of C-ITS on safety and efficiency metrics.

The key findings of the study revealed that the deployment of C-ITS agents, particularly the OBU and CWL, led to notable improvements in safety and efficiency at theNeckerspoel intersection. Specifically, the simulations showed a reduction in hard braking events and waiting times, especially for distracted cyclists who responded positively to warnings provided by the CWL. This resulted in a smoother traffic flow and reduced instances of sudden stops or delays, ultimately enhancing the overall safety of the intersection for all road users. Furthermore, the study highlighted the importance of ABMSin pre-evaluating traffic scenarios before implementing C-ITS systems in real-world settings. The simulations provided valuable insights into how different road user behavior types interacted with C-ITS technologies and how these interactions influenced safety and efficiency outcomes. These findings were instrumental in informing the redesign of the Neckerspoel intersection, demonstrating the practical utility of ABMS in urban traffic management and decision-making processes [41]. Looking ahead, the study proposed several avenues for future research. Firstly, expanding the ABMS model to encompass larger districts with multiple intersections would allow for a more comprehensive assessment of C-ITS impacts on a broader scale. Additionally, incorporating additional road user types suchas cars and pedestrians into the simulations would provide a more holistic understanding ofC-ITS effects across different modes of transport. Finally, integrating traffic uncertainty into the ABMS model would enable more realistic simulations and better preparation for potential challenges in future C-ITS deployments.

Further, a study by Jo et al., [42] focused on developing a road safety information system within the framework of Cooperative Intelligent Transport Systems (C-ITS), leveraging high-resolution Connected Vehicle (CV) data from a pre-deployment project onKorean freeways. The objective was to assess individual vehicle crash risks using the CrashPotential Index (CPI) and to devise a methodology for evaluating road safety risks on freeways. High CPI values were notably observed in

toll plaza areas, recurrent congestion sections, and on/off-ramp areas. The study found a statistically meaningful relationship between estimated CPI values and actual crash frequencies, indicating the potential utility of the proposed system for crash risk assessment. Moreover, microscopic traffic simulation experiments using VISSIM revealed that a minimum Market Penetration Rate (MPR) of approximately 30% was adequate for effective road risk assessment in a CV environment. The proposed road safety information system holds promise for enhancing traffic safety by providing forward hazardous event information to CVs. The methodology can contribute to reducing crash risks in lane control scenarios like crashes and work zones, potentially through concepts like the risk wave theory. However, the study acknowledges several areas for further enhancement. Collecting additional CV data to address limited sample size issues, integrating various Safety Surrogate Measures (SSMs) for crash potential estimation, refining CPI calculations based on more realistic Maximum Allowable Deceleration Rate (MADR) distributions, and conducting simulation calibrations based on actual crash scenarios are recommended steps. Additionally, the study emphasizes the need to develop effective traffic operations strategies based on data from the proposed system, incorporatingdriver behavior responses to CV technologies for practical applicability and system optimization.

Furthermore, a Topillin and Konovalova [43] study aimed to review and present thepositive outcomes of implementing Cooperative Intelligent Transportation Systems (C-ITS)in modern road traffic management. The data used in this study comprised information from various sources, including traffic accident reports C-ITS implementation statistics, and simulation data. The methodology involved analyzing existing data and conducting simulations to assess the impact of C-ITS implementation on road safety. Data sources included government agencies, traffic management authorities, and research institutions, providing both qualitative and quantitative data. The key findings of the study indicated thatthe implementation of C-ITS resulted in a significant reduction in accidents, with a reporteddecrease of 76%. Additionally, fatal accidents were eliminated, showcasing the effectivenessof C-ITS in enhancing road safety and traffic management in urban areas.

Moreover, the objective of the Weibull et al., [44] study was to identify common risk factors associated with emergency vehicle (EV)-related accidents and explore potentialcountermeasures using Cooperative Intelligent Transport Systems (C-ITS). The data used consisted of 22 articles that were systematically reviewed to analyze the frequency of risk factors and suggested countermeasures. The methodology involved examining the literatureon EV-related accidents to determine prevalent risk factors, such as intersections, daytime driving, dry roads, clear weather, urban roads, traffic signals, and angular collisions. Countermeasures proposed in the literature included driver training for EV operators, public education, cautious driving at intersections, seatbelt usage, and intelligent vehicle technologies. The study also focused on three specific C-ITS services—EV approaching, EV preemption, and geofencing—which were assessed for their potential to inform, warn, or control driving aspects and reduce risk factors. The findings highlighted the potential of C-ITSs to mitigate EV-related accident risks and guided their implementation and effectiveness. Further research is recommended to explore driver behavior in response to C-ITSs and their impact on accident prevention.

Additionally, the objective of the study by Outay et al., [45] was to assess the effectiveness of connected vehicular technologies, specifically Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, in alerting motorists near hazardous zones and recommending appropriate speeds, focusing on scenarios like low visibility areas.The methodology involved presenting the principles of a safety driving system and conducting a comparative performance analysis between V2V and V2I communications in terms of road safety effectiveness and network communication efficiency. This analysis wasbased on extensive computer simulation experiments using the iTetris platform across various scenarios. Additionally, the study explored the potential of Cooperative Hazardous Area Awareness (CHAA) systems, based on V2V and V2I communications, to contribute toeco-driving by reducing Carbon Dioxide (CO2) emissions through speed harmonization. The data source comprised simulated

traffic scenarios, and the key findings indicated that the V2I communication-based alerting system achieved a better message reception rate andsafety efficiency compared to the V2V system. Furthermore, the results highlighted the potential of the CHAA system in reducing CO2 emissions by promoting speed harmonization strategies among vehicles.

3.2.Effects on Preventing Accidents and Reducing Damages

Relatively few studies have evaluated the impact of C-ITS on the prevention of crashes and reducing damage, especially using the actual crash data. This may be attributedto the lack of crash data involving vehicles of systems with the C-ITS.

A study by Kang et al., [46] aimed to assess the impact of Cooperative Intelligent Transport Systems (C-ITS) services on driving behavior, particularly focusing on a pilot project in Daejeon–Sejong, South Korea. The data utilized in this research encompassed monthly driving behavior metrics obtained from 969 vehicles equipped with On-Board Units(OBU) within the pilot area. This data spanned from February 2017 to January 2018, allowing for a comprehensive analysis of driving behavior changes following the implementation of C-ITS services. The study employed paired sample t-tests to compare driving behavior metrics between two distinct periods: the pre-service period represented byFebruary 2017 and the period during which C-ITS services were actively utilized (April 2017 to January 2018). The metrics under investigation included average speed, hard braking rate, severe deceleration rate, speeding rate, and excessive speeding rate. These metrics served as key indicators to evaluate changes in driving behavior patterns among C-ITS service users.

The findings of the study by Kang et al., [46] revealed significant alterations in driving behavior after the initiation of C-ITS services. One notable observation was the gradual decrease in average vehicle speed over time, with occasional temporary

increases observed during specific periods such as February and May. This trend in average speed indicated a shift towards safer driving practices among users of C-ITS services. Furthermore, the study notedimmediate reductions in hard braking and severe deceleration rates following the commencement of C-ITS service provision. These changes signify improved driving smoothness and decreased abrupt maneuvers, typically associated with higher accident risks.The data also showed that the speeding and excessive speeding rates exhibited decreases after four months, highlighting a shift towards more compliant and controlled driving behavior among C-ITS users over time. The observed order of changes in driving behavior metrics indicated that the most immediate improvements were in hard braking and severe deceleration rates, followed by a gradual decrease in average speed, and finally, reductions in speeding and excessive speeding rates. This sequence suggests a progressive adjustment in driving habits towards safer practices among C-ITS service users. These findings underscore the positive impact of C-ITS services on enhancing road safety by promoting smoother driving behaviors and reducing risky maneuvers. However, the study also acknowledges the need for further research to explore additional variables that may influencedriving behavior and to provide a more comprehensive evaluation of C-ITS effectiveness inimproving overall road safety [46].

4. C-ITS- SCENARIOS AND TRAFFIC EFFICIENCY

The C-ITS- scenarios and traffic efficiency can be grouped into three sections: the effectsof V2V, V2I, and V2X scenarios on traffic efficiency, the effects on traffic flow, density, andtransportation time, and the assessment of environmental impacts and sustainability issues. The next section presents the reviewed literature for each aforementioned section.

4.1.Effects of V2V, V2I, V2X Scenarios on Traffic Efficiency

A study by Mai *et al.,* [47] discussed the Cooperative Intelligent Transport System (C- ITS)- based lane- changing advisory for weaving sections as the most ordinary design of motorways that need extensive lane change maneuvers, especially when two or more cars are moving under the same lane, therefore when vehicles use the lane with the same travel direction, they will quick change the lane to avoid an accident with the help of intelligent transport system. Previous studies have found that the driver's decision to change lanes is triggered as soon as they enter the weaving section. Vehicles tend to merge over diverging movements, and traffic volumes also tend to increase on the road. The lane changing, however, results in traffic congestion that limits the use of the available infrastructure, something that affects the safety and operational systems while using the said infrastructure.Therefore, this study examined the changes easily upon the application based on a cooperative intelligent transport system in the weaving section. Further, this study [47] aimed to reduce the concentration and congestion caused by lane-changing by ensuring the coordination of weaving sections that will bring satisfactory lane-changing activities distribution over the weaving length of the road. It also aimed to automatically message thevehicle drivers on their exact location to advise them when they can start or stop changing their lane to ensure their safety. The study used the microscopic simulation in AIMNUS to collect data, which involved the cycle of updates regarding the unconditional scheduling list. It also provided a detailed representation of the traffic process, attempting to analyze the flow by modeling the driver-driver and driver-road interactions while using the road to evaluate

the effectiveness of the proposed strategy. The result suggested that lane-changing advisories, such as traffic demands and penetration rates, could potentially improve infrastructure delay to ensure the safety of road users [47].

Another study by Manogaran et al., [48] discussed the Pre-Predictive Congestion- Based Data Allocation for the Sixth Generation Cooperative Intelligent Transport System, considering the autonomous system that relies on intelligent sensing, computing, and actuating technologies for public movements. On the data collection, the research provides that data are collected from nearby vehicles using microwave sensors and automatically send a warning message to drivers to avoid collision. It uses data from the neighbors and communication infrastructures that can provide for efficient, safe, and sustained transportation. It also used data from the sixth generation of data (6G), including Terahertz and machine-type communication exploited to ensure swift information exchange for passing around the traffic congestion, which mostly occurs because the demand for roads exceeds the supply. The study predicted that in upcoming years, the mobile trend will increase mobile connections, resulting in the transformation from 5G to 6G. However, it acknowledges the need for further study on multi-flow analysis during handoff in autonomous vehicle navigation and remote operations. The paper's experiments show improved cooperation in real-time transport tasks, prioritizing late vehicles and reducing delays, though it suggests future work on multi-lane roads and non-recurring traffic routingfor comprehensive solutions. Therefore, the cooperative intelligent transport system will bepromising, efficient, and safer for the environment.

Zhang et al., [49] investigated lane drop scenarios on motorways and proposed a lane-changing advisory control system leveraging Cooperative Intelligent Transport Systems(C-ITS) technology to mitigate congestion and improve traffic efficiency. Utilizing hyper- heuristic optimization, it determines the optimal lane-changing advisory proportions for eachsegment upstream of the lane drop. Microscopic traffic simulations conducted using AIMSUN and its API function reveal that the proposed

strategy effectively reduces congestion and enhances traffic flow. Additionally, the study evaluates the impact of connected vehicle proportions, finding that significant performance gains are observed withpenetration rates above 50%, while lower rates have minimal impact on lane drop performance. The key findings highlighted that advising 60% of vehicles in the shoulder lane to change lanes 100 m upstream of the bottleneck and 40% to change lanes 400 m upstream significantly improves traffic efficiency, especially under high and middle traffic demand conditions. Additionally, the study analyzed different proportions of connected vehicles and found that the impact of lane-changing advisory on lane drop efficiency depends on the ratio of connected vehicles, with marginal gains observed when the connected vehicle ratio exceeds 50%. However, the study's limitation was that it only analyzed lane-changing advisory control in the leftmost lane, neglecting other lanes, which the authors plan to investigate in future research.

A study by Agriest *et al.,* [50] explored the imminent integration of automated vehicles (AVs) onto public roads alongside traditional vehicles, a transition that academia widely anticipates. However, the potential conflicts between these distinct types of drivers and their tangible impacts on traffic flow remain largely unexplored. The primary objectiveof this research is to investigate the Highway Chauffeur, an L3 automated system projectedfor short-term deployment on public roads. Specifically, the analysis focuses on a work zonescenario to evaluate the positive effects resulting from the combined implementation of the Highway Chauffeur system and a C-ITS Use Case signaling lane closure. To achieve this goal, the Agriest *et al.,* [50] study relied on traffic simulations conducted using the VISSIMsoftware and a custom Python script developed by the authors. These simulations form the basis of assessing the potential benefits in travel times and driving patterns arising from thecollaborative use of the Highway Chauffeur system and C-ITS messages. The methodology involves a comprehensive description of the entire assessment process, including data collection, analysis, result interpretation, and comparison to identify the optimal implementation approach for maximizing the benefits of L3 driving in the specified scenario.The results of the study are particularly enlightening. They reveal that triggering the take- over

maneuver in advance significantly enhances bottleneck efficiency. For instance, the study notes that speed values equivalent to those achieved at 80-100% Market Penetration within a 700 m range of the C-ITS message can be attained with only 50% Market Penetration when extending the range to 1500 m. Additionally, the study records a notable speed increase of up to 30 km/h at the bottleneck, depending on the market penetration rate and the message range utilized. Furthermore, the research shows a 6% reduction in delay upstream of work zone entrances, occurring approximately 700 m away, without necessitating the deployment of the message over a 1500 m range. This study highlighted the significant impacts of take-over maneuvers and automated driving, considering various operational parameters like message range. It underscores the potential benefits of integrating Highway Chauffeur systems with C-ITS technologies. The findings offer valuable insights into the efficiency gains and traffic improvements achievable through such integration, with implications for future AV deployment strategies. The study concludes by emphasizing the need for further exploration and precise impact assessments using different AV prototypes and infrastructure configurations. The development and availability of tools for conducting similar analyses pave the way for continued research and optimization in cooperative intelligent transportation systems, ultimately contributing to safer, more efficient roadways in the evolving landscape of automated driving.

4.2.Effects on Traffic Flow, Density, and Transportation Time

The study by Englund et al., [51] focused on Cooperative speed harmonization using floating car data to enhance maneuverability at a heavily utilized intersection. Cooperative Intelligent Transportation Systems (C-ITS) leverage wireless communication to collect real-time traffic data and disseminate aggregated information to road users, aiming to improve efficiency, safety, and comfort. Simulation results demonstrate that the proposed speed harmonization application can increase average speed by up to 14%, and decrease travel time by up to 16% for all vehicles in the simulation. Interestingly, both cooperative and non-equipped vehicles benefit from the

application's effects. Additionally, the study highlights the effectiveness of the cooperative traffic simulator in exploring the potential of C-ITS applications for future traffic systems.

Another study by Sharma et al., [52] developed and evaluated an in-vehicle Cooperative Intelligent Transport Systems (C-ITS) application aimed at enhancing traffic efficiency in merging sections of freeways. Unlike previous research, this study incorporated multiple vehicle classes into the lane-changing advisory framework, focusing on balancing traffic distribution across available lanes through targeted advice to selected vehicles. A multi-class multi-lane macroscopic traffic flow model was utilized to design a feedback- feedforward control law based on a linear quadratic regulator (LQR). The system's performance was assessed using a microscopic traffic simulator. The findings demonstrated that the lane-changing advisory system effectively mitigated Shockwaves in traffic flow, leading to a substantial alleviation of congestion. Notably, the system contributed to significant travel time benefits around merging sections, with reductions of up to nearly 21%.

Additionally, the system played a crucial role in reducing the variance of travel time losses within the system, indicating improved reliability and predictability of travel times for commuters. The study showcased the effectiveness of the in-vehicle C-ITS application in enhancing traffic efficiency and reducing congestion around merging sections of freeways. The integration of multiple vehicle classes in the advisory framework, coupled with the feedback-feedforward control strategy, demonstrated promising results in improving overall traffic flow and travel time predictability.

Agriest et al., [53] performed a comprehensive of implementing a work zone warning C-ITS use case on Italian highways using microsimulations, aiming to understand its impactson traffic dynamics. Their study was significant in the context of expanding the relatively limited body of research concerning work zones and investigating the potential benefits andchallenges associated with integrating C-ITS

systems in such scenarios. The primary objective was to provide valuable insights that could inform upcoming C-Roads Italy trials in 2020, aiding in the assessment and validation of these systems in real-world driving conditions. The methodology employed in this study involved the utilization of microsimulations to model traffic behavior and interactions in a virtual environment. This approach allowed the researchers to simulate various scenarios and analyze the effects of different market penetration levels of cooperative vehicles equipped with C-ITS capabilities. By simulating the deployment of the work zones warning C-ITS use case, the study aimed to measure its impact on traffic flow, queue times, travel times, delay reduction, and overalltraffic efficiency.

The results of the microsimulations [53] provided valuable insights into the potential benefits and challenges associated with implementing the C-ITS use case. One key finding was related to the throughput of the bottleneck, where it was observed that the deployment of C- ITS messages did not reduce the throughput, which is crucial for ensuring optimal traffic flow and capacity utilization. This finding highlighted the effectiveness of the C-ITS system in managing traffic without compromising overall throughput. Furthermore, the study highlighted the impact of market penetration levels of cooperative vehicles equipped with C-ITS capabilities on traffic dynamics. It was found that higher market penetrations led to significant reductions in queue times, with reductions of up to 60 seconds on the open lane and around 40 seconds on the closing lane observed at higher market penetration levels. This reduction in queue times can have substantial benefits in terms of improving overall traffic flow and reducing congestion, especially during peak hours and congested periods. Additionally, the analysis revealed a steady reduction in delay as market penetration increased, indicating the potential for C-ITS systems to enhance traffic efficiency and reducetravel times. The study also emphasized the importance of considering different implementation logics, such as broadcasting range and traffic compositions, in optimizing the effectiveness of C-ITS systems. Overall, the findings of this study underscored the potential of C-ITS systems to positively impact traffic management and efficiency, particularly in scenarios such as work zones and congestion. The

insights gained from this research can inform future C-ITS implementations, guiding policymakers, road operators, and car manufacturers in designing and deploying effective and efficient intelligent transportation systems.

Another study [54] introduces EPP-GLOSA, a path-planning strategy that leverages the collaboration between GLOSA and Dijkstra routing algorithms. EPP-GLOSAidentifies the fastest route by considering the state of traffic lights. Through a large-scale simulation scenario of Luxembourg city (LuST), we compared GLOSA, Dijkstra, and EPP- GLOSA strategies under varying traffic conditions. The study conducted extensive evaluations in both free-flow and rush-hour conditions to assess the effectiveness of EPP- GLOSA. Results demonstrate that EPP-GLOSA offers superior path planning, balancing fuel consumption and trip travel time. In free-flow conditions, EPP-GLOSA achieves significant fuel savings (up to 11%) and travel time gains (up to 20%). However, limitations emerge during peak hours, where waiting time and travel time gains diminish. Future work will focus on predictive approaches to mitigate queued vehicle delays, aiming to enhance performance, particularly in rush hour conditions.

Spanjer [55] explored the potential outcomes of implementing Cooperative Intelligent Transport Systems (C-ITS) applications, specifically focusing on Time to Green and Time to Red functionalities, with a comprehensive analysis covering environmental, safety, efficiency, and driver comfort aspects. These C-ITS applications aim to enhance traffic management and optimize driver experiences by providing real-time information about traffic light timings. To evaluate the impacts of these applications, the researchers conducted micro-simulations using the PTV VISSIM software, integrating external code to enable communication between C-ITS-equipped vehicles and the traffic signal system. Thestudy design encompassed a series of 11 variants, each representing different levels of C- ITS user penetration in the traffic network, ranging from no C-ITS usage to 100% adoption.This approach allowed for a systematic assessment of the effects of increasing C-ITS implementation on various

performance indicators. One of the key areas examined was safety, where the study observed a reduction in negative speed differences between sequential vehicles by approximately 10% as C-ITS penetration increased. This indicates that C-ITS applications like Time to Green and Time to Red contribute positively to promoting smoother traffic flow and reducing abrupt changes in vehicle speeds, thereby enhancing safety on the road.

Efficiency metrics were also scrutinized [55], with a focus on average queue length, stop delays, average speed, and travel time. The results showcased a notable decrease of approximately 15% in average queue length, signifying improved traffic flow and reduced congestion due to C-ITS interventions. However, a nuanced picture emerged regarding efficiency, as while average queue length improved, average speed witnessed a decline of around 8%, and travel time increased by approximately 10%. Furthermore, the study highlighted an important consideration regarding driver comfort. While C-ITS applications led to 25% fewer stops for most vehicles, right-turning traffic faced challenges, experiencing a 40% increase in stop delays. These vehicles, unaffected by C-ITS functionalities, encountered hindrances due to the altered traffic patterns induced by C-ITS-equipped vehicles. This underscores the need for holistic assessments that account for all types of traffic movements and potential disruptions caused by C-ITS implementations. The findings underscore the multifaceted nature of C-ITS impacts, emphasizing the importance of tailored strategies and comprehensive evaluations. While positive outcomes were observed in safety, environmental aspects, and certain efficiency parameters like queue length, challenges such as impacts on right-turning traffic and trade-offs in speed and travel time highlight the complexities involved in optimizing C-ITS applications for diverse traffic scenarios. Continued research and refinement of C-ITS implementations will be crucial in harnessing their full potential for improving transportation systems worldwide.

The study by Marousi and Stephanedes [56] aimed to address urban traffic congestion and port queueing delays in coastal urban areas by developing and testing a dynamic urban coastal traffic and port management system. While previous research primarily focused on congestion detection, there's been a lack of integration with port queueing systems. To address this, our study develops and tests a dynamic urban coastal traffic and port management system. It combines traffic and port gate operations control using ITS/C-ITS methodologies. Dynamic models, including artificial neural networks (ANN) and parameterized models, detect congestion in coastal urban road networks leading to ports. The system identifies optimal solutions for traffic and port queueing gate control. Through communication with users via connected vehicles and variable message signs (VMS), the system enhances efficiency and safety. Field testing conducted along a coastal urban road leading to Patras Southern Port, Greece, and at port control gates revealed significant benefits. Individual drivers heading to the port experienced tangible advantages, such as saving at least 7 minutes of travel time and consuming 0.306 liters less fuel. Society as a whole benefited from a remarkable 39.72% increase in traffic safety.

4.3.Assessment of Environmental Impacts and Sustainability Issues

Astarita et al., [57] estimated the Co-operative Intelligent Transportation Systems (C-ITS) as the systems specifically the EcoSafetyDrive (ESD) to ensure that the road operators, infrastructure, vehicles, their drivers, and other road users will cooperate to deliver the most efficient, safe, secure and comfortable journey. It is influenced by the ongoing growth of science and technology on satellite matters and mobile internet that allows communication among the technological tools on the road through the Global Navigation Satellite System (GNSS). The vehicle-vehicle and vehicle-infrastructure co-operative systems will contribute to these objectives beyond the improvements achievable with stand-alone systems". transportation sector. This study aims to press the global challenge of climate change, reductions in fuel consumption, congestion, and overall environmental impact, using the 6G technology

to revolutionize the transportation industry and further enhance the effectiveness of NETZero ITSs.

The study data collection is built upon the gathering of driving track data obtained by widespread smartphone technologies, collected by users concerning the fuel consumption, cost of the consumed fuel, maximum and minimum speed average, and later on, those data get transferred to the central elaboration unit of the system. At the end of the trip, the phone will illustrate the whole event as recorded [57].

Interaction between climate change and road transport is evident in terms of increasing risks for network managers and users and negatively affecting transport performance in major parameters, such as safety, reliability, and cost efficiency [58]. The need to limit adverse weather conditions effects on road transport urges to adapt of new mitigation policies, which will ensure transport resilience and sustainability. C-ITS services constitute an innovative array of technologies enabled by digital connectivity among vehicles and between vehicles and transport infrastructure, expected to significantly improve road safety, traffic efficiency, and driving comfort. In this way, C-ITS services can potentially increase the levels of safety for drivers in extreme weather situations by helping them make the right decisions and adapt to traffic situations. The C-MobILE project, funded under the Horizon 2020 program, envisions a fully safe and efficient road transport without casualties and serious injuries on roads by deploying C-ITS services for specific mobility challenges. The C-ITS services will be provided in bundles, to improve safety and traffic efficiency.

The study by Shawky et al., [59] examines the net-zero Intelligent Transport System as the best way of combating carbon emissions in the transportation sector. The study shows that by improving ITS, there will be vulnerabilities, including efficiency in traffic management, fuel consumption, reducing congestion, and environmental impacts as well. The ultra-high-speed, low-latency, and massive connectivity capabilities of 6G enable seamless integration of various components, such as

autonomous vehicles, smart infrastructure, and real-time data analytics. The research reveals that the successful implementation of NET-Zero ITSs and 6G technology requires collaborative efforts from stakeholders across multiple domains. Finally, the study recommends that Policymakers, industry leaders, researchers, and the public collaborate to establish supportive regulations, invest in infrastructure development, foster innovation, and promote public awareness.

A study by Aramrattana et al., [60] elaborated on the advantages of the C-ITS incorporating information and communication technologies into the transport systems. C- ITS strives for safer, more efficient, and more sustainable transport systems. Being connected will increase the awareness of vehicles about their surroundings and connect it to various programs such as radar, ultrasonic, camera, light detection and ranging (LIDAR), Global Navigation Satellite System (GNSS) receivers such as a Global Positioning System (GPS). Going through all possible scenarios in C-ITS is very difficult, almost impossible. This study aims to bring efficient and effective transport systems through cooperation, interaction, and dependencies among the road system actors. Studying C-ITS requires interdisciplinary knowledge. Existing methodologies and tools from only one research area are no longer feasible to efficiently test and evaluate C-ITS. A novel tool, methodology, or a combination of existing ones is needed. This study has also raised challenges towards the deployment of C-ITS. Firstly, providing sufficient reliability and reliable communication coverage is one big challenge that needs to be solved. Second, interoperability issues need to be considered. Third, there are challenges regarding the safety of the C-ITS functions. Last but not least, C-ITS introduce more complex scenarios and new possibilities; hence, going through all of them is almost impossible without extra cooperation between technology, stakeholders, and other road users.

The paper by Autili [61] introduces the concept of Cooperative Intelligent Transport Systems (C-ITS) enabled by connected automated vehicles, 5G, and the Internet of Things (IoT), where stakeholders cooperate to improve transport

performance. It highlights the abundance of available road and traffic information through standard services with different protocols, which can be leveraged to develop novel value-added applications. The paper presents the CHOReVOLUTION Integrated Development and Runtime Environment (IDRE), a choreography-based service composition platform. It discusses its utilization in accelerating the development of a choreography-based Urban Traffic Coordination (UTC) application. The UTC application focuses on eco-driving services, which provide real-time eco-route evaluation to assist drivers in achieving eco-friendly and comfortable driving experiences. These services, implemented through choreography, are accessible via a mobile app for online navigation. The paper details how the CHOReVOLUTION IDRE facilitates the realization of the UTC application by automating the generation of distributed logic to properly bind, coordinate, and adapt interactions among involved parties from specification to deployment to execution. Finally, the benefits of CHOReVOLUTION IDRE are assessed by evaluating Key Performance Indicators (KPIs).

Spanjer [55] explored the implementation effects of Cooperative Intelligent Transport Systems (C-ITS) applications, specifically focusing on Time to Green and Time to Red functionalities. These systems aim to revolutionize traffic management by providingreal-time information about traffic light timings, impacting environmental sustainability, safety, efficiency, and driver comfort. From an environmental perspective, the study revealedfavorable outcomes related to vehicle acceleration and deceleration patterns. C-ITS- equipped vehicles exhibited reduced acceleration and more gradual braking, resulting in approximately a 5% decrease in fuel consumption and emissions. This aligns with the broader goal of C-ITS to promote eco-friendly driving behaviors and mitigate environmentalimpacts associated with transportation.

The study by Karoui et al., [62] aimed to investigate the impact of cooperative intelligent transportation systems (C-ITS) on traffic efficiency, safety, and environmental sustainability. Specifically, it focused on analyzing data from a

simulation model to assess the benefits of C-ITS technologies in reducing traffic congestion, enhancing road safety, and minimizing environmental impacts. The study utilized a combination of real-world traffic data and simulated scenarios to evaluate the effectiveness of C-ITS. The real-world data included traffic flow rates, vehicle speeds, and incident reports obtained from local transportation authorities, while the simulated data involved scenarios generated through a traffic simulation model. The researchers employed a quantitative approach, utilizing statistical analysis and simulation modeling techniques to measure the impact of C-ITS on various performance metrics. The study compared traffic conditions and outcomes between scenarios with and without C-ITS technologies implemented. The analysis revealed significant improvements in traffic efficiency with the implementation of C-ITS, including a 20% reduction in average travel times during peak hours and a 15% decrease in overall congestion levels. Moreover, the introduction of C-ITS contributed to a 25% reduction in traffic accidents and a 30% decrease in carbon emissions, highlighting the positive impacts on both safety and environmental sustainability. Additionally, the study identified specific C-ITS applications, such as predictive traffic management and intelligent intersection control, as key drivers of these improvements. These findings underscored the potential of C-ITS to revolutionize transportation systems by enhancing efficiency, safety, and environmental performance.

The objective of the study by Gurrieri et al., [63] was to assess the environmental impacts of a smart motorway compared to those of a traditional motorway, considering global policy implications. The researchers focused on the impacts related to infrastructure construction and maintenance, as well as traffic emissions, incorporating smart technologies and truck platooning regulation. Using a classical life cycle assessment (LCA) approach, they adopted a one km-long smart motorway with a two m-high embankment as the functional unit and considered realistic traffic conditions. The study compared the environmental effects of using virgin material versus Reclaimed Asphalt Pavement (RAP) under two maintenance plans. C-ITS systems were found to significantly enhance safety on smart motorways, leading to reduced environmental impacts, particularly in impact categories like Global

Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), and Eutrophication Potential (EP) during the maintenance phase of zinc-coated steel safety barriers and traffic emissions. The study also estimated the impact of safety barriers throughout their life cycle and noted a 30% decrease in GWP, POCP, AP, and EP related to safety barrier maintenance compared to traditional motorways. Truck platooning mode, influenced by the percentage of heavy vehicles in Truck Platooning mode, led to a GWP reduction of close to 4%. Additionally, combining lime stabilization and RAP resulted in significant reductions in energy consumption (up to 35%) and pollutant emissions (up to 34% of CO2) compared to using only virgin material. The study highlighted that the environmental advantages of smart motorways increase with higher Average Annual Daily Traffic (AADT), truck platooning percentages, and heavy vehicle percentages, indicating the potential for substantial environmental benefits with the adoption of smart transportation technologies.

Further, Edwards et al., [64] assessed the environmental and efficiency impacts of Cooperative Intelligent Transport Systems (C-ITS), focusing on the Compass4D project's deployment of a C-ITS system across seven European cities. The study evaluated the effectiveness of C-ITS in real-world driving conditions, specifically targeting safety and environmental objectives. The data used included field trial results and microscopic simulation studies to understand network-wide impacts. The key findings indicated that heavy vehicles experienced sustained improvements in emissions/efficiencies, with savings of 2–5% based on modeled emissions and higher fuel consumption savings in real-world conditions. Light vehicles also showed relative improvements in emissions/efficiencies, although with lower absolute reductions. The impact on buses varied by site, with some showing significant savings in CO2 emissions per trip while others exhibited no improvement or reduced efficiency. Intersection crossing times and average stop numbers improved in most cases, albeit with variations due to specific conditions at pilot sites.

In a study by Pariota et al., [65], the primary objective is to address the stop-and-go phenomenon in vehicle flow to enhance traffic quality. The researchers employed a C-ITS service, specifically a Single Segment GLOSA (Green Light Optimized Speed Advisory), utilizing V2I communication to recommend or enforce a particular speed profile for vehicles approaching intersections. Although the algorithm's logic control initially lacked an eco- friendly focus, the study observed a notable positive impact of GLOSA on fuel consumption and emissions, showing reductions of approximately 4.5% and 8%, respectively, across three different gas emissions categories. The findings underscore the potential benefits of integrating eco-friendly strategies into GLOSA algorithms, highlighting the need for further investigation into factors such as surrounding vehicles and communication technologies. Such investigations are crucial for creating a more realistic testing environment and gaining a clearer understanding of the service's overall benefits in terms of fuel efficiency and emission reductions [65].

A study by Englund et al., [51] focused on assessing the energy efficiency potential of a Cooperative speed harmonization application implemented in a heavily utilized and frequently congested road section in Gothenburg. This application introduces a wave-based control mechanism to manage vehicle arrival times at intersections, grouping cooperative vehicles into waves and alternating their arrival times to improve maneuverability within the intersection. The application's benefits extend to traffic merge scenarios like on-ramps and intersections. Simulation results reveal a significant reduction in emissions—approximately 5% lower emissions at a 40% employment rate and 11% lower emissions at a 100% employment rate compared to non-cooperative vehicles. Energy savings of up to 550 W per vehicle are also observed in the simulated road section. The study highlights the application's positive impact on overall traffic efficiency and emission reduction, especially under high traffic loads. Future investigations aim to explore how non-cooperative vehicles can also benefit from cooperative behavior, particularly in scenarios with lower traffic flow and rates of cooperative vehicles. Distributed coordination and communication among vehicles are also areas of interest for further research in this domain.

5. COMPARATIVE EVALUATION OF PERFORMANCE OF C-ITSs ACROSS SCENARIOS AND REGIONS

This chapter presents a comparative analysis of the performance of C-ITSs across various scenarios and regions. It covers the comparative evaluations between different scenarios and geographical regions and an in-depth analysis of the findings.

5.1.Types of C-ITS's Safety Applications Across the Regions

Several countries are actively developing and deploying C-ITS technologies. The following section presents a comparative analysis of the C-ITS across regions, which includes the United States, Europe, and Asia.

The United States Department of Transportation (DOT) actively promotes Cooperative Intelligent Transportation Systems (C-ITS) through its Intelligent Transportation Systems (ITS) program. The US Department of Transportation (DOT) spearheads C-ITS initiatives focusing on safety applications. Pilots in various cities explore vehicle-to-vehicle (V2V) andvehicle-to-infrastructure (V2I) communication for improved safety and traffic management [66]. Further, the European Commission promotes C-ITS through the C-Roads Platform. European countries prioritize interoperability across borders. The EU invests in standards development and pilot projects for applications like lane management and cooperative collision avoidance. Data privacy regulations and high infrastructure investment costs present challenges [58], [67]. Moreover, in Asian countries, the focus has been on C-ITS applications that address specific regional challenges like congestion management and driverawareness. Highlighted below are the details on the C-ITS applications and evaluation efforts in the United States, Europe, and Asia:

5.1.1. Types of C-ITS Applications in the United States

At least 25 states have operational connected vehicle deployments [68]. Table 5.1 and Table 5.2 provide details for the deployments across the States.

Table 5.1 C-ITS Applications across the United States.

State	**Project(s)**
Alabama	Univ of AL/ALDOT SPaT
Arızona	Anthem Test Bed
Calıfornıa	California CV Test Bed, San Jose, CA (2)
Colorado	Road X I-70
Delaware	DelDOT SPaT
Florıda	Tampa CV Pilot, Tallahassee SPaT, Orlando, FL (2)
Georgıa	Atlanta Smart Corridor Demo, GDOT Atlanta SPaT, Marietta Emerg Vehic Signal Preemption
Hawaıı	Honolulu
Idaho	Ada County Hwy District
Indıana	Indiana CV Corridor
Maryland	Howard County SPaT
Mıchıgan	AACVTE, Ann Arbor, Lansing M-43 Project, Macomb County Dept. Roads Projects (3), MCity Test Bed, Ann Arbor, MDOT Wayne County Project, MichDOT I-75 Connected Work Zone, MichDOT I-94, Road Commission for Oakland Cty, Safety Pilot, Ann Arbor, Southeast MI, St. Clair and Lapeer Counties, MI, Ypsilanti Township, MI
Mınnesota	Minneapolis, MN, TH-55 (Mpls. /I-94)
Nevada	Las Vegas Freemont Street SPaT, Corridor, I-580/Washoe County, NV
New Hampshıre	NHDOT SPaT, Dover

Table 5.1. C-ITS Applications across the United States. (cont.)

State	**Project(s)**
North Carolına	NCDOT SPaT, Cary
New York	Long Island, NY, NYS Thruway, NY (NYC) CV Pilot
Ohıo	OH Turnpike
	US 33, OH
Pennsylvanıa	PennDOT SPaT, Harrisburg, PennDOT SPaT, PHILA, PennDOT SPaT, Pittsburgh, PennDOT SPaT, Ross Township, Smart Belt Coalition, PA, SmartPGH
Tennessee	TnDOT SPaT, Knoxville
Utah	Provo OREM BRT, Salt Lake Valley Snow Plow, Preemption, UTAH SPaT
Vırgınıa	Fairfax County, VA, VA Smart Roads
Washıngton	King County, WA
Wısconsın	Madison, WI
Wyomıng	Wyoming CV Pilot

Table 5.2 Details of the C-ITS applications across the United States.

State/Region	Project Name	Lead Organization	Performance Highlights (Source)
Wyoming	Wyoming C-ITS Pilot Program	Wyoming Department of Transportation (WYDOT)	○ Early reports suggest a significant reduction in winter weather-related crashes ○ About 30 percent of the valid forward collision events were resolved within 10s after alert onset; ○ The average traffic speed was higher by about 2.2 mph and the average time headway between vehicles was lower by about 36 s in 2022 than in 2017 during the January-April timeframe [69]. ○ Little evidence is available that suggests any direct or indirect impact on mobility [70]. ○ The analysis shows the potential fuel consumption benefits if the CV technology could successfully prevent this hypothetical closure from occurring [71]

Table 5.2. Details of the C-ITS applications across the United States. (cont.)

State/Region	Project Name	Lead Organization	Performance Highlights (Source)
Florida	Tampa BayNextGen Corridor	Tampa Hillsborough Expressway Authority	o There were 508 V2V alert events and 7,565 V2I alert events [68]. o Prevented 21 potential pedestrian crashes, o Delivered 19 red light violation warnings, o Avoided 17 potential vehicle collisions, o Alerted 14 wrong-way drivers, and issued over 20,000 safety advisories [72]

Table 5.2. Details of the C-ITS applications across the United States. (cont.)

State/Region	Project Name	Lead Organization	Performance Highlights (Source)
New York	New York City Connected Vehicle Pilot	New York City Department of Transportation (NYCDOT)	○ Response to active alerts showed a decrease in speed non-compliance, red light violation rate, rear-end near-crash rate, lane change rate, and unsafe lane change rate [73]. ○ The SPDCOMP application triggers an alert when either HV exceeds the recommended speed by a configured amount or for a configured time by time of day. However, no sufficient data were available to allow a direct assessment of this application on mobility because of limited sample sizes and the change in the deployment fleet from vehicle-for-hire to city-owned fleet vehicles [74] ○ CSPDCOMP application advises the driver in time to reduce vehicle speed to the posted speed limit before the vehicle enters the curve, if the vehicle speed is greater than the posted curve speed. ○ SPDCOMPWZ application advises the driver in time to reduce vehicle speed to the posted speed limit before the vehicle enters the zone, if the vehicle speed is greater than the reduced speed zone.

Table 5.2. Details of the C-ITS applications across the United States. (cont.)

State/Region	Project Name	Lead Organization	Performance Highlights (Source)
New York	New York CityConnected Vehicle Pilot	New York City Department of Transportation (NYCDOT)	○ RLVW application triggers a driver alert for an HV approaching a signalized intersection when it determines that a stop is required and the HV will violate the Red Light stop bar at a signalized intersection based on its current speed, heading, acceleration, location, and the location of stop bars. ○ PEDINXWALK application monitors the vehicle's location, heading, and speed, and issues a warning to the driver if they determine that an impact is likely with a pedestrian in the crosswalk [73]. ○ Field studies of the PED-SIG application showed that the average wait time for sight-impaired pedestrians was 31.0 seconds, and the average crossing speed of these individuals was 3.6 feet per second, slightly above the 3.5 feet per second walking speed recommended by the MUTCD [74]. ○ It was estimated that by preventing collisions at each of the four hypothetical crash locations, the deployment would save 144.8 gallons of gasoline and reduce greenhouse gas emissions by 1,287 Kg [75]

Table 5.2. Details of the C-ITS applications across the United States. (cont.)

State/Region	Project Name	Lead Organization	Performance Highlights (Source)
Texas	Commercial Truck Platooning Demonstration in Texas Level 2 Automation	Texas Departmentof Transportation (TxDOT) andTexas A&M Transportation Institute	o Truck platooning can reduce fuel consumption by up to 12 percent on average. From the individual trucks' viewpoint, the upper ranges of savings were observed at 40 percent for the follower and 20 percent for the leader in a platoon. o Freeway capacity can be increased with two-vehicle platooning without any large-scale infrastructure expansion [76]
California	I-710 Truck Platooning Demonstration	California Department of Transportation (Caltrans)	o When heavy trucks utilize Cooperative Adaptive Cruise Control (CACC) with time gaps ranging from 0.6 seconds to 1.5 seconds, a three-truck convoy hauling standard, fully-loaded dry goods trailers can achieve fuel savings of approximately 6% to 5% at a cruising speed of 65 mph. The lead truck does not benefit significantly from fuel savings, whereas the second truck saves between 7% and 6%, and the third truck saves between 11% and 9%

Table 5.2. Details of the C-ITS applications across the United States. (cont.)

State/Region	Project Name	Lead Organization	Performance Highlights (Source)
California	I-710 Truck Platooning Demonstration	California Department of Transportation (Caltrans)	○ When heavy trucks are equipped with side skirts and boat tails on their trailers to reduce drag, the energy savings exceed the sum of the individual benefits from using shorter CACC gaps and aerodynamic improvements. The combination of CACC and aerodynamic modifications enhances each other, resulting in an additional fuel saving of between 0.5% and 2.0% beyond the savings achieved from these strategies individually [77].
Michigan	Connected Vehicle Safety Model Deployment.	Michigan Department of Transportation (MDOT)	○ Deployment of an active traffic management system with a dynamic shoulder lane in Michigan reduced crashes by 17 percentand yielded a benefit-cost ratio of up to 3.01 [78] ○ The integrated crash warning system had a statistically significant effect on the frequency of lane departures, decreasing the rate from ○ 14.6 departures per 100 miles during baseline driving to 7.6 departures per 100 miles during the treatment condition [79]

Red Light Running Vehicle Warning (RLVW): V2V and V2I communication allows vehicles to transmit alerts about upcoming red lights, prompting drivers to slow down and prevent collisions. Pilots in Wyoming and Michigan demonstrated significant reductions inred-light violations after RLRW deployment [69].

In the United States, the pilot Red Light Running Vehicle Warning (RLVW) application in Wyoming aimed to enhance road safety by advising drivers about upcoming signalized intersections and providing alerts or warnings when their vehicle may potentially violate a red light based on their speed and distance from the intersection. This application utilizes data from both infrastructure-based sensors (such as traffic signals) and vehicle-based sensors to determine if a vehicle needs to stop for a red light. It then delivers in-vehicle messages to alert and warn the driver, ensuring they have enough time to stop at the intersection's stop bar [80]. The application's performance requirements encompass both infrastructure and vehicle components to guarantee consistent and coordinated messaging tothe driver. This approach aims to effectively capture the driver's attention and prevent any conflicting or confusing messages that could compromise safety. By integrating data from multiple sources and providing timely alerts, this application contributes to promoting saferdriving behavior and reducing the risk of red-light violations at signalized intersections [80].

Wrong Way Driver Warning (WWDW): In Tampa, Florida, the Tampa Hillsborough Expressway Authority (THEA) spearheaded the CV Pilot Deployment to reduce collision risks through the use of CV technology. One specific scenario targeted by the deployment was the detection and prevention of wrong-way driving at the downtown terminus of the Reversible Express Lanes (REL), a known entry point for wrong-way drivers. To mitigate this risk, THEA implemented a Wrong Way Entry CV application. This application provides real-time alerts to drivers of CV-equipped vehicles attempting to enter the REL in the wrong direction, thereby preventing potential accidents.

Additionally, the project aimed to reduce collisions involving transit vehicles, particularly those on the TECO Line Streetcar System, an electric trolley line running along Channelside Drive between downtown Tampa and Ybor City. For this purpose, THEA equipped eight TECO Line streetcars with onboard devices enabling wireless communication with other connected vehicles. They also deployed the CV application "Vehicle Turning Right in Front of Transit Vehicle," which alerts streetcar operators when avehicle is turning right at an intersection where the streetcar is approaching. Conversely, theapplication also warns drivers of connected vehicles when they are turning right in front of a streetcar, enhancing overall safety.

In Arizona, V2V communication detects vehicles traveling in the wrong direction and sends alerts to approaching vehicles or the traffic management system, mitigating head-on crashes. A Pilot project in Arizona and Tampa showed promising results with a decrease in wrong-way driving incidents [81], [82]. Furthermore, in January 2018, the Arizona Department of Transportation (ADOT) initiated the use of a pioneering wrong-way detection system along a 15-mile stretch of Interstate 17 in Phoenix. This innovative system encompasses 90 thermal detection cameras strategically positioned above exit ramps and the mainline of Interstate 17, spanning from the Interstate 10 stack interchange to the Loop 101 interchange. The system's primary objective is to enhance safety by swiftly identifying and responding to wrong-way drivers, while also providing advisories for drivers traveling in thecorrect direction along I-17. The operational mechanism of the system involves several keycomponents:

Thermal Detection Cameras: These cameras are designed to detect the presence of wrong- way vehicles based on thermal imaging technology.

Warning Signs and Advisories: Upon detecting a wrong-way vehicle, the system activates warning signs for the errant driver and provides advisories for drivers proceeding in the correct direction along I-17.

- Automated Alerts: The system automatically notifies the Highway Patrol when a wrong-way vehicle is detected, enabling troopers to intervene swiftly.
- Live Video Feed: Operators at ADOT's operations center receive a live video feed from the thermal cameras, allowing them to assess the situation and take appropriateaction.
- Digital Message Boards: Operators can activate digital message boards along the freeway to alert drivers of the potential hazard and advise them to exit the freeway.
- Illuminated Wrong-Way Signs: In cases where the detection occurs at an off-ramp, an internally illuminated wrong-way sign with flashing red light-emitting diodes (LEDs) activates to attract the attention of the wrong-way driver.
- Coordination with Law Enforcement: Automated alerts are also sent to the Arizona Department of Public Safety to facilitate rapid response by troopers to the scene.

ADOT officials assessed the system's effectiveness as of 8 August 2018, revealing that it accurately detected 33 vehicles that had entered I-17 off-ramps and frontage roads, triggering alarms for immediate action. This proactive approach to wrong-way detection and response demonstrates ADOT's commitment to enhancing roadway safety and preventing potentially catastrophic incidents caused by wrong-way drivers. By leveraging advanced technology and real-time monitoring, ADOT aims to minimize the risks associated with wrong-way driving and protect motorists traveling along Interstate 17 in the Phoenix area [81].

The New York City (NYC) Connected Vehicle (CV) pilot deployment represented a substantial deployment of CV technology, primarily emphasizing safety applications dependent on vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and infrastructure- to-pedestrian (IVP) communications. The project's goals were to enhance safety by reducing crashes, injuries, and fatalities among both vehicles and pedestrians and to improve mobility and reliability through crash prevention and

mitigation [83].

Led by the New York City Department of Transportation (NYCDOT), the pilot included the installation of 470 roadside units (RSUs) and the equipping of 3,000 city fleet vehicles with six V2V and six V2I applications. Additionally, two pedestrian applications were tested. These applications provided drivers with alerts to help them avoid crashes or reduce the severity of injuries or damage.

One notable pedestrian application was the Mobile Pedestrian Signal System (PED-SIG), a custom smartphone app designed to convey intersection geometry and pedestrian signal status to users. This app was field-tested in November 2021 with 24 participants who had vision disabilities, and feedback was collected through pre- and post-experiment surveys.

From January 2021 to November 2021, the NYC CV pilot collected 189,374 events, defined as warnings, alerts, or other triggers within vehicles. To address privacy concerns, all event data were obfuscated. The performance evaluation utilized a control-treatment and before- after experiment design, employing statistical analysis and surrogate safety measures (SSMs) to assess the safety benefits of the CV applications. Driver reactions, crash-based analysis, and SSM simulations were also analyzed. Driver perceptions and experiences with CV apps were gathered through three surveys conducted at different stages of deployment.

For the PED-SIG app, 24 volunteers with vision disabilities were recruited via local and national organizations. These participants navigated semi-protected signalized intersections using Pedestrian Information Devices (PIDs), accompanied by Institutional Review Board (IRB)-certified researchers. Data for the PED-SIG app were collected from operational logs, field observations, and pre- and post-experiment surveys [83].

5.1.2. Types of C-ITS Applications in Europe

The European Commission spearheads C-ITS evaluation through various initiatives. European countries prioritize interoperability across borders. The EU invests in standards development and pilot projects for applications like lane management and cooperative collision avoidance. Data privacy regulations and high infrastructure investment costs present challenges [58].

European C-ITS applications prioritize safety, efficiency, and interoperability across borders. Table 5.3 presents several examples of C-ITS applications in European countries. The next section discusses various C-ITS applications across European countries.

Table 5.3 Details of the C-ITS applications across Europe.

Country	Project Name	Lead Organization	Performance Highlights (Source)
Multi-National (EU)	C-Roads Platform	European Commission, Member States, Road Operators	- Increased awareness of emergency vehicles by 30% [84]
Germany	simTD (Simulator for Traffic Management based on C-ITS)	Autobahn GmbH	- A testing platform for C-ITS applications in a simulated environment [85].
Netherlands	Talking Traffic	Rijkswaterstaat (Dutch Ministry of Infrastructure and Water Management)	- Improved route optimization for drivers through traffic information sharing [84]
France	SCOOP (System for Cooperative On-Street Parking)	Ministère de la Transition écologique (French Ministry of Ecological Transition)	- Reduced congestion from parking searches through real-time parking availability information [86], [87]

Table 5.3. Details of the C-ITS applications across Europe. (cont.)

Country	Project Name	Lead Organization	Performance Highlights (Source)
Austria	Austrian Cooperative ITS (Austroads)	Bundesministerium für Klimaschutz, Umwelt, Energie, Innovation und Technologie (BMK)	- Testing of C-ITS applications for improved traffic flow and safety on highways
Sweden	Drive Sweden - C-ITS Pilot Program	Trafikverket (Swedish Transport Agency)	- Improved winter weather hazard warnings for increased safety
Finland	FITS (Finnish Transport Infrastructure Agency C-ITS)	Finnish Transport Infrastructure Agency (FTA)	- Reduced emissions through optimized traffic flow
Denmark	Danish Cooperative ITS Platform (COOP)	Danish Road Directorate	- Improved situational awareness for drivers, potentially reducing accidents [84]

Table 5.3. Details of the C-ITS applications across Europe. (cont.)

Country	Project Name	Lead Organization	Performance Highlights (Source)
Spain	C-MobILE Project	Spanish Ministry of Transport, Mobility and Urban Agenda (MITMA)	- Traffic information sharing app for drivers, aimingto improve route optimization and reduce congestion [84]
Italy	C-ITS Corridor of Brenner Motorway	ASPI (Autostrade per l'Italia)	- Improved safety and efficiency on a major freight route [84]
Netherlands	Dutch A27 Corridor Pilot	Rijkswaterstaat	- Pilot focusing on cooperative lane changing and merging for improved traffic flow [84]
Germany	Autobahn A9 Pilot Project	Autobahn GmbH	- Testing of C-ITS applications for improved safety and traffic management on a major highway [84]

Cooperative Maneuver Assist (CMA): V2V communication facilitates coordination between vehicles during lane changes or merging, promoting safer and more efficient traffic flow. Pilots in Spain and Italy demonstrated positive outcomes with reduced incidents during merging maneuvers.

Harmonized Traffic Information for Low-Emission Vehicles (HARLEM): This unique application uses V2X communication to provide real-time information on border crossing procedures and wait times, specifically for low-emission vehicles. Pilots at European borders like Denmark-Germany and Austria-Slovenia aimed to facilitate smoother and greener border crossings.

C-Roads Platform: This joint initiative by European member states and road operators facilitates testing, implementation, and evaluation of C-ITS services across borders. The platform focuses on interoperability and harmonization of systems for broader European deployment. For example, the C-Roads platform coordinated the HARLEM pilot at various European borders, evaluating its effectiveness in facilitating green border crossings for low- emission vehicles.

EU Framework Programmes for Research and Innovation (FPs): The European Commission funds research projects through FPs to test and evaluate C-ITS applications. These projects involve collaborations between research institutions, industry partners, and public authorities. For example, the SCOOP (Safety Cooperation for Optimized and Integrated Traffic Management) project funded by FP7 evaluated the effectiveness of various C-ITS safety applications like DAW and WWDW in real-world pilot deployments across Europe.

National Evaluation Programs: Individual European member states also conduct their own C-ITS evaluations. These evaluations focus on specific applications and their impact within the national context. For example, Germany's Bundesanstalt für

Straßenwesen (Federal Highway Research Institute) conducted a comprehensive evaluation of the GLOSA pilot, analyzing its effectiveness in reducing emissions and improving traffic flow at intersections.

Danger Ahead Warning (DAW): V2V and V2I communication provide real-time alerts about hazards like sudden braking, slippery roads, or disabled vehicles on the road. Pilots across Europe demonstrated positive impacts on driver awareness and reduced accident rates. One reviewed literature indicates that the objective of the weather conditions service was to enhance safety in adverse weather scenarios such as ice, fog, rain, snow, sleet, hail, and wind. The main impacts were anticipated through direct in-vehicle modifications of the driving task, where drivers receive real-time information about adverse weather conditions.In clearly perceptible dangers like heavy rain, the notification serves to remind drivers of potential hazards, increasing their awareness. For less perceptible dangers such as strong cross-winds or black ice, drivers receive crucial information about local weather hazards thatthey might not otherwise know. In both cases, the driver becomes better prepared and can adjust their speed accordingly, preventing sudden maneuvers like braking, accelerating, swerving, or overtaking.

Rebound effects from over-reliance on the system are expected to be negligible because the information used to deliver the service will partly come from other vehicles further ahead. Therefore, drivers cannot always assume that there will be suitably equipped vehicles ahead to provide timely warnings. DRIVE C2X scaled up safety impacts by examining the effect on driver speeds, awareness, and the headway between vehicles. Using values from Field Operational Test (FOT) data, expert estimates, and previous projects like CODIA and eIMPACT, a high scenario for 2030 projects a 3.43% reduction in fatalities and a 3.35% reduction in injuries for cars and freight on all road types. Other studies corroborate these potential impacts. For example, the EasyWay project used the CODIA methodology to estimate that low friction warnings could reduce injury crash risk by 5% and fatal crash risk by 10%, while fog warnings could

reduce injury crashes by 12% and fatal crashes by 23%. Averaging these figures, EasyWay reported overall impacts of 8.5% on injury crashes and 16.5% on fatal crashes.

The eIMPACT project evaluated a wireless location danger warning service, which included weather warnings. It estimated a 4.5% reduction in fatalities and a 2.8% reduction in injuries, assuming 100% penetration in the EU-25. These values are slightly higher than DRIVE C2X estimates, likely because eIMPACT also considered stationary vehicle warnings.

SAFESPOT assessed two weather warning services: road departure (V2V) and hazard and incident warning (V2I). For the road departure use case, which informs drivers of conditions like slippery roads, SAFESPOT estimated an 8.6% reduction in injuries and a 16.4% reduction in fatalities. These figures are similar to EasyWay estimates. However, for the hazard and incident warning use case, involving conditions like ice, rain, or fog, the impactwas significantly less, with a 1.6% reduction in fatalities and a 0.7% reduction in injuries.

Finally, the eSafetyForum reported that a weather conditions service could lead to a 2-4% reduction in fatalities and injuries, aligning with the figures from DRIVE C2X. Overall, these studies suggest that the implementation of weather warning services can significantly enhance road safety by reducing the number of crashes and their severity in adverse weather conditions [88]

5.1.3. Types of C-ITS Applications in Asia

Asian countries are focusing on C-ITS applications that address specific regional challenges like congestion management and driver awareness. However, little information is available on the deployment of the C-ITS projects in Asia. Table 5.4 presents a summary of the existing projects in Asian countries.

Table 5.4 Details of the C-ITS applications across Asia.

Country	Project Name	Lead Organization	Performance Parameters
Japan	Smart Mobility Demonstration Project in Yokohama	Ministry of Land, Infrastructure, Transport and Tourism (MLIT)	- Improved green light wave efficiency, and reduced travel time [89]
South Korea	K-City C-ITS Pilot	Ministry of Land, Infrastructure and Transport (MOLIT)	- Enhanced pedestrian safety, and reduced trafficcongestion around construction zones [90]
China	Beijing C-ITS Pilot	Beijing Transport Commission	- Improved traffic flow efficiency, reduced average travel time [91]
Singapore	C-AV Test CETRAN	Land Transport Authority (LTA)	- Testing and evaluation ofConnected and Autonomous Vehicles (CAVs) [92], [93]
India	Mobile ad hoc networks (MANET) Vehicular ad hoc networks (VANET)	National Transport Development Policy Committee (NTDPC)	-Focus on safety for vulnerable road users (motorcycles, bicycles, pedestrians) [94]
Taiwan	Provincial Highway No. 61	Ministry of Transportation and Communications	- Improved travel time based on real-time data [95]

5.2.Safety Application Evaluation Results

Only a relatively few studies have utilized actual data to evaluate the safety effectiveness of C-ITS deployment. Among the projects, the New York City (NYC) Connected Vehicle (CV) pilot [88] revealed various benefits of CV applications.

Speed Compliance (SPDCOMP): Analysis of 40,635 SPDCOMP events showed that compared to scenarios without warnings, there were 47 additional events per 1,000 where drivers slowed to the speed limit when warnings were active. Drivers decelerated an extra 0.148 m/s² on average after receiving speed compliance warnings.

Curve Speed Compliance (CSPDCOMP): Analysis of 27 CSPDCOMP events indicated an 8.75 mph reduction in vehicle speeds at curve entry, a 0.691 m/s² reduction in lateral acceleration, and a 0.908 m/s² decrease in deceleration difference.

Speed Compliance in Work Zones (SPDCOMPWZ): Analysis of 2,665 SPDCOMPWZ events revealed an additional 0.427 m/s² deceleration on average following warnings, along with a 2.26-second reduction in the time taken to slow to the speed limit.

V2V Applications: The Intersection Movement Assist (IMA) application showed a reduction in conflict risk between host and remote vehicles after warnings were issued. Blind Spot Warning (BSW) and Lane Change Warning (LCW) applications also demonstrated positive effects in reducing conflict risks, based on microsimulation results.

Red Light Violation Warning (RLVW): Both statistical and simulation-based SSM analysis indicated that RLVW had a positive safety effect, with drivers

decelerating approximately 0.137 m/s² more after warnings were issued.

Pedestrians in Crosswalk (PEDINXWALK): Simulation results indicated a positive impact of the PEDINXWALK application in reducing conflict risks. In addition, a survey of the drivers was performed to understand their perception concerns and driving behaviors. Among the surveyed drivers, 38% reported that CV alerts helped them drive more safely. The main concerns were distractions (45%), false alerts or warnings (40%), and too many alerts or warnings (46%). Further, 30% of drivers indicated that CV alerts affected their driving, with 58% of these drivers reporting a positive or very positive effect.

Pedestrians were also surveyed to understand their perceptions, safety benefits, and issues. Results show that 83% of participants felt safer using the PED-SIG app. All participants (100%) believed pedestrians would benefit from the PED-SIG technology. 96% felt they had sufficient time to cross intersections using the app. Participants experienced problems such as inaccurate location information, slow response times, and inaccurate orientation.

Further, to evaluate safety benefits, the study analyzed participants' behavioral responses to the V2V and V2I applications. The absence of in-vehicle video cameras led to the development of data-driven algorithms to detect longitudinal and lateral reactions to evasive maneuvers. For each use case, the analysis estimated false positive, false negative, true positive, and true negative rates by emulating the applications' logic to identify and quantify V2V interactions and conflicts. Mobility impact evaluation used an interrupted time-series regression analysis, comparing before and after deployment conditions. Participant perceptions were collected through surveys at three points: initial, interim, and exit, with 1,058, 389, and 369 responses respectively.

The study evaluated six use cases with various V2V and V2I applications. These included scenarios like morning backups, wrong-way entries, pedestrian conflicts, transit signal priority, streetcar conflicts, and traffic progression. The mobility impacts revealed that the End of Ramp Deceleration Warning (ERDW) application led to a 2.1% reduction in mean travel times, a 1.8% reduction in idle time, a 1.8% reduction in queue length, and nearly a 30% reduction in the travel time index.

In terms of safety, the Wrong-Way Entry (WWE) application correctly warned 74% of potential conflicts during the PM peak period and had false positive rates of 28% in the PM and 2.8% in the AM. Forward Collision Warning (FCW) and Electronic Emergency Brake Light Warning (EEBL) showed true positive rates of 41% and a decrease in conflict rates forFCW and EEBL by 9% and 23% respectively. The Vehicle Turning Right in Front of Transit Vehicle (VTRFTV) application had a 13% true positive rate among its warnings.

Participant perceptions were generally positive, with 56% of participants somewhat or very satisfied with their participation in the study. Around 76% found the ERDW application effective, and 51-66% found other applications like VTRFTV, PCW, IMA, FCW, and EEBL effective. Safety was perceived as the greatest benefit of CV technology by 66% of participants, with 70% confirming clear administration of warnings and 59-77% satisfied with the timeliness of the warnings provided. Additionally, the study showed reductions in concerns about privacy and receiving too many alerts.

5.3.Traffic Flow Efficiency Evaluation Results

V2X communication provides drivers with real-time data on travel times and alternative routes, enabling informed route selection and congestion avoidance. This section highlights these applications' efficiency results using pilots in Wyoming, the

Netherlands, and France.

The Wyoming Cooperative Vehicle-Pilot Deployment (CVPD) aimed to evaluate the impact of Connected Vehicle (CV) technologies on mobility, speed compliance, and safety on Interstate 80 (I-80) during severe weather events. However, the analysis of the pilot deployment yielded inconclusive evidence regarding the direct or indirect impact of CV technologies on mobility and speed compliance [70].

Specifically, there was no conclusive evidence indicating that the Wyoming CVPD had any discernible impact on mobility along I-80, whether directly or indirectly. Similarly, there was limited evidence to support the notion that the deployment influenced speed compliance with posted speed limits or speed variability. Moreover, insufficient data were available to suggest that CVs exhibited better compliance with posted speed limits compared to non-equipped vehicles. While the case study analysis did indicate that drivers of CVs sometimes took appropriate actions in response to alerts received through the CV technologies, the absence of data from a control group prevented definitive conclusions about the direct influence of these alerts on driver behavior. It remained uncertain whether the actions taken were a direct response to the alerts or merely reflective of drivers' standard reactions to prevailing circumstances.

Nonetheless, these outcomes were not unexpected, as the primary focus of the Wyoming CVPD was on enhancing safety and showcasing the feasibility of utilizing CV technology to disseminate critical information during severe weather conditions. The project recognized that adverse weather conditions often contribute significantly to mobility challenges, and the emphasis was on preventing collisions rather than optimizing mobility during such situations. Furthermore, the low market penetration of CV technologies during the deployment, with only 325 vehicles equipped, further limited the potential impact on mobility and speed compliance. Nearly half of these equipped vehicles belonged to friendly fleet partners such as WYDOT snowplows, maintenance vehicles, and highway patrol units, whose primary mission during severe

weather was ensuring the safety of other travelers rather than prioritizing mobility optimization.

Despite the challenges in demonstrating direct impacts on mobility and speed compliance, the Wyoming CVPD achieved success in integrating CV technology data with existing WYDOT systems to enhance situational awareness. This integration facilitated improved coordination and response capabilities during severe weather events. Another notable success was the validation of satellite communications for disseminating traveler information systems. The partnership established during the CVPD with a major satellite communication provider enabled WYDOT to expand the reach of its travel information messages beyond I-80 to all state and federal highways in Wyoming. This technological advancement allowed CV drivers to receive timely information and alerts statewide, contributing to enhanced safety and awareness.

While the direct impact of CV technologies on mobility and speed compliance remained inconclusive, the Wyoming CVPD pilot demonstrated valuable successes in enhancing situational awareness, expanding traveler information dissemination capabilities, and contributing to industry standardization efforts. These achievements laid the groundwork for further advancements in connected vehicle technologies and their application in improving transportation safety and efficiency [80].

Green Light Optimal Speed Advisory (GLOSA), a V2I communication transmits information about upcoming traffic signals, allowing drivers to adjust speed for a smoother flow and reduced idling at red lights.

Pilots in the Netherlands and France showcased improved intersection efficiency and reduced emissions [54], [62]. The Green Light Optimal Speed Advisory (GLOSA) systems are known for their mobility and environmental benefits, but there is insufficient knowledge about their safety implications. For safe deployment, it is crucial

to identify and address potential safety issues in the design process. GLOSA systems could potentially improve safety by reducing traffic conflicts associated with interrupted traffic flow at signalized intersections. However, more research from field and simulation-based studies is needed to evaluate safety impacts under various real-world scenarios. As part of the LEVITATE project under the European Union's Horizon 2020 Programme, a study was conducted to examine the safety impacts of GLOSA systems under mixed traffic compositions with varying market penetration rates (MPR) of connected and automated vehicles (CAVs). This study used a calibrated and validated microsimulation model (developed in Aimsun) of the Greater Manchester area, focusing on three signalized intersections in a corridor where the GLOSA system was implemented. An improved GLOSA algorithm was developed by identifying potential issues and limitations in existing algorithms. The behaviors of CAVs were modeledbased on a comprehensive literature review. Safety analysis was performed by processing simulated vehicular trajectories in the Surrogate Safety Assessment Model (SSAM) developed by the Federal Highway Administration (FHWA). The results showed a small improvement in safety with the GLOSA implementation at multiple intersections in the testnetwork, but only at low MPR (20%) scenarios of CAVs compared to scenarios without GLOSA. No significant safety improvement, or even slightly lower improvement, was observed with GLOSA implementation under mixed fleet scenarios with 40% or higher MPR of 1st or 2nd Generation CAVs. Additionally, GLOSA implementation affected the types oftraffic conflicts. While rear-end conflicts decreased, there was a slight increase in lane- change conflicts. However, these changes were not consistent across all MPR scenarios. These findings indicate that while GLOSA can contribute to safety improvements under certain conditions, its overall impact on safety, especially in mixed traffic scenarios with higher CAV penetration rates, requires further investigation [96].

5.4.Challenges and Opportunities

5.4.1. Challenges and Opportunities in the United States

While the US has made significant progress in C-ITS development, some challenges remain. These include fragmented deployment, data security concerns, and the need for more standardized protocols [66].

Fragmented Deployment: C-ITS pilots are currently scattered across different cities and states, hindering widespread adoption and data collection for broader impact assessment.

Data Security Concerns: Ensuring the security of data transmitted through V2X communication is crucial. Concerns about data privacy and potential hacking vulnerabilities require robust cybersecurity frameworks.

Standardization Issues: The lack of complete standardization across communication protocols and data formats creates interoperability challenges, potentially hindering seamless communication between vehicles and infrastructure from different vendors.

Despite these challenges, the following opportunities exist:

Public-Private Partnerships (PPPs): Collaboration between government agencies, research institutions, and private companies can accelerate C-ITS deployment by leveraging combined expertise and resources. PPPs can facilitate the development of standardized protocols and encourage private sector investment in infrastructure

upgrades.

Integration with Automated Vehicles (AVs): As AV technology advances, C-ITS will play a critical role in supporting safe and efficient AV operation. Real-time traffic data exchange through C-ITS can enhance situational awareness for AVs, leading to smoother traffic flow and improved safety.

National Deployment Strategy: A comprehensive national C-ITS deployment strategy could unify efforts across different states and cities. This strategy could focus on infrastructure investment, data standardization, and public awareness campaigns to drive broader adoption and maximize benefits.

5.4.2. Challenges and Opportunities in Europe

Despite significant progress, some challenges persist in European C-ITS development [97]:

Data Privacy Concerns: Strict European data privacy regulations like GDPR (General Data Protection Regulation) necessitate robust data anonymization and user consent mechanisms for C-ITS data collection and utilization.

Infrastructure Investment: Upgrading transportation infrastructure to support widespread C- ITS deployment requires significant investment in roadside units, communication networks, and data centers across Europe.

Public-Private Collaboration: Strong collaboration between public authorities and private companies is crucial for harmonizing standards, attracting private sector investment, and encouraging broader C-ITS adoption.

Despite these challenges, exciting opportunities exist:

Focus on Sustainability: C-ITS applications like HARLEM and GLOSA demonstrate Europe's commitment to using C-ITS for promoting green transportation and reducing emissions within the transportation sector.

Integration with Automated Vehicles (AVs): Similar to the US, Europe recognizes the crucial role of C-ITS in supporting safe and efficient AV operation. Research initiatives are underway towards C-ITS integration with emerging AV technologies.

5.4.3. Challenges and Opportunities in Asia

While Asia shows significant progress in C-ITS development, some challenges remain [98]:

Spectrum Allocation: Standardization and allocation of dedicated spectrum for C-ITS communication is crucial. Different Asian countries might have varying regulations, potentially hindering seamless communication across borders .

Infrastructure Investment: Upgrading transportation infrastructure in densely populated Asian cities necessitates substantial investment in roadside units, communication networks, and data management systems.

Integration with Existing Systems: Many Asian countries already have established traffic management systems. Integrating C-ITS with these existing systems requires careful planning and consideration of interoperability.

Despite these challenges, several opportunities exist:

Focus on Sustainability: C-ITS applications like RMC and CIM can contribute to reduced traffic congestion and associated emissions, promoting sustainable transportation practices in Asian cities.

Public Awareness and Education: Increasing public awareness of C-ITS benefits can generate greater support for investment and broader adoption of the technology.

6. CONCLUSIONS AND RECOMMENDATIONS

This section presents the conclusion and recommendations for future studies. The conclusion provides a summary of the study and lessons learned. On the other hand, the recommendations for future study section show the areas that researchers may focus on in the future.

6.1.Conclusions

The exploration of Cooperative Intelligent Transport Systems (C-ITS) reveals a revolutionary potential in enhancing the safety and efficiency of traffic through improved communication between vehicles and infrastructure. The advancements in C-ITS technologies, including Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Everything (V2X) communication, present a paradigm shift in how we approach transportation, promising numerous benefits across different regions, although several challenges need to be addressed.

One of the primary benefits of C-ITS is its significant impact on traffic safety. The reduction in accidents is a noteworthy achievement attributed to the application of C-ITS. For instance, V2V communication allows vehicles to share real-time data about road conditions and potential hazards, enabling drivers to take preventive actions well in advance. This early warning system significantly contributes to preventing collisions, especially in conditions where human reaction time alone may not suffice. Similarly, V2I communication plays a critical role in optimizing traffic signals and managing traffic flows, which reduces the likelihood of accidents at intersections, a common site for vehicular collisions. This optimization leads to smoother traffic movements and less abrupt stopping and starting, further enhancing overall road safety.

Enhanced situational awareness provided by C-ITS is another crucial aspect contributing to traffic safety. The integration of C-ITS technologies improves the situational awareness of both human drivers and automated vehicles, leading to better decision-making and quicker response times. Real-time updates and early warning systems embedded within C-ITS enable vehicles to react to changing road conditions, such as sudden weather changes, obstacles, or work zones, thereby reducing the chances of accidents. This heightened awareness is particularly beneficial in urban environments with high traffic density, where split-second decisions can make a significant difference in preventing accidents.

Beyond safety, C-ITS technologies significantly enhance traffic efficiency. By facilitating smoother traffic movements, C-ITS helps reduce congestion, which is a major issue in urban areas. Systems such as Green Light Optimal Speed Advisory (GLOSA) assist vehicles in maintaining optimal speeds to pass through green lights, minimizing stops, reducing fuel consumption, and lowering emissions. This not only improves the efficiency of traffic flow but also contributes to environmental sustainability by lowering the carbon footprint of transportation.

The efficiency of public transport systems also benefits from C-ITS. Implementation of these technologies in public transport has shown increased speeds and fewer stops, resulting in more reliable and efficient services. Improved public transport efficiency has a ripple effect on overall traffic conditions, as it encourages more people to opt for public transportation over private vehicles, thereby reducing the number of vehicles on the road. This shift can significantly ease traffic congestion and contribute to a more sustainable urban mobility ecosystem.

However, the development and deployment of C-ITS are not without challenges. Different regions face unique obstacles in the implementation of these technologies. In Europe, for instance, substantial progress has been made in C-ITS deployment, with a strong emphasis on sustainability and integration with automated vehicles.

Nevertheless, challenges such as data privacy concerns and the need for significant infrastructure investment continue to pose hurdles. Addressing these challenges requires a coordinated effort from both public and private sectors to ensure that the benefits of C-ITS are fully realized.

In the United States, the deployment of C-ITS has been somewhat fragmented, with varying standards and data security concerns. Despite these challenges, public-private partnerships and national strategies offer promising pathways to overcome these obstacles and accelerate the adoption of C-ITS technologies. By fostering collaboration and standardization, the US can leverage its technological advancements to create a cohesive and efficient C-ITS infrastructure.

Asia, particularly in densely populated cities, has shown remarkable advancements in C- ITS. The challenges here include spectrum allocation and integration with existing traffic management systems. However, the opportunities for sustainable transport solutions and increased public awareness are immense. By addressing these challenges through innovative approaches and leveraging the region's technological prowess, Asia can set a benchmark for C-ITS deployment in urban settings.

The progress made in different regions demonstrates the potential of C-ITS but also underscores the need for a concerted global effort to overcome the challenges. Standardization, infrastructure investment, public-private partnerships, data security, and public awareness are key areas that require focused attention.

By addressing these areas, future studies can contribute to creating a safer, more efficient, and sustainable transportation future. Collaboration and innovation will be essential in navigating the complexities of C-ITS deployment and ensuring that the benefits are realized across different regions and communities. The successful

implementation of C-ITS will depend on the collective efforts of governments, private sectors, research institutions, and the public. By focusing on standardization, infrastructure investment, cybersecurity, integration with automated vehicles, public awareness, and international collaboration, future research can pave the way for the widespread adoption and effective deployment of C-ITS technologies.

6.2.Recommendations for Future Studies

This section presents the recommendations for future studies. It covers the standardization and interoperability of C-ITS, investment, security, data integration, automated vehicles, public awareness, and international collaboration.

Standardization and Interoperability: Future studies should focus on developing unified standards for communication protocols, data formats, and security measures to ensure seamless communication across different regions and systems, enhancing the effectiveness of C-ITS technologies. Promoting interoperability between C-ITS and existing traffic management systems is crucial for maximizing the benefits. Achieving standardization requires collaboration among international bodies, regional governments, and industry stakeholders. Studies could explore successful models of standardization in other industries, such as telecommunications, to draw parallels and propose frameworks for C-ITS. Furthermore, research could investigate the barriers to standardization, such as geopolitical differences and varying regulatory landscapes, offering strategies to overcome these challenges.

Infrastructure Investment: Research should prioritize strategies for securing the necessary funding for upgrading transportation infrastructure, including roadside units, communication networks, and data centers. Studies could explore the role of public-private partnerships (PPPs) in accelerating infrastructure development, leveraging combined expertise and resources to overcome financial and logistical barriers. In-depth

case studies of successful PPPs in other sectors could provide valuable insights into structuring these partnerships for C-ITS. Additionally, research could analyze the economic impacts of C-ITS infrastructure investments, presenting a compelling case for funding by highlighting potential returns in terms of safety, efficiency, and environmental benefits.

Cybersecurity and Data Privacy: Ensuring the security of data transmitted through C-ITS is paramount. Future research should focus on establishing robust cybersecurity frameworks to protect against hacking and data breaches. Mechanisms for data anonymization and user consent must be developed to comply with data privacy regulations, such as the General Data Protection Regulation (GDPR) in Europe. Studies should explore advanced encryption methods, intrusion detection systems, and decentralized data storage solutions to enhance cybersecurity. Furthermore, research could assess the effectiveness of existing data privacy regulations and propose enhancements tailored to the unique challenges posed by C-ITS. Understanding public perceptions of data privacy and developing strategies to address concerns will also be critical for gaining public trust.

Integration with Automated Vehicles: As automated vehicle technology progresses, C-ITS will be integral in supporting the safe and efficient operation of AVs. Research should focus on the synergies between C-ITS and AVs, conducting pilot programs and real-world testing to refine the technologies before wider deployment. Future studies should investigate the potential benefits and challenges of integrating C-ITS with AVs, including issues related to communication protocols, data sharing, and system interoperability. Understanding the interaction between human drivers and automated vehicles in a C-ITS-enabled environment will also be essential for optimizing the safety and efficiency of mixed-traffic scenarios.

Public Awareness and Stakeholder Engagement: Increasing public awareness about the benefits of C-ITS is crucial for generating support for its adoption and

investment. Future studies should explore effective communication and education strategies to build public trust and support. Engaging with stakeholders, including local communities, transport authorities, and policymakers, is essential for addressing concerns and garnering widespread acceptance. Research should analyze successful public awareness campaigns from other sectors and propose tailored strategies for C-ITS. Furthermore, studies should investigate the role of media and social platforms in shaping public perceptions of C-ITS technologies and develop guidelines for effective stakeholder engagement.

International Collaboration: International collaboration and harmonization of regulations can play a significant role in overcoming implementation challenges. Future research should focus on facilitating global cooperation to create an environment conducive to the successful deployment and widespread adoption of C-ITS technologies. Studies could explore models of international cooperation in other fields, such as climate change and public health, to derive lessons applicable to C-ITS. Research should also identify best practices for regulatory harmonization and propose frameworks for international standardization. Understanding the political, economic, and cultural factors influencing international collaboration will be critical for developing strategies that foster global cooperation.

By addressing these areas, future studies can contribute to creating a safer, more efficient, and sustainable transportation future. Collaboration and innovation will be essential in navigating the complexities of C-ITS deployment and ensuring that the benefits are realized across different regions and communities. The successful implementation of C-ITS will depend on the collective efforts of governments, private sectors, research institutions, and the public. By focusing on standardization, infrastructure investment, cybersecurity, integration with automated vehicles, public awareness, and international collaboration, future research can pave the way for the widespread adoption and effective deployment of C-ITS technologies.

REFERENCES

1. Jo, Y., A. Jung, H. Park, J. Park, and C. Oh, “Prioritizing Driving Safety Indicators Using Real-World C-ITS Data to Identify Hazardous Freeway Sections,” Journal of Korean Society of Transportation, 2022 40:6, vol. 40, no. 6, pp. 863–878, 2022.

2. Turetken, O., O. E. Adalı, R. Blokpoel, and P. W. P. J. Grefen, “C-ITS (Cooperative Intelligent Transport Systems) Deployment In Europe-Challenges and Key Findings,” 2018, https://www.researchgate.net/publication/330663321, accessed on February 21, 2024.

3. Lin, H. Y., J. M. Dai, L. T. Wu, and L. Q. Chen, “A Vision-Based Driver Assistance System with Forward Collision and Overtaking Detection,” *Sensors*, vol. 20, no. 18, p. 5139, 2020.

4. Singh, P. K., S. K. Nandi, and S. Nandi, “A Tutorial Survey on Vehicular Communication: State of the Art and Future Research Directions,” *Vehicular Communications*, vol. 18, p. 100164, 2019.

5. Bahonar, M. H., M. J. Omidi, and H. Yanikomeroglu, “Low-Complexity Resource Allocation for Dense Cellular Vehicle-to-Everything (C-V2X) Communications,” *IEEE Open Journal of the Communications Society*, vol. 2, pp. 2695–2713, 2021.

6. Carrenho, G., “Enhancing Transportation with Vehicle-to-Everything (V2X) Communication,”, https://www.encora.com/insights/enhancing-transportation-with-vehicle-to-everything-v2x-communication, accessed on June 12, 2024.

7. Sedar, R., F. V. Gallego, R. Casellas, R. Vilaalta, R. Munoz, R. Silva, and L. Dizambourg “Standards-Compliant Multi-Protocol On-Board Unit for the Evaluation of Connected and Automated Mobility Services in Multi-Vendor Environments,” *Sensors*, vol. 21, no. 6, p. 2090, 2021.

8. Yusuf, S. A., A. Khan, and R. Souissi, “Vehicle-to-Everything (V2X) in the Autonomous Vehicles Domain – A Technical Review of Communication, Sensor, and AI Technologies for Road User Safety,” *Transportation Research Interdisciplinary Perspectives*, vol. 23, p. 100980, 2024.

9. Gelbal, S., Zhu, S., Anantharaman, G., Aksun Guvenc, B, "Cooperative Collision Avoidance in a Connected Vehicle Environment," SAE Technical Paper 2019-01-0488, 2019.

10. Hollborn, S., “Intelligent Transport Systems in Japan”, Technische Universtat Darmstadt, 2002

11. U.S. Department of Transportation. “History of Intelligent Transportation Systems 2021 Update,” 2021, https://www.its.dot.gov/history/pdf/HistoryofITS_book.pdf, accessed on February 21, 2024.

12. Andrei, R., “Deployment Strategy for Cooperative Intelligent Transport Systems in Japan: Toward ETC 2.0,” *Journal of Materials Processing Technology*, vol. 1, pp. 1–8, 2015.

13. Kotsi, Areti, Evangelos Mitsakis, and Dimitris Tzanis. "Overview of C-ITS Deployment Projects in Europe and USA." In *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*, pp. 1-6. IEEE, Rhodes, Greece, 2020.

14. The C-Roads Platform. "An Overview of Harmonized C-ITS Deployment in Europe," 2020, https://www.c-roads.eu/fileadmin/user_upload/media/Dokumente/C-Roads_fact_sheet_2020.pdf, accessed on February 21, 2024.

15. Saleem, F., Nodes, S., Gettman, D., Burgess, L., Head, L., Mirchandani, P.B., Ahn, S., Golub, A., Provenzano, F. and Leader, S., “Arizona E-VII Program Overview”, In *15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual MeetingITS AmericaERTICOITS JapanTransCore*, New York NY, United States, 2008.

16. Robinson, Ralph, and François Dion. “Multipath SPAT Broadcast Project.” University of Michigan Transportation Research Institute, 2013.

17. US Department of Transportation “Safety Pilot Model Deployment Data - Catalog.”, https://catalog.data.gov/dataset/safety-pilot-model-deployment-data, accessed on March 16, 2024.

18. Belzowski, B. M., and S. J. Cook. “Integrated Mobile Observations 2.0 Project Final Report,” 2014.

19. Bevly, D, “Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment: Phase One Final Report,” 2015.

20. “Intelligent Transportation Systems - ITS Deployments.”, https://www.its.dot.gov/pilots/technical_assistance_events.htm, accessed on March 16, 2024.

21. “New York City (NYC) DOT Pilot - Connected Vehicle Pilot Deployment Program.”, https://www.its.dot.gov/pilots/pilots_nycdot.htm, accessed on March 16, 2024.

22. "Tampa (THEA) Pilot - Connected Vehicle Pilot Deployment Program.", https://www.its.dot.gov/pilots/pilots_wydot.htm, accessed on March 16, 2024.

23. "Wyoming (WY) DOT Pilot - Connected Vehicle Pilot Deployment Program.", https://www.its.dot.gov/pilots/pilots_thea.htm, accessed on March 16, 2024.

24. "Smart City Challenge: Lessons for Building Cities of the Future | US Department of Transportation.", https://www.transportation.gov/policy-initiatives/smartcity/smart-city-challenge-lessons-building-cities-future, accessed on March 16, 2024.

25. "Smart City Challenge Promotes Innovation in Government | FHWA.", https://highways.dot.gov/public-roads/novemberdecember-2016/smart-city-challenge-promotes-innovation-government, accessed on March 16, 2024.

26. Choosakun, A., Y. Chaiittipornwong, and C. Yeom. "Development of the Cooperative Intelligent Transport System in Thailand: A Prospective Approach," *Infrastructures*, vol. 6, no. 3, p. 36, 2021.

27. Njord, J., J. Peters, M. Freitas, B. Warner, K. C. Allred, R. L. Bertini, and R. Bryant, "Safety Applications of Intelligent Transportation Systems in Europe and Japan,", www.international.fhwa.dot.gov, accessed on August 17, 2024.

28. Menon, A., and R. Sinha. "Implementation of Internet of Things in Bus Transport System of Singapore," *SSRN,* https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2371776, accessed on August 17, 2024.

29. Debnath, A. K., M. M. Haque, H. C. Chin, and B. Yuen. "Sustainable Urban Transport," *Transportation Research Record*, vol. 2243, pp. 345–369, 2011.

30. Huang, W., Y. Wei, J. Guo, J. Cao, C. Huang, and W. Y. Guo. "Next-Generation Innovation and Development of Intelligent Transportation System in China," *Science China Information Sciences*, vol. 60, no. 11, p. 110201, 2017.

31. Zhu, T., and Z. Liu, "Intelligent Transport Systems in China: Past, Present, and Future," in *Proceedings of the 2015 7th International Conference on Measuring Technology and Mechatronics Automation (ICMTMA 2015)*, pp. 581–584, Piscataway New Jersey United States, 2015.

32. Javed, M. A and Elyes, B. H., "Measuring Safety Awareness in Cooperative ITS Applications." In *2016 IEEE Wireless Communications and Networking Conference*, pp. 1-7. IEEE, Doha, Qatar, 2016.

33. Elhenawy, M., A. Bond, and A. Rakotonirainy, “C-ITS Safety Evaluation Methodology based on Cooperative Awareness Messages,” in *IEEE Conference on Intelligent Transportation Systems, Proceedings (ITSC)*, pp. 2471–2477, Maui, Hawaii, United States, 2018.

34. Biral, F., G. Valenti, E. Bertolazzi, and A. Steccanella, “Cooperative Safety Applications for C-ITS Equipped and Non-Equipped Vehicles Supported by an Extended Local Dynamic Map Built on SAFE STRIP Technology,” in *Proceedings of the 15th Annual International Conference on Distributed Computing in Sensor Systems (DCOSS 2019)*, pp. 733–740, Santorini, Greece, 2019

35. E. De Britto E Silva, S. A. Hadiwardoyo, C. E. Costa, and J. M. Marquez-Barja, “Reinforcing Traffic Safety by Using CAM to Verify Velocity Accuracy,” in *Proceedings of the 2021 IEEE/ACM 25th International Symposium on Distributed Simulation and Real-Time Applications (DS-RT 2021)*, Valencia, Spain, 2021.

36. Rämä, P., and S. Innamaa, “Safety Assessment of Local Cooperative Warnings and Speed Limit Information,” *IET Intelligent Transport Systems*, vol. 14, no. 13, pp. 1769–1777, 2020.

37. T. Lara , “Impact of Safety Message Generation Rules on the Awareness of Vulnerable Road Users,” *Sensors*, vol. 21, no. 10, p. 3375, 2021.

38. Chalkiadakis, C., M. Kanavou, and E. Vlahogianni, “Investigating the Importance of Connected Cooperative and Automated Mobility Towards Mitigating the Impacts of Extreme Weather Events,” in *2023 8th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS 2023)*, Nice, France, 2023.

39. Lu, Q., A. Tesone, and L. Pariota, “Impacts of Connected Automated Vehicles on Large Urban Road Network,” in *International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS) - Proceedings*, pp. 378–385, Prague, Czech Republic, 2023.

40. Hepner, E., C. Zhao, K. Seipel, and R. Hoyer, “Optimization of the Traffic Flow in Public Transport through C-ITS,” in *2021 7th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS 2021)*, Heraklion, Greece, 2021.

41. Karkhanis, P., Y. Dajsuren, M. G. J. Van Den Brand, and J. Josten, “Modelling and Simulating Safety and Efficiency at an Unsignalised Intersection,” in *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC 2020)*, Rhodes, Greece, 2020.

42. Jo, J. Jang, S. Park, and C. Oh, “Connected Vehicle-Based Road Safety Information System (CROSS): Framework and Evaluation,” *Accident Analysis and Prevention*, vol. 151, p. 105972, 2021.

43. Topilin, I., and D. Konovalova, “The Role of Cooperative Intelligent Transport Systems in Road Traffic Safety,” *E3S Web of Conferences*, vol. 403, p. 07023, 2023.

44. Weibull, K., B. Lidestam, and E. Prytz, “Potential of Cooperative Intelligent Transport System Services to Mitigate Risk Factors Associated with Emergency Vehicle Accidents,” *Transportation Research Record*, vol. 2677, no. 3, pp. 999–1015, 2023.

45. Outay, F., F. Kamoun, F. Kaisser, D. Alterri, and A. Yasar, “V2V and V2I Communications for Traffic Safety and CO2 Emission Reduction: A Performance Evaluation,” *Procedia Computer Science*, vol. 151, pp. 353–360, 2019.

46. Kang, J., S. Tak, and S. Park, “Analyzing the Impact of C-ITS Services on Driving Behavior: A Case Study of the Daejeon–Sejong C-ITS Pilot Project in South Korea,” *Sustainability*, vol. 15, no. 16, p. 12655, 2023.

47. Mai, T., R. Jiang, and E. Chung, “A Cooperative Intelligent Transport Systems (C-ITS)-based Lane-Changing Advisory For Weaving Sections,” *Journal of Advanced Transportation*, vol. 50, no. 5, pp. 752–768, 2016.

48. Manogaran, G., I. Alrayes, A. Alshaikhi, and D. B. Rawat, “Pre-Predictive Congestion-Based Data Allocation for Sixth Generation Cooperative Intelligent Transportation Systems,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 10, pp. 18655–18667, 2022.

49. Zhang, C., N. R. Sabar, E. Chung, A. Bhaskar, and X. Guo, “Optimisation of Lane-Changing Advisory at the Motorway Lane Drop Bottleneck,” *Transportation Research Part C: Emerging Technologies*, vol. 106, pp. 303–316, 2019.

50. Agriesti, S. A. M., M. Ponti, G. Marchionni, and P. Gandini, “Cooperative Messages to Enhance the Performance of L3 Vehicles Approaching Roadworks,” *European Transport Research Review*, vol. 13, no. 1, pp. 1–19, 2021.

51. Englund, C., L. Chen, and A. Voronov, “Cooperative Speed Harmonization for Efficient Road Utilization,” in *2014 7th International Workshop on Communication Technologies for Vehicles (Nets4Cars-Fall 2014)*, pp. 19–23, St. Petersburg, Russia, 2014.

52. Sharma, S., I. Papamichail, A. Nadi, H. Van Lint, L. Tavasszy, and M. Snelder, "A Multi-class Lane-changing Advisory System for Freeway Merging Sections," *IFAC-PapersOnLine*, vol. 54, no. 2, pp. 93–98, 2021.

53. Agriesti, S. A. M., L. Studer, G. Marchionni, P. Gandini, and X. Qu, "Roadworks Warning—Closure of a Lane, the Impact of C-ITS Messages," *Infrastructures*, vol. 5, no. 3, p. 27, 2020.

54. Karoui, M., G. Chalhoub, and A. Freitas, "An Efficient Path Planning GLOSA-based Approach Over Large Scale and Realistic Traffic Scenario," *Internet Technology Letters*, vol. 4, no. 4, p. e194, 2021.

55. Spanjer, W. B., "Evaluation of Cooperative Intelligent Transport Systems Time to Red and Time to Green according to various Key Performance Indicators". Bachelor's thesis, University of Twente, 2022.

56. Marousi, K. P., and Y. J. Stephanedes, "Dynamic Management of Urban Coastal Traffic and Port Access Control," *Sustainability*, vol. 15, no. 20, p. 14871, 2023.

57. Astarita, V., D. C. Festa, P. Giofrè, G. Guido, and D. W. E. Mongelli, "Co-operative ITS: ESD a Smartphone-Based System for Sustainability and Transportation Safety," *Procedia Computer Science*, vol. 83, pp. 449–456, 2016.

58. "A European Strategy on Cooperative Intelligent Transport Systems, a Milestone Towards Cooperative, Connected and Automated Mobility", https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52016DC0766, accessed on May 25, 2024.

59. Shawky, M. A., "Cooperative Intelligent Transport Systems for Net-Zero," *The Role of 6G and Beyond on the Road to Net-Zero Carbon*, pp. 167–191, Jan. 2023.

60. Aramrattana, M., T. Larsson, J. Jansson, and C. Englund, "Dimensions of Cooperative Driving, ITS, and Automation," *IEEE Intelligent Vehicles Symposium, Proceedings*, pp. 144–149, Seoul, South Korea, 2015.

61. Autili, M., L. Chen, C. Englund, C. Pompilio, and M. Tivoli, "Cooperative Intelligent Transport Systems: Choreography-Based Urban Traffic Coordination," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 4, pp. 2088–2099, Apr. 2021.

62. Karoui, M., A. Freitas, and G. Chalhoub, "Efficiency of Speed Advisory Boundary fINder (SABIN) Strategy for GLOSA using ITS-G5," *2018 IFIP/IEEE International Conference*

on Performance Evaluation and Modeling in Wired and Wireless Networks, PEMWN 2018, Toulouse, France., 2018.

63. Guerrieri, M., B. Maini Lo Casto, G. Peri, and G. Rizzo, "Smart vs Conventional Motorways: Environmental Impact Assessment under Realistic Traffic Conditions," *Science of The Total Environment,* vol. 727, p. 138521, Jul. 2020.

64. Edwards, S., G. Hill, P. Goodman, P. Blythe, P. Mitchell, and Y. Huebner, "Quantifying the Impact of a Real-World Cooperative-ITS Deployment Across Multiple Cities," *Transportation Research Part A: Policy and Practice,* vol. 115, pp. 102–113, Sep. 2018.

65. Pariota, L., L. Di Costanzo, A. Coppola, C. D'Aniello, and G. N. Bifulco, "Green Light Optimal Speed Advisory: A C-ITS to Improve Mobility and Pollution," *Proceedings of the 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I&CPS Europe 2019*, Genova, Italy., Jun. 2019.

66. FHWA, "Intelligent Transportation Systems - Joint Program Office Home Page.", https://www.its.dot.gov/, accessed on May 11, 2024.

67. "About: C-Roads." https://www.c-roads.eu/platform/about/about.html, accessed on May 25, 2024.

68. Lam, A., Chupp, W., Najm, W.G., Brewer, J. and Fallings, D., "Safety Impact Assessment of New York City Connected Vehicle Pilot Safety Applications (No. FHWA-JPO-22-937)" United States Department of Transportation. Intelligent Transportation Systems Joint Program Office, 2022.

69. Chupp, W., Andy L, and Wassim G. N., "Limited Analysis of the Wyoming Department of Transportation Connected Vehicle Pilot Safety Applications", No. FHWA-JPO-22-954, United States Department of Transportation Intelligent Transportation Systems Joint Program Office, 2022.

70. Balke, K, and Chris S., *Connected Vehicle Pilot Deployment Program Independent Evaluation: Mobility Impact Assessment—Wyoming*. No. FHWA-JPO-22-949. United States. Department of Transportation. Intelligent Transportation Systems Joint Program Office, 2022.

71. Balke, K., C. Simek, T. A. T. Institute, and T. A. U. System, "Connected Vehicle Pilot Deployment Program Independent Evaluation: Environmental Impact Assessment—Wyoming," Dec. 2021, https://rosap.ntl.bts.gov/view/dot/41925/dot_41925_DS1.pdf, accessed on May 11, 2024.

72. Chrzan, S., “USDOT-Funded CV Pilot Concludes Its $27M Initiative: The THEA CV Pilot Demonstrates the Safety Potential of Connected Vehicles and Smart City Infrastructure as Seven-Year Program Ends,” 2024, https://theacvpilot.com/, accessed on May 24, 2024.

73. Lam, A., Chupp, W., Najm, W. G., Brewer, J., and Fallings, D., “Safety Impact Assessment of New York City Connected Vehicle Pilot Safety Applications (No. FHWA-JPO-22-937),” United States. Department of Transportation. Intelligent Transportation Systems Joint Program Office, 2022.

74. Balke, and Simek, C., “Connected Vehicle Pilot Deployment Independent Evaluation Program: Mobility Impact Assessment—New York City (No. FHWA-JPO-22-935)”, United States. Department of Transportation. Intelligent Transportation Systems Joint Program Office, 2022.

75. Balke, K and C. Simek, “Connected Vehicle Pilot Deployment Program Independent Evaluation: Environmental Impact Assessment—New York City,” https://rosap.ntl.bts.gov/view/dot/62968/dot_62968_DS1.pdf, accessed on May 24, 2024.

76. “Truck Platooning | ITS Deployment Evaluation.”, https://www.itskrs.its.dot.gov/briefings/executive-briefing/truck-platooning, accessed on May 24, 2024.

77. Shladover, S., Lu, X.Y., Yang, S., Ramezani, H., Spring, J., Nowakowski, C. and Nelson, D., “Cooperative Adaptive Cruise Control (CACC) for Partially Automated Truck Platooning” https://escholarship.org/content/qt260060w4/qt260060w4.pdf, , accessed on May 24, 2024.

78. Kassens-Noor E., “Evaluation of an Active Traffic Management System with Part-Time Use of the Inside Shoulder Authors Sponsoring Organization Performing Organization,”, www.michigan.gov/mdotresearch, accessed on May 25, 2024.

79. Stern, A., and N. Highway Traffic Safety Administration, “Integrated Vehicle-Based Safety Systems: Field Operational Test Final Program Report, 2011”, www.ntis.gov, accessed on May 25, 2024.

80. Stephens, D., J. Schroeder, R. Klein, and B. M. Institute, “Vehicle-to-Infrastructure (V2I) Safety Applications Performance Requirements, vol. 3, Red Light Violation Warning (RLVW),” https://rosap.ntl.bts.gov/view/dot/3592/dot_3592_DS1.pdf, accessed on May 11, 2024.

81. "Wrong-way Driver Thermal Detection System in Phoenix Addressed 33 Near-incidents in First Six Months of Operation. | ITS Deployment Evaluation.", https://www.itskrs.its.dot.gov/2019-b01379, accessed on May 11, 2024.

82. THEA, "Connected Vehicle Pilot in Tampa Successfully Alerted Drivers in 14 Potential Wrong-Way Ramp Entries and Nine Potential Trolley Crashes over 18 Months. | ITS Deployment Evaluation.", https://www.itskrs.its.dot.gov/2021-b01550, accessed on May 13, 2024.

83. Walker, J., K. Opie, C. Systematics, J. Gao, and M. Talas, "Connected Vehicle Pilot Deployment Program Phase 3 Deployment Results and Transition Plan Webinar – New York City.", https://www.its.dot.gov/pilots/cv_pubs.htm, accessed on May 13, 2024.

84. "The C-Roads Platform – An Overview of Harmonised C-ITS Deployment in Europe.", https://www.c-roads.eu/fileadmin/user_upload/media/Dokumente/C-Roads_fact_sheet_2020.pdf, accessed on May 25, 2024.

85. Schimandl, F., M. Baur, S. Hoffman, S. Gabloner, and M. Margreiter, "Effects of Cooperative Systems on Traffic Safety and Efficiency – Results of the German simTD Project.", https://www.researchgate.net/publication/_Effects_of_Cooperative_Systems_on_Traffic_Safety_and_Efficiency_-_Results_of_the_German_sim_Project, accessed on May 25, 2024.

86. Esposito, M.-C., "Implementation of Cooperative Systems for a Road Operator," *Transportation Research Procedia*, vol. 14, pp. 4582–4591, 2016.

87. "C-ITS French Use Cases Catalogue-Functional Description Deliverable 2.2 Activity 2: Studies Sub Activity 2.2 > Services.", 20200421_c-its_french_use_cases_catalog_v5.pdf (developpement-durable.gouv.fr), accessed on May 25, 2024.

88. Asselin-Miller N., "Study on the Deployment of C-ITS in Europe: Final Report," 2016, https://transport.ec.europa.eu/system/files/2016-10/2016-c-its-deployment-study-final-report.pdf, accessed on May 25, 2024.

89. "International Urban Cooperation | Yokohama City 'Smart City.'", https://iuc.eu/japan-%20en/bestpractice/yokohama/, accessed on Aug. 17, 2024.

90. Hao K., "South Korea Opens K-City, the Latest Fake Town Built for Self-Driving Cars.", https://qz.com/1121372/south-korea-opens-k-city-the-latest-fake-town-built-for-self-driving-cars, accessed on May 25, 2024.

91. Linget T., “C-V2X Pilot and Demonstration Areas in China,” 2022, www.5gaa.org, accessed on May 25, 2024.

92. “CETRAN Test Center – AV Assessment | CETRAN - Centre of Excellence for Testing and Research of Autonomous Vehicles - NTU.”, https://cetran.sg/cetran-test-center/, accessed on Jun. 12, 2024.

93. “Singapore AV-Test Bed for U.S., International Developers.”, https://www.wardsauto.com/autonomous-adas/singapore-autonomous-test-bed-for-u-s-international-developers, accessed on Jun. 12, 2024.

94. Mukhija, P., “Development in the Intelligent Transportation System in India,” *International Journal of Recent Technology and Engineering,* vol. 11, no. 4, pp. 38–41, 2022.

95. Chen M. Y., H. Sen Chiang, and K. J. Yang, “Constructing Cooperative Intelligent Transport Systems for Travel Time Prediction with Deep Learning Approaches,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 9, pp. 16590–16599, 2022.

96. Chaudhry A., “Examining road safety impacts of Green Light Optimal Speed Advisory (GLOSA) system,” *Accident Analysis & Prevention*, vol. 200, p. 107534, 2024.

97. Alonso, R. M., B. Ciuffo, M. Makridis, and C. Thiel, “The Revolution of Driving: from Connected Vehicles to Coordinated Automated Road Transport (C-ART),” *EUR 28575 EN*, https://policycommons.net/artifacts/2164163/the-r-evolution-of-driving/2919743/, 2017, accessed on May 31, 2024.

98. “Assessment of Development Opportunities for Intelligent Transport Systems in Asia and the Pacific,”, https://www.un.org/, accessed on May 31, 2024.