Connected Vehicle Pilot Deployment Program Phase 3

Understanding and Enabling Cooperative Driving for Advanced Connected Vehicles in New York City

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16. Abstract

This white paper explores the applicability of cooperative driving for advanced connected vehicles (CD for ACV) on urban roadways based on insights, data analysis, and stakeholder feedback documented as a part of the USDOT Connected Vehicle Pilot Deployment (CVPD). Three testable use cases are identified and mapped for New York City (NYC) applications: 1) pedestrian and bicyclist safety through cooperation, 2) cooperative work zones, and 3) cooperative intersection management. This mapping accounts for both classes of vehicle cooperation, identifies additional data needs, and assesses the existing agency-owned and third-party data sources available in NYC, alongside potential Cooperative Automated Transportation (CAT) data that may contribute to CD for ACV. More specifically, thermal-based pedestrian detection technology that has already been instrumented by NYC Department of Transportation (NYCDOT) that is currently used for the Pedestrian in Crosswalk Connected Vehicle (CV) application is evaluated. The white paper also provides a detailed recommendation of future needs and opportunities by the introduction of CD for ACV technologies.

17. Key Words

Connected Vehicles, CV, DSRC, V2V, V2I, Safety, CD, CD for ACV, New York City

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Finally, the team wants to thank the USDOT for sponsoring this project and laying the foundation for future connected vehicle deployments.

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1 Introduction

Cooperative Driving (CD) aims to improve traffic safety and traffic flow, and/or facilitate road operations by sharing information that can be used to support vehicle movements and influence dynamic driving task performance by one or more nearby road users (SAE International 2021). This synchronization of vehicles is enabled by Vehicle-to-Everything (V2X) communication services, such as an inter-vehicle communication system in which road participants exchange information to coordinate, validate, and support the actions of fellow drivers. In the V2X environment, drivers can obtain information such as the status of front vehicles and traffic signals anytime and anywhere, which creates the conditions for cooperative driving. Recent developments in navigation systems, telecommunications, artificial intelligence, electronic toll collection systems, and wireless communications have propelled the field of cooperative driving. With improvements in positioning accuracy and reduction in communication latency, telematics has enabled new safety and mobility applications which include providing real-time updates of traffic maneuvers, alerting the driver about an imminent danger and even active interference with the vehicle controls (Herrtwich and Nöcker 2003).

In CD, different types of individual road users coordinate their microscopic aims and actions in light of improved overall macroscopic effects for everyone (ANDATA Artificial Intelligence Labs 2021). Moreover, as defined by the Society of Automotive Engineers (SAE) J3216 Standard (SAE International 2021), cooperative driving automation (CDA) enables automated vehicles (AVs) to communicate between vehicles, infrastructure devices, and road users such as pedestrians and cyclists. Based on SAE J3216, CDA has four (4) classes of cooperation, A through D, with an increasing amount of cooperation associated with each successive class: 1) Class A: Status-sharing; 2) Class B: Intent-sharing; 3) Class C: Agreement-seeking; and 4) Class D: Prescriptive (FHWA 2021a). However, one of the prime challenges faced by many of the AV-specific applications is that they require near 100% or 100% penetration of V2X technology, or AVs equipped with V2X technology, to optimize their benefits (European Commission 2017). This is where CD technologies with advanced connected vehicles (ACVs) can help implementation of these benefits, as a 100% AV environment is still a distant reality. ACVs are connected vehicles (CVs) with enhanced sensors, computer vision, wireless communication, and data analysis features embedded. Although many transportation agencies are deploying infrastructure to support Connected and Automated Vehicles (CAVs), there is a need to better understand the role of infrastructure in supporting and enabling CD for ACV, especially in an urban environment. In urban areas, connected cars, connected pedestrians, and V2X communication scenarios have the potential to improve both operational efficiency and safety. The inclusion of pedestrians and non-motorized transportation modes to the arsenal of possible applications is especially important given the relatively high rates of injuries and fatalities suffered by these groups of highly "vulnerable" travelers.

1.1 Purpose

New York City (NYC), one of three sites selected for the USDOT Connected Vehicle Pilot Deployment (CVPD) Program (https://www.its.dot.gov/pilots), provides a unique opportunity to develop and test advanced mobility and safety solutions. The New York City Department of Transportation (NYCDOT), the lead agency for the NYC deployment, has made significant investments linking wirelessly capable roadside, in-vehicle, and mobile technologies to address local safety and mobility goals. While CD for ACV has not been a CVPD program focus, the technologies deployed and use cases studied have significantly advanced an understanding of both progress and challenges toward building shared perception among drivers, pedestrians, and other users of the roadway system, a critical requirement for any potential future CD for ACV implementation.

This white paper captures insights gained, and challenges identified as a part of the CVPD experience related to the consideration of CD for ACV operating in/around urban intersections in NYC. Shared perception is especially valuable for exchanging information about road users and entities that are outside of the communication range or lack communication capabilities (i.e., vulnerable road users (VRUs) and non-CAVs) and contributes additional data to reduce uncertainty. Through a complete scan of existing literature and the resources currently available to NYC, several use cases were identified. And the details of three (3) use cases that are most relevant to NYC are discussed in detail. These use cases are: 1) pedestrian and bicyclist safety cooperation, 2) cooperative work zones, and 3) cooperative intersection management. A data-driven analysis is conducted to identify additional data needs and assess the existing agency-owned and third-party data sources available in NYC, alongside potential Cooperative Automated Transportation (CAT) data that may contribute to CD for ACV. Reliability, applicability, and appropriateness for proposed CD for ACV use cases are examined for each data. The reliability deals with accuracy and completeness of the data. Data applicability helps determine if the granularity/resolution of the data (e.g., data update frequency) is good enough to be applied to the proposed use cases. And data appropriateness aims to see if the data is suitable for the intended purpose of the proposed use cases. These are discussed in each of the subsections in Chapter 4.

More specifically, NYCDOT has already instrumented intersections with pedestrian detection equipment which can detect objects in the configured zones and provide inputs to the traffic controller. This technology is currently being used for the Pedestrian in Crosswalk application in the NYC Connected Vehicle Pilot Deployment (CVPD) to provide information indicating the presence of a pedestrian in the crosswalk. As part of the data analysis, the deployed pedestrian detection system is evaluated at multiple signalized intersections with different levels of pedestrian density. This white paper also provides recommendations for implementing/piloting each use case and identifies future needs and opportunities to implement CD for ACV in NYC.

2 Literature Review

CD has been implemented and tested with various levels of success in different parts of the world. The current state of CD technology, in both real-world and academic settings, is discussed in this section. Most of these pilot projects are based on collaboration between private technology providers and city or state agencies, with broader goals of improving safety for vehicles and pedestrians, traffic throughput, and fuel efficiency. To achieve an accident-free traffic state, researchers from around the world have devised new methodologies to collect, process, and transmit relevant knowledge about current driving conditions to vehicles and drivers. To maximize vehicular environment perception by gathering information of all the actors contributing to the highly dynamic traffic scene, it is necessary but difficult to fuse directly measured data such as vehicle speeds and headways with highly contextual, unpredictable data like driver intention and safety perception. Due to the uncertainly and unpredictability of some of these signals due to human involvement, sensors and algorithms need to be robust enough to accurately predict the trajectories of nearby vehicles. When it comes to traffic safety, robustness of this task is of paramount importance. However, some of this uncertainty can be significantly reduced using appropriate coordination strategies, which have been tested in many of the developments in CD and will be discussed in this white paper. Most of the strategies designed for CD are continuously evolving as more tests are being performed in real-world and simulation settings.

The following sub-sections will provide an overview of some CD projects underway in the United States (US) and elsewhere. It will also provide insights into the advances made by Federal Highway Administration (FHWA) Cooperative Automation Research Mobility Applications (CARMA), the NYCDOT's Connected Vehicle Pilot, and the FHWA at the federal and state level. The state-of-the-art research done by fellow researchers in this domain are also acknowledged.

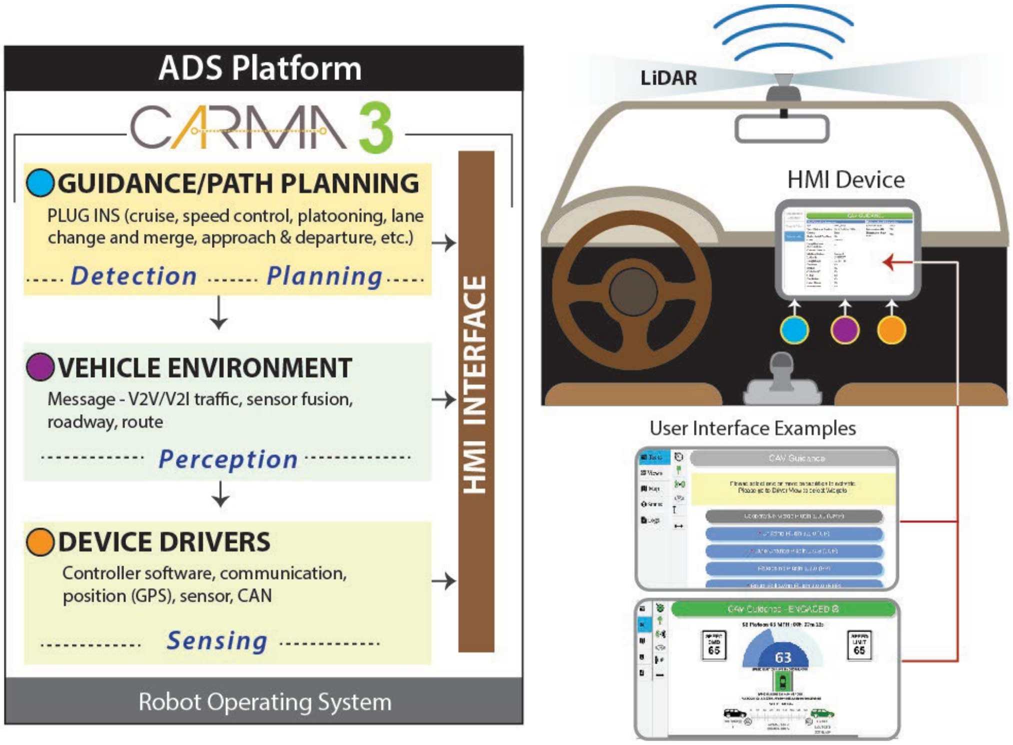
2.1 Cooperative Driving in the US

2.1.1 National/Relevant USDOT Practices

In the US, several CD projects have been tested over the last two (2) decades. Some of the earliest projects concerned with CD in the US were in vehicle-to-vehicle (V2V) communications, which began under the Vehicle Infrastructure Integration (VII) Initiative in 2003. VII is a cooperative effort between federal and state departments of transportation (DOTs) and automobile manufacturers, with a broad goal of improving transportation safety and overall mobility. This was made possible by the 5.9 GHz safety band reserved for the intelligent transportation system communications among devices that support CAVs (Opiola 2006).

More recently at the federal level, the FHWA developed the innovative Cooperative Automation Research Mobility Applications (CARMA) platform (https://highways.dot.gov/research/operations/CARMA) to encourage research and collaboration among industry, academia, and federal, state, and local governments with the goal of improving transportation efficiency and safety. CARMA enables the research and development of cooperative automated driving system (CADS) capabilities to support the advancement of transportation systems management and operations (TSMO) using automated driving technology (FHWA 2021a). Designed with open-source software (OSS) and to be vehicle/technology agnostic, the unique CARMA platform leverages wireless communication to CVs and road infrastructure to help automated driving systems make safe maneuvers (FHWA 2021c).

In 2014, CARMA1 developed FHWA's first cooperative AV fleet and demonstrated a proof of concept (PoC) of a five-vehicle cooperative adaptive cruise control (CACC). The roadway tests were performed to combine speed harmonization with connected automation technologies such as platooning and cooperative merging on managed lanes (FHWA 2021a). Next, CARMA2 was developed as OSS to engage with the industry in developing cooperative automation. CARMA2 runs on a Linux computer of a vehicle that not only interacts with the vehicle's devices and microcontrollers via the vehicle's Controller Area Network (CAN) but also interfaces with the onboard unit (OBU) that functions as a two-way radio for dedicated short-range communications (DSRC) with other vehicles and infrastructure (FHWA 2021a). CARMA3, the current version of CARMA that was kicked off in August 2018, is an open-source (OS) platform (Figure 1) developed using an agile software development process to collaborate with the stakeholder community for the research and development of CDA (Nallamothu et al. 2020b).

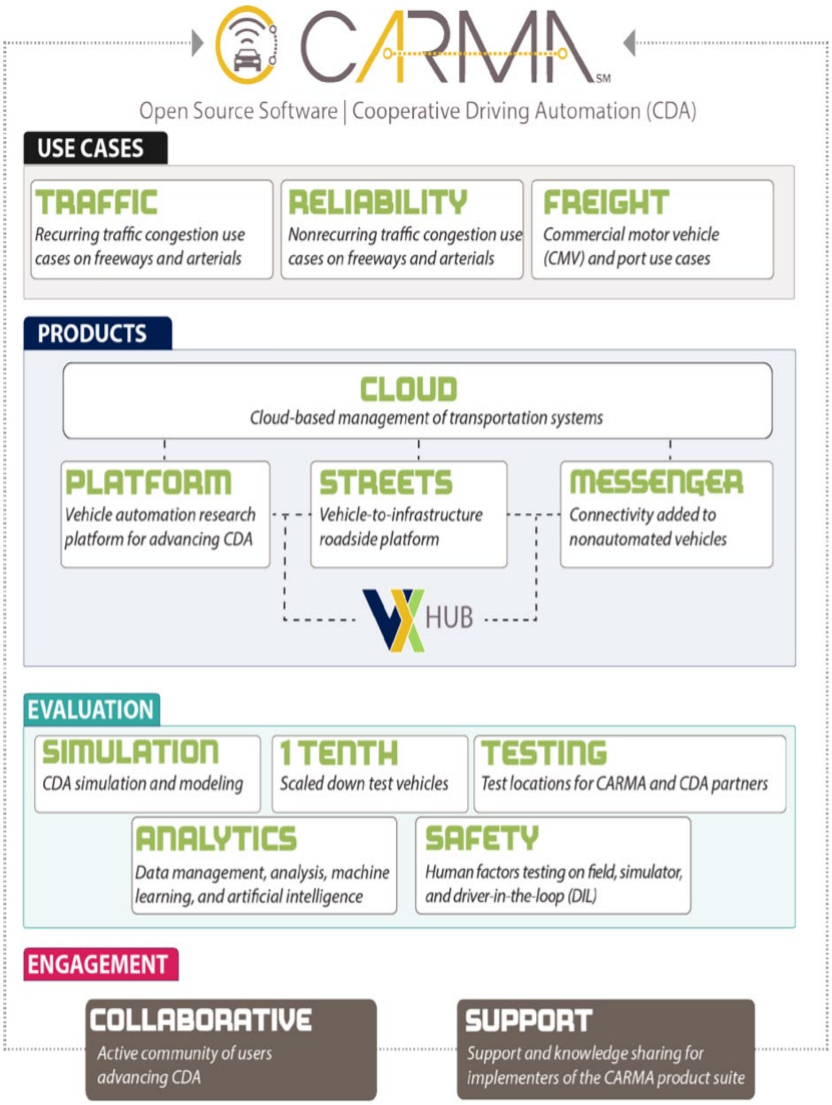


(Source: FHWA)

(HMI = human–machine interface; CAN = Controller Area Network; LiDAR = light detection and ranging; CAV = cooperative and autonomous vehicle; V2I = vehicle-to-infrastructure; GPS = Global Positioning System; V2V = vehicle-to-vehicle.)

Figure 1: CARMA3 Architecture

CARMA includes four (4) tools supporting informed and dynamic cooperation among vehicles. These tools are CARMA Cloud, CARMA Platform, CARMA Messenger, and CARMA Streets. All four (4) CARMA products work together with the V2X Hub, a separate multimodal OSS system enabling networked, wireless communications between automated vehicles, infrastructure devices, and personal communications devices (Tiernan et al. 2019). CARMA covers three main use cases: traffic, reliability, and commercial motor vehicle (CMV) and port use cases. Traffic refers to use cases related to recurring traffic congestion on freeways and arterials, covering transit and traffic signals. In terms of reliability, CARMA is concerned with non-recurring traffic congestion use cases on freeways and arterials, which include work zones, weather events, and traffic information management system (TIMS). For freight or CMV and post use cases, truck platooning and port drayage are included. The latest version of CARMA is an extensible vehicle platform that can be used with multiple vehicles. The CARMA tools, use cases, and the architecture of CARMA3 are shown in Figure 2.



(Source: FHWA)

Figure 2: CARMA Tools

Two OS simulation tools, CARLA (Dosovitskiy et al. 2017) and Simulation of Urban Mobility (SUMO) (Behrisch et al. 2011) are often used for CDA research in the US. The main goal of CARLA, an OS simulator based on Unreal Engine and OpenDRIVE standard, is to support development, training, and validation of autonomous urban driving systems. SUMO, a microscopic and continuous multi-modal traffic simulation package, can be used alone and/or in co-simulation with CARLA, allowing task distribution to exploit the capabilities of each simulation in favor of the user. For example, in the case of an AV simulation, CARLA can provide inputs to AV sensors such as photorealistic images resembling the real world, whereas SUMO can be used to generate the neighboring vehicles interacting with the AVs. Moreover, these tools being OS democratizes autonomous driving research and development, allowing users easy access and customization that can be applied to different use cases within the general problem of driving (e.g., learning driving policies, training perception algorithms, etc.). Control over the simulation is granted through an application program interface (API) handled in Python and C++ that is constantly growing as the project evolves (Dosovitskiy et al. 2017; Dunlap et al. 2019).

In addition, the FHWA published 2020 reports (Nallamothu et al. 2020a, 2020b) which outline a high-level concept of operations (ConOps) in support of the CARMA platform to identify testable use cases for CDA capabilities to support Transportation Systems Management and Operations (TSMO) strategies. For each use case, the operational needs, operational design domain, stakeholders, conceptual diagrams, information flows, triggers, and functional requirements were identified. The example situations presented are designed to allow for building associated algorithms, integrating the algorithms into CARMA, and testing the algorithms under proving ground or on road conditions within the next steps of CARMA (Nallamothu et al. 2020a, 2020b). Detailed ConOps for TSMO and CDA use cases and scenarios (Nallamothu et al. 2020a) and several PoC reports (Soleimaniamiri, Li, Yao, Ghiasi, Vadakpat, Bujanovic, Lochrane, Stark, Blizzard, et al. 2021; Soleimaniamiri, Li, Yao, Ghiasi, Vadakpat, Bujanovic, Lochrane, Stark, Hale, et al. 2021) were published in 2020 and 2021.

Other standards and resources may also be valuable in developing operational CD scenarios. Examples of these resources include the following:

- SAE J3216 Taxonomy and Definitions for Terms Related to Cooperative Driving Automation for On-Road Motor Vehicles, July 16, 2021.
- SAE J2735SET V2X Communications Message Set Dictionary™ Set, July 23, 2020.
- SAE J2945/9 Vulnerable Road User Safety Message Minimum Performance Requirements, March 21, 2017.
- SAE J2945/8 Cooperative Perception System (Work in progress), September 18, 2018.
- SAE J2945/6 Performance Requirements for Cooperative Adaptive Cruise Control and Platooning (Work in progress), January 27, 2015.
- SAE J3224 V2X Sensor-Sharing for Cooperative & Automated Driving (Work in progress), December 11, 2019.
- SAE J3256 Infrastructure-based prescriptive cooperative merge (Work in progress), June 11, 2021.
- SAE J3251 Cooperative perception CDA feature: Jaywalking pedestrian collision avoidance (Work in progress), April 19, 2021.
- AASHTO, ITE and ITS America, Infrastructure Owner Operators Guiding Principles for Connected Infrastructure Supporting Cooperative Automated Transportation, February 2020.

2.1.2 Other Domestic Projects

At the state and local levels, efforts for CD are at different stages, ranging from planning to testing to deployment and policy recommendations. In California, the UC Berkeley PATH program focuses on cooperative truck platooning systems, maintaining coordinated driving of clusters of heavy trucks using automatic control of their speed and separation, extension of adaptive cruise control (ACC) and so on (Shladover 2017). Many states have established frameworks for Cooperative Automated Transportation (CAT), generated data to enable automation of vehicles and the infrastructure which vehicles share with other CAT users, and envisioned a roadmap to test initiatives such as CD. In Iowa, CAT is part of the state's broader TSMO strategic plan (IOWA DOT 2019). Similarly, Washington state has implemented a CAT protocol with some current activities including first/last mile connections, data, work zone safety, traffic signals (WSDOT 2021).

In addition, a few independent private companies and education institutes have also tested some cooperative driving technologies in controlled, supervised environments. Most notable among these are the

M-City (University of Michigan) at the University of Michigan North Campus (Ann Arbor) - this test site consists of various road surfaces, up to four-lane roads, roundabouts and tunnels, fixed and variable street lighting, as well as fixed and moveable buildings. Uber established a mock city in Pittsburgh called the “Almono” in 2017, which spans an area of 170,000 m^2 and comprises a giant roundabout, fake cars, as well as roaming mannequins and containers meant to simulate pedestrians and buildings (Goldberg 2017). In California, Google’s Waymo project created a fake city called “Castle” which occupies an area of 370,000 m^2 (Madrigal 2017). While private company participation is important, the implementation of these technologies at a city-wide scale hinge on national and state-level policies. Some initiatives in this regard are explained in the following two (2) sections.

2.2 International Projects

The European Commission (EC) has been making significant efforts since setting up a Cooperative-Intelligent Transportation Systems (C-ITS) platform in early 2014 to set up a reference framework for supporting Cooperative, Connected, and Automated Mobility (CCAM) policies (European Commission 2017). The C-ITS strategy in Europe aims to combine the efforts undertaken by different stakeholders and member countries to develop a common vision across the European Union (EU). Later in 2016, EC and its member States launched the C-Roads Platform to coordinate the C-ITS deployment across the EU. The C-Roads program follows a learning-by-doing approach to C-ITS applications and released an overview of the pilot sites across EU in December 2017 (Kernstock 2017). The details of this are illustrated in Table 1 below. Besides the C-ITS deployment, European Telecommunication Standards Institute (ETSI) also published a technical report 103 562 in 2019 (V2.1.1) that focuses on the analysis of the Collective Perception Service (CPS) (ETSI 2019).

Against a total budget of EUR 300M for CD development by the EU’s framework program Horizon 2020, certain trends emerged across all EU countries. Among the communication technologies adopted, ITS-G5 and cellular based communications were seen as the most mature and well-developed, as they combine the benefits of both communication services and broadens the range of potential use cases (Botte et al. 2019). They are implemented in Austria, Germany, the Netherlands, Czech Republic, France, Italy, and Slovenia. Similar hybrid models were also tested in Portugal and Hungary. Among the use cases tested, road works warning (similar to “work zone” described later in this white paper) is the only one that appears across all the countries. Other most commonly tested use cases were Probe Vehicle Data (PVD), Slow or Stationary Vehicle (SSV) and in-Vehicle Signage (VSGN). Reported lags in implementation seem to stem from the vehicle-side technology, such as inadequate in-vehicle cameras, inefficient adaptive cruise control, unavailability of self-packing systems and so on (Botte et al. 2019). Further advancement and large-scale deployment are expected as more personal vehicles adopt these new technologies; combining the universality of cellular communication with the robustness of an ITS-G5 infrastructure is the direction the EU cooperative driving framework is moving towards.

Table 1. C-Roads projects in various European countries

Country	Use Cases/Benefits	Communication	Pilot sites
Austria	300 km of motorways	ITS-G5	Eco-AT–European Corridor Austrian Testbed
Germany	Motorways and interurban	ITS-G5 and cellular	Lower Saxony and Hessen
The Netherlands	Multimodal cargo transport, Infotainment	ITS-G5 and cellular network hybrid	South of the Netherlands (Noord-Brabant and Utrecht)
Belgium	Motorways	Cellular with the HERE Location Cloud and TMC	Flanders and Wallonia

France	Urban environment & urban/interurban interface and parking	Both ITS-G5 and cellular	Paris, Strasbourg, Brittany, Bordeaux and Isère
Nordic Countries (Denmark, Sweden, Norway, and Finland)	Peripheral networks, rural roads, snowy and icy arctic conditions	Cellular	Cities of Gothenburg, Stockholm, Södertälje and Uppsala
Portugal	Designing a National Single Point of Access (SPA) prototype		Pilot 1
	Metropolitan areas, interurban roads, streets, and highways	Hybrid G5/cellular	Pilot 2: Valença and Caia, Lisbon and Porto
	Providing CAVs with automation on levels two and three of the Trans-European Networks-Transport (TEN-T)	Hybrid G5/cellular	Pilot 3
	Traffic monitoring, travel time prediction, parking availability, an in-vehicle app, transit priority and last mile	G5/cellular	Pilot 4: Lisbon and Porto urban node
	Investigating applications on traffic prediction	Cellular and WiFi	Pilot 5: Lisbon and Porto urban node
Spain	Test areas that present a high level of heterogeneity, thus allowing a wide spectrum of use-cases	3G and 4G/LTE	Madrid, Cantabrian, Mediterranean (Catalonia and Andalucia)
Czech Republic	Public transport safety	Both ITS-G5 and cellular	München /Nurnberg – Praha, Praha – Brno, and Plzen, Brno and Ostrava
Hungary	Highway, truck platooning, passenger cars highway chauffeur, and combined scenarios of trucks and passenger cars.	Hybrid DSRC/cellular	Motorways M1, M7, city of Győr by motorway M1
Italy	Truck platooning, passenger cars highway chauffeur, and combined scenarios of trucks and passenger cars	ITS-G5 and cellular communication	Brenner Motorway, Autovie Venete Motorway
Slovenia	Traffic jam ahead warning, Hazardous location notification, Road works warning, Weather conditions, In-vehicle signage, In-vehicle speed limits, Alert wrong way driving	ITS-G5 and cellular networks	TEN-T core network covering 100 km. Located on the A1 highway (section Ljubljana – Koper), A3 (section Divača - Sežana) and H4 (section Razdrto – Vipava)

In addition, there are two “simulated” urban environments which are currently operational in Europe. First, CERMcity in Germany (Aldenhoven Testing Center) was built by RWTH Aachen University with funding from the Federal Ministry of Education and Research. This site comprises parking areas, pedestrian walkways, intersections, straights, parking areas, and a multifunctional area. Second, the Zala City in

Hungary (AVL) is a test environment launched in 2017 and managed by the Automotive Proving Ground Zala Limited. This test site plans to cover a total area of 250 hectare and has the capacity to test both classic vehicle dynamics and CD functions in addition to electric vehicle validation tests.

2.3 Recent Research in Cooperative Driving

CD is a constantly evolving and growing field of research as the technologies powering it have advanced. Cooperative perception, one of the latest advancements in CD, increases situational awareness of vehicles without substantial additional costs. In order to enable cooperative perception, the distributed information from multiple vehicles need to be fused properly (Kim et al. 2015). A recent research related to intersection management and energy efficiency is the Cooperative Vehicle Intersection Control (CVIC) algorithm, proposed by (Lee and Park 2012). CVIC can be used to assign safe maneuver to vehicles approaching the signalized intersection without having a traffic signal. In this simulation-based study, the objective function of CVIC uses nonlinear constraints and minimizes the length of the overlapped trajectory along the intersection. Through this, CVIC can reduce CO2 emissions and fuel consumption up to 44%. With the objective of reducing fuel consumption, a recent model was proposed by (Kamalanathsharma and Rakha 2016), which divided the speed profiling to optimize fuel into arrival and departure from the signal. They concluded that if both the upstream and downstream maneuvers are considered, some of the previous studies around reduced fuel consumption cannot be proven.

Various studies have assessed the efficacy of the cooperative adaptive cruise control (CACC) (Van Arem, Van Driel, and Visser 2006) that has been successful in reducing the headway gaps between leading and following vehicles to as low as 0.5 seconds. Combining V2V technologies with adaptive cruise control allows CACC to achieve this level of precision since V2V technology provides more information to the drivers. CACC has been proven to reduce the average speed compared to the scenario with no CACC penetration at low penetration rates (20% to 60%) and can further contribute to traffic stability for penetration rates of over 60%.

Another concern regarding CD and ACV ,which has gained a lot of attention recently, is the threat of cyber-attacks and vulnerability of security systems. A research study by (Petrillo, Pescape, and Santini 2020) tackles this problem of “cyber-secure leader tracking” by proposing a new cooperative adaptive strategy that is resilient to not only cyber-attacks but also to internal network induced phenomena such as communication impairments. Researchers have proved the effectiveness of their hypothesis using the Lyapunov–Krasovkii approach.

The reliability and latency requirements for CD have been studied by various researchers so far. More recently, the safety gaps of less than 5m between cars have been a point of concern. Introducing the concept of Tactile Internet for CD (Dressler et al. 2018) integrates interdisciplinary concepts from control theory, mechanical engineering, and communication protocol design to overcome the unreliable nature of wireless communications for situations where the sensor information from other cars in the order of about 10 Hz needs to be transferred real-time.

2.4 Communication Technology

CD combines information obtained from on-board sensors on a vehicle with inputs communicated from the road environment and other road users with the help of personal devices or road infrastructures. This enables real-time cooperation and coordination between them. Real-time communication is essential to realizing a future with accident-free traffic. Among communication techniques between vehicles and infrastructure to transfer messages, the most widely used are the following: DSRC that are one-way or two-way short-range to medium-range wireless communication channels, wireless technology (i.e., ITS-G5) as defined by the European Telecommunications Standards Institute (ETSI), and cellular network-based technologies that include 3G, 4G/Long Term Evolution (LTE) and 5G services.

Overall, these communication techniques can be divided into two (2) types based on FHWA (Nallamothu et al. 2020b):

i. Short-range communications: short-distance communications, including the dedicated short-range communications suite of protocols, such as Wireless Local Area Network (WLAN) protocol, Institute of Electrical and Electronics Engineers (IEEE) 802.11p.
ii. Long-range communications: long-distance communications, such as 3G, 4G/LTE, 5G, or cellular vehicle-to-everything, which support wide area communication over a cellular network.

2.4.1 Short-range communication techniques

A key component of the current CV communication in the U.S. is DSRC in the 5.9 GHz band that contains a secure communication channel (channel 172) and WAVE Service Announcements (WSAs) that advertise the availability of other information and services on other channels (ITSJPO 2021). For example, the New York and Tampa CV teams use dual radios: channel 172 and the other to obtain supplementary information such as Traveler Information Messages (TIM) from other channels (ITSJPO 2021). In 1999, the Federal Communications Commission (FCC) dedicated a bandwidth of 75 MHz for DSRC technology in the 5.9 GHz band. The driver’s privacy is also protected using DSRC because although the receiving vehicle validates the authenticity of received messages, they are not linked to the vehicle. The location, headway, and speed of every vehicle is broadcasted 10 times per second in a secure and anonymous manner. All the neighboring vehicles receive this information, and each vehicle then estimates the risk imposed by the transmitting vehicle. In this manner, dangerous situations like road obstacles and potential collisions with road users can be detected and assessed even before they are visually noticed by the driver.

Although DSRC is based on relatively old physical layer protocol, it has been tested for various CV safety applications and has been proven to meet the needs in term of range and latency (Miucic 2018). As of 2019, there are about 2,000 DSRC radios deployed in the U.S., mainly in pilot schemes (Zagajac, Mulligan, and Misener 2019). The more recent Cellular Vehicle-to-Everything (C-V2X) technology has the same purpose of direct communication link between vehicles. C-V2X is defined by Third Generation Partnership Project (3GPP) based on cellular modem technology, leading to fundamentally different non-interoperable access layer with DSRC (Papathanassiou and Khoryaev 2017). Aside from that, the two (2) technologies are addressing identical use cases with identical network, security, and application layers.

In December 2020, the United States Department of Transportation (USDOT) presented its efforts in V2X technologies in “Leveraging Existing V2X Investments in a Changing Spectrum Environment” (Nallamothu et al. 2020a; Opiola 2006), where they announced their 2021-22 focus will be on LTE-V2X when it comes to technology bands. The industry is watching the new rule proposed by FCC as it plans to divide the allocated 5.9GHz band between V2X and WiFi. This can be a fundamental change to the vehicle communications market in the U.S. with a narrowed spectrum via C-V2X technology instead of widely used DSRC. A detailed letter to the Secretary of Transportation in March 2021 by the Intelligent Transportation Society of America (ITSA) and the American Association of State Highway and Transportation Officials (AASHTO) elucidated the beneficial impact V2X technologies will have on reducing roadway fatalities, improving safety of vulnerable road users, and contributing to economic savings by reducing the more than $830 billion in annual costs associated with crashes and expressed the need of preserving the full 75 MHz of spectrum within the 5.9 GHz band for transportation safety (ITS America and AASHTO 2021).

On the other hand, WiFi-based V2X technology (ETSI ITS G5 / IEEE 802.11p, an extension of the general WiFi standard modified for vehicle operation in an automotive environment) has been tested for more than 10 years and is ready for deployment (Turley et al. 2018). The readiness, range, and compatibility of these technologies are pivotal in ensuring the safety of road users (Turley et al. 2018).

2.4.2 Long-range communication techniques

Among long-range communication techniques, 5G is quickly gaining momentum as a reliable, easily accessible method in the next decade. Unlike some of the other communication techniques, a 5G-based communications solution has the advantage of wider reach allowing more reliable communications among vehicles. The pre-5G PoC at AstaZero (Castiglione et al. 2020) uses LTE radio with 5G Evolved Packet Core (EPC) and is designed to support low-latency, ultra-reliable communications. This would be an ideal candidate for safety-critical autonomous driving applications. Compared to current technologies of 4G and LTE, 5G will reduce latency and increase reliability (Shah et al. 2018)while enabling applications such as sharing of real-time local updates or trajectory between vehicles and propelling the efforts of coordinated driving. V2X communication based on 5G will support latency at ten (10) milliseconds end-to-end and one (1) millisecond over the air (OTA) — in the case of edge computing (Szalay et al. 2020). Similarly, 5G provides very high reliability for ultra-reliable transmissions (targeting 99.999%) (Soós et al. 2020).

Overall, the environment for 5G-targeted vehicles can be very diverse, including slow-moving industrial automated guided vehicles, urban traffic scenarios, and vehicles moving at a high speed on freeways (Szalay et al. 2020). The 5G Automotive Association (5GAA), representing both the automotive and telecommunications industries involved in the deployment of V2X, highlighted that many advanced driving use cases would require 5G-V2X radios. These use cases include Cooperative Maneuvers and Sensor Sharing, Traffic Information and Local Hazard, HD Map Sharing for AVs, Collective Awareness/Complex Interactions for VRU, Dynamic Intersection Management, Dynamic Cooperative Traffic Flow, and so on (5GAA, 2020). Based on their recent whitepaper (5GAA, 2020), the spectrum needs for direct communication correspond to between 10 and 20 MHz at 5.9 GHz for basic safety and an additional 40 MHz or more at 5.9 GHz for advanced driving. For mobile network-based communications, additional spectrum availability in mid-bands (1-7GHz) is needed to deliver advanced driving capabilities in urban environments (5GAA, 2020).

While V2X and 5G standardization are still ongoing, early adaptations of these technology ties are available and have been deployed (i.e., 5G Non-Standalone (NSA)) (Szalay et al. 2020). Various real-world 5G applications are being developed in different fields, such as the Internet of Things (IoT) and healthcare. However, comprehensive study of the current state-of-the-art about 5G-capable automated vehicles on freeways are still missing at this time (Szalay et al. 2020).

3 Cooperative Driving Use Cases Mapping to NYC Applications

3.1 CD Uses Cases, Benefits and Applications

The main benefits of CD lie in improving vehicle safety and flow, increasing comfort and driving performance, and reducing the environmental footprint of vehicles. These benefits can be achieved by a plethora of use cases pertaining to different traffic conditions, infrastructure availability, data requirements, and practical applications. In this section, specific use cases and the applications behind them are presented, with an emphasis on the ones currently tested/projected by CARMA and the European C-ITS programs. CD features such as VRU warning, lane changing and merging, speed harmonizing, truck platooning and so on are categorized under the use cases. The eight (8) cooperative driving use cases identified are:

i. Pedestrian and Bicycle Safety
ii. Work Zone
iii. Congestion
iv. Freight Management
v. Intersection Management
vi. Urban Roadways
vii. Weather (Icy and Snowy Road Conditions)
viii. Freeway Management

Table 2 below shows the different CD services for each use case, the category it falls under, their benefits, application type, and where the pilot has been applied. Some of the use cases that are most relevant to NYC are discussed in further depth in the following section. The use cases are also categorized based on their benefits in the domain of safety, operational efficiency, traffic management, and fuel efficiency.

Table 2. Cooperative Driving Use Cases and Benefits

CD Use Cases	CD Services	Category	Benefits	Type	Pilot Applied
Pedestrian and Bicycle Safety	Vulnerable Road User (VRU) Warning	Safety	i. Improve safety of VRUs ii. Reduce collision risks .	V2X, V2P	C-ITS Europe
Work Zone	Lane Change and Merge (feature)	Safety, Operational Efficiency	i. Increase efficiency in lane changing and merging through coordination ii. Increase efficiency in lane changing through lane assignment prior to entering work zone	V2I, V2V	C-ITS Europe

	Speed Harmonizing	Traffic management, Fuel efficiency	i. Minimize traffic jams and limit back-end congestion ii. Reduce command speed entering work zone	V2V	CARMA (U.S. Army's ATC in Aberdeen, Maryland)
	Sensing Driving	Safety, Traffic Management	i. Facilitate safer driving by providing overtaking warning, ii. Reduce intersection collision risks iii. Reduce backlog by prioritizing Special Vehicles (e.g., construction trucks)	V2V	C-ITS Europe, CARMA (Summit Point Raceway, WV)
Congestion	Traffic Jam warning	Operational efficiency, Traffic management	i. Mitigate traffic congestion ii. Increase network efficiency by allowing drivers to reroute/reschedule trips	V2V	CARMA, PATH
Freight Management	Truck Platooning	Operational efficiency, Fuel efficiency	i. Energy Savings ii. Efficient freight management	V2V	California PATH CARMA (Aberdeen, MD
	Vehicle Energy Management	Fuel efficiency	i. Increase fuel economy	V2I	C-ITS
	Commercial Motor Vehicles (CMV)	Safety	i. Increased safety in freeways ii. Reduce crashes, injuries, and fatalities involving large trucks	V2V, V2I	CARMA
Intersection Management	Unsignalized/ signalized intersection	Fuel/energy efficiency, Safety	i. Reduce safety risks by providing collision-free path for each vehicle (non-signalized) ii. Reduction in energy consumption (signalized)	V2X, V2V	C-ITS, CARMA
	Vehicle Energy Management	Fuel efficiency	i. Increase fuel economy	V2I	C-ITS
	Traffic signals	Traffic management, Safety	i. Better negotiation with other vehicles and infrastructure on specific maneuvers	V2V, V2I	CARMA
Urban Roadways	Collective perception	Operational efficiency, Safety	i. Allows cars to inform nearby vehicles of	V2I, V2X	CARMA, PATH

			objects to increase situational awareness		
	Cruising	Traffic management	i. Efficient traffic management ii. Maintain uniform speed	V2V	CARMA
	Cooperative Maneuver Coordination	Safety, Operational Efficiency	i. Enable safe, efficient maneuvers by allowing vehicles to express their cooperation needs	V2V	C-ITS Europe
Weather	Traffic information and smart routing	Safety	i. Avoid snowy roads, temporarily closed ii. Suggest alternative smart routes to improve safe driving	V2I	C-ITS Europe
	Connected and cooperative navigation	Operational efficiency, Fuel efficiency	i. Avoid bad road conditions and decrease fuel usage	V2V	PATH
Freeway management	Vehicle Platooning	Fuel/Energy efficiency	i. Enable collaboration between vehicles at close range in a single lane to reduce fuel usage ii. Reduce road usage	V2V	CARMA (Aberdeen, MD)

NYC, as one (1) of the three (3) pilot sites selected by the USDOT, is implementing a suite of CV applications and technologies tailored to meet unique transportation needs for NYC's dense urban grid network. As of 2021, the NYC CV pilot site is in Phase 3 for operations and maintenance. The NYC CV pilot study led by NYCDOT (https://www.cvp.nyc) aims to improve the safety of travelers and pedestrians throughout NYC via deployment of V2V and V2I CV technologies and to reach its Vision Zero goals of eliminating traffic related fatalities (NYCDOT 2021a). To this end, fourteen (14) different safety applications have been identified under V2V (Emergency Electronic Brake Lights, Forward Crash Warning, Intersection Movement Assist, Blind Spot Warning, Lane Change Warning, Vehicle Turning Right in Front of Bus Warning), V2I (Red Light Violation Warning, Speed Compliance, Curve speed compliance, Speed Compliance in Work Zone, Oversize Vehicle Compliance, Emergency Communications and Evacuation Information) and Mobility (Pedestrian in Signalized Crosswalk Warning, Mobile Accessible Pedestrian Signal System) categories (NYCDOT 2021a). It is important to identify an area in the current NYC CV Pilot site as a location for supporting ACVs to better understand the role of infrastructure in enabling connected driving in an urban environment. Based on these, three (3) of the most relevant use cases with respect to New York City are identified and discussed in greater detail over the following sections.

The first use case, "Pedestrian/Bike Safety through Cooperation," furthers NYC'S Vision Zero goal by leveraging CV, AV, and CD for ACVs. NYC's status as one of the most walkable cities in the country presents a unique set of challenges for pedestrians and cyclists as well as vehicles—but it also provides a great opportunity to test CD technologies in NYC. The second use case, "cooperative work zone", was chosen because it involves safety for vehicles and workers and makes the traffic flow more efficient. A well-functioning cooperative system would be extremely beneficial to road and construction works in NYC. The third use case, "cooperative intersection management", allows all benefits of CD to be exhibited in a dense urban traffic network: improving traffic throughput and optimizing signal timing through key corridor/grid area coordination and simultaneously improving safety by conflict avoidance or tracking Illegal parking blocking turn lanes.

3.2 Pedestrian and Bicyclist Safety Through Cooperation

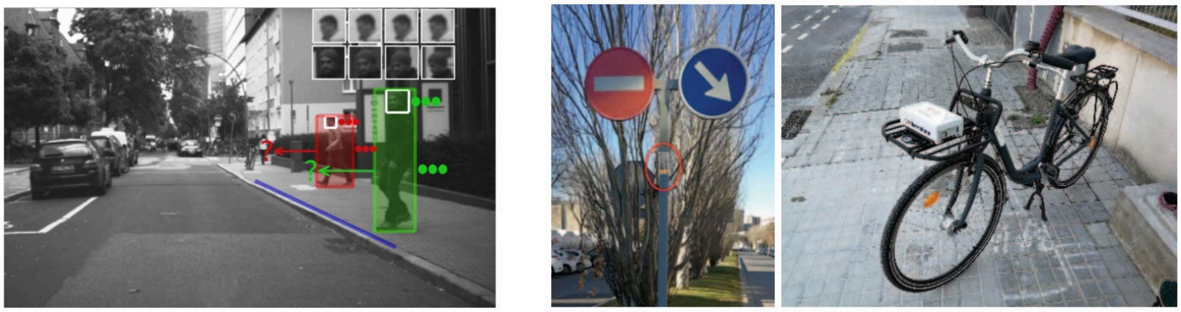
Pedestrian and bicycle safety through cooperation refers to the safe interaction of vehicles with pedestrians, vehicles with bicyclists, pedestrians with bicyclists and pedestrians/bicyclists within the road environment. As mentioned in the previous section, pedestrian and bicycle safety is of great importance as it can help achieve Vision Zero targets regarding zero traffic-related deaths in NYC. The NYC pedestrian safety study & action plan reported that from 2005 to 2009, 52% of traffic fatalities involved a pedestrian and nearly 36% of these crashes resulted in pedestrians killed or seriously injured, with driver inattention cited as a reason (Viola, Roe, and Shin 2010). Moreover, 27% of fatal pedestrian crashes involved a driver's failure to yield. Pedestrian-vehicle crashes involving unsafe speeds are twice as deadly as other crashes. In addition, serious pedestrian crashes are about two-thirds deadlier on major street corridors than on smaller local streets. All of this makes the pedestrian and bicycle safety use case a top priority for NYC.

3.2.1 Existing Pedestrian and Bicyclist Safety Pilots and Practices

Much of pedestrian and bicycle safety testing in the real world has been in conjunction with AV technology. For example, in 2019 Mercedes Benz showcased its "Luxury in Motion" in Consumer Electronics Show (CES) Las Vegas, and Mitsubishi in Tokyo Japan. In this concept AV, a series of Light-Emitting Diode (LED) lights were used at the rear end of the car to let other vehicles know that a pedestrian is crossing and ask them to slow down or stop as necessary. The LED fields at the front end of the vehicle indicates whether the vehicle is in manual or autonomous mode and projects zebra crossing on the ground for safe crossing of pedestrians (AG. 2015).

Moreover, pedestrians and their interactions with AVs have been studied extensively through real-world and simulation studies. In some recent works, pedestrian intent is estimated using motion trajectories (Saleh, Hossny, and Nahavandi 2018; Goldhammer et al. 2019) or social and environmental context (Kooij et al. 2014; Schneemann and Heinemann 2016). For example, pedestrians' head orientation relative to the vehicle can be used to measure their awareness level. A graphical model taking into account factors such as pedestrian trajectory, distance to the curb, and awareness of pedestrians has been researched (Kooij et al. 2014). This study concluded that if a pedestrian is looking towards the car, this means that they noticed it and therefore are less likely to cross the street. Besides explicit tracking of pedestrian behavior, various studies have been conducted to solve the intention estimation problem based on classification approaches. Researchers (Köhler et al. 2012) have classified pedestrian posture as 'about to cross' or 'not crossing' using extracted information in the form of silhouette body models from motion images generated by background subtraction via a support vector machine (SVM) algorithm.

An example of a bike safety through cooperation project is shown in Figure 3(b). This is a pilot showcase deployed during the Barcelona's Mobile World Congress 2019 to validate the capacity of the deployed prototype to prevent collisions between bicycles and vehicles. A total of eight (8) ultra-wide band (UWB) anchors powered by batteries were installed at a height of 2.5 m - 3 m in the area to provide coverage for the location system. The global positioning system (GPS) location of the UWB anchors was exactly measured by a surveyor to minimize errors of the location algorithm. The positioning prototype was installed in the front of a bicycle. The main board of the prototype implements the C-ITS protocol stack and is configured to report location updates every 100 ms using Cooperative Awareness Messages (CAMs) to a Multi-access Edge Computing machine deployed for the pilot. Finally, the demonstration car enabled with an OBU receives this information and determines if a potential collision danger exists. For this, "danger zones" for car and bicycle were defined as shown in Figure 3(a).



(a) (b)

(Source: Barcelona Mobile World Congress 2019)

(a) Intention perception by looking at pedestrian movement (Source: (Saleh, Hossny, and Nahavandi 2018)
(b) UWB anchors and bicycle device at the Barcelona Mobile World Congress 2019

Figure 3: Examples of Existing Pedestrian and Bicyclist Safety Through Cooperative

The deployment of CD for ACV for pedestrian and bicycle safety needs a multi-stakeholder cooperation. Key actors include V2X equipment deployed near the road known as Roadside Unit (RSU), devices in vehicles known as onboard unit (OBU), car manufacturers that integrate OBUs in their vehicles, and operators that deploy RSUs and connect them to the main communication network. Nevertheless, sometimes there will be no RSU coverage in certain areas, and OBUs can connect directly to base stations of cellular operators which provide communications. As an additional service, it is possible to add a certain level of intelligence to the infrastructure, which can be located at traffic management centers (TMC) or closer to the vehicles, near the RSUs, as Multi-Access Edge Computing (MEC) that provides faster responses in critical situations. Finally, a low latency communication network such as 5G will need to be prevalent.

3.2.2 Infrastructure and Data Needs

The following section maps the NYCDOT CV applications and CARMA CDA features that align most closely to pedestrian and bicycle safety. It also states what efforts are required in terms of infrastructure and data compared to what is already available to NYC:

- Applicable area type: Urban intersections
- Related NYCDOT CV applications: Pedestrian in Signalized Crosswalk warning, Mobile Accessible Pedestrian Signal System, Red Light Violation Warning
- Can utilize current infrastructure/data NYC has: Yes
- Efforts needed to meet infrastructure requirement: Low
- Efforts needed to meet data requirement: Moderate
- Related CARMA CDA features: Cooperative Right of Way (CRW), Cooperative Safety, Cooperative Accessible Transportation (CAT)

Table 3 goes into greater detail about data requirements and their implementation priorities for the use case. This also includes the newly defined message types by the CARMA Ecosystem, such as mobility messages, to enable V2X communication between vehicles and other entities for various CDA cooperation classes, as defined in SAE J3216, which allow true cooperative behavior (Lochrane 2021).

Table 3. Pedestrian and Bicycle Safety Data and Infrastructure Needs

Metric/Data Need	Description	Priority	Available in NYC?
Pedestrian related crash rates	Crash rates with and without application warnings	High	Yes
SPaT/Geofence and MAP Messages	Signal Phase and Timing/pedestrian sensor data, Width, Length, Location of Pedestrian Crossings, Existence and Duration of countdown timers	High	Yes
Pedestrian-related conflicts/hard braking events	Useful when actual crash rates not available (as a surrogate measure)	Optional	Partial
Vulnerable Road User (VRU) device	The VRU device can be either stand-alone (e.g., a smartphone), or integrated in the VRU vehicle (bicycle) or a tethered device (sensors in the vehicle, communication using smartphone）	High	Partial
VRU interaction with external (vehicles & road conditions) systems	The VRU has a device which can only transmit data (i.e., a tag or beacon), e.g., a transmitter attached to a backpack	High	Partial
VRU presence detection	Infrastructure that can detect VRUs in the configured zones and provide an input to the traffic controller	High	Yes
Basic Safety Messages (BSM) and/or Event-triggered messages	Basic Safety Message or Event-triggered messages broadcast to warn road users about a hazardous event. Delivered to vehicles in a particular geographic region, in the area affected by the event	High	Yes
Mobility Messages	A common set of information that includes fixed identifications for the sender and optional identifications for a targeted recipient (either of which could be a vehicle, infrastructure, pedestrian, or cyclist), as well as temporary basic safety message (BSM) and plan identifications and timestamps.	High	No
Bicycle Danger Warning	Crowdsourcing logs of “near-crash” events	Medium	No
Pedestrian Crossing Warning	Determine “close call” scenarios with pedestrians during the “Don’t Walk” signal phase	High	Yes
Traffic and crowdsourcing data (e.g., travel time data from local agency or third parties)	Data transfer to a data sharing platform and special app-providers. Data transfer to backend server will be via a connected device such as smartphone, to be used by the pedestrians and bicyclists involved	Medium	Partial
Traffic Signal Data Exchange	Installing signal equipment to improve intersection safety and mobility by improving system communication with vehicles, bicyclists and pedestrians and partnerships with the telecom industry	Medium	Partial
Roadside Units (RSU)	Sensors installed specifically at intersections or high VRU crash locations	High	Partial
Collision Detection	Messages exchanged contain accurate data to estimate the trajectories of the different road users, to make a risk assessment of potential collision. To avoid a high number of “nuisance” warnings, high positional accuracy is required.	High	Partial

3.2.3 Use Case and Applications

Figure 4 and Table 4 describe the representative CD for ACV applications for pedestrian and bicycle safety use case based on stakeholder feedback. The applications are categorized based on their goal (crash prevention or increase general situational awareness). These applications provide a basic understanding of applicable CD for ACV scenarios and related data; they are not intended to be all-inclusive. Applications 1-1 to 1-5 aim to improve crash prevention and requires higher level of cooperation; applications 1-6 to 1-8 aim to provide risk indicators, such as crash risk or high-speed road segments during nighttime to potentially increase situational awareness of VRUs to pay more attention when crossing the streets. Application 1-9 can be an expansion of the current *Mobile Accessible Pedestrian Signal System* app used in the NYC CVPD that was original designed for people with vision disabilities. A general version of it can be used by all groups and is applicable for locations that do not have a countdown signal but have available signal, phasing, and timing (SPaT) messages. Several performance metrics can be used to evaluated applications under the VRU use case, such as pedestrian detection accuracy and latency, crash rate, surrogate safety measures such as time-to-collision (TTC) or post-encroachment time (PET) for vehicle-VRU conflicts, vehicle yielding compliance rate (YCR), and driver response rate. Details of the related data of each application is further explained in Chapter 4.

(Source: NYU C2SMART Center)

Figure 4: Demonstration of Use Case 1: Pedestrian and Bicyclist Safety Through Cooperation

Table 4. Use Case 1: VRU Applications - Pedestrian and Bicycle Safety Through Cooperation

Identifier	Scenario	Goals	Description	Related Data	SAE Cooperative Class
1-1	Pedestrian/bike presence at the crosswalk	Crash prevention	Moving/turning vehicles conflict with pedestrians walking on the crosswalk	FLIR, BSM, MAP, SPaT, CSR, Camera, CDD, PSM	A, B
1-2	Mid-block Jaywalking	Crash prevention	Sensors (infrastructure/in the vehicles) to detect jaywalkers and pass information to surrounding vehicles	FLIR, BSM, MAP, CSR, Camera, CDD, PSM	A, B
1-3	Pedestrian/cyclist intention prediction	Crash prevention	Predict pedestrian's/cyclist's intention to travel outside the crosswalk/bike lanes	Camera, CDD, PSM	A, B
1-4	Road obstacle/blind spot	Crash prevention	Pedestrian and vehicles have a limited line of sight with heavy vehicles and illegal parking	BSM, CSR, RSA, Camera, PSM	A, B
1-5	School Zone Crossing	Crash prevention	Share info and alert surrounding drivers about school zone crossings and load/unload of students from school buses.	FLIR, BSM, MAP, CSR, Camera, CDD, PSM	A, B
1-6	Risk indication – Nighttime High-speed Road link	Increase situational awareness	Real-time link speed information if link speed exceeds a certain threshold	Travel time / speed, PVD, TIM, RSM, PSM, Private Sector/Third Party Data	A
1-7	Risk indication - High ped/bike crash location	Increase situational awareness	Indicate a high-crash location to vehicles and ped/bike when approaching that location	Crash Records, MAP, TIM, PSM	A
1-8	Risk indication - High ped/bike density location	Increase situational awareness	Indicate a real-time high ped/bike density location to alert vehicles of increased potential risk	Traffic camera, TIM, PSM	A
1-9	Intersection crossing assistance	Increase situational awareness	Inform pedestrian of the signal status and provides orientation to assist in street crossing	CDD, SPaT, MAP, FLIR, Camera	A, B, (potentially C, D)

These following sections will discuss application 1-1 to 1-5 in greater detail, along with the motivation for their implementation in NYC.

3.2.3.1 Pedestrian/bike presence at the crosswalk

The current V2I application *Pedestrian in Signalized Crosswalk* in the NYC CVPD detects pedestrians through fixed thermal sensors installed at selected intersections and provides one-way warning to alert the driver of the presence of pedestrians crossing at a signalized intersection. Application 1-1 aims to expand to enable communication between vehicle to infrastructure (not limited to the current thermal sensors, but also other potential detection sensors such as traffic cameras), vehicle to pedestrian (via pedestrian information devices such as smartphone), and pedestrian to infrastructure. The goal is to improve crash prevention by identifying moving/turning vehicle conflicts with pedestrians walking on the crosswalk. Figure 5 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 5: Demonstration of Use Case 1-1: Pedestrian/bike presence at the crosswalk

3.2.3.2 Mid-block Jaywalking

Application 1-2 focuses on mid-block jaywalking. Jaywalking is nothing new to urban cities like NYC. However, unpredictable crossing by jaywalkers, especially midblock, often create conflicts with moving vehicles and lead to insufficient reaction time for the drivers to safely stop their vehicle. A study from Seoul reported that 40% of the pedestrian fatalities in 2010 in Seoul occurred whilst pedestrians were jaywalking and lives can be saved if effective methods preventing jaywalk crashes are applied (Choi et al. 2013). Jaywalking activities also have detrimental impacts on the vehicle flow such as increased delays, excessive fuel consumption, and increased emissions due to more inconsistent flow and stop-and-go motion (Liu et al. 2018). With the recent developments in machine learning based algorithms, it is possible to predict a jaywalker’s trajectory across the road. These algorithms can work with CAV technologies by allowing vehicles to safely navigate through both clustered and individual jaywalkers (Anik, Hossain, and Habib 2021).

This application is a special sub-scenario of use case 1-3 pedestrian/cyclist intention prediction, and it aims to provide a solution to this unique urban challenge and increase awareness of the dangers brought by jaywalking. Roadside or in-vehicle sensors will detect jaywalkers and pass information to surrounding vehicles. In addition, if a connected pedestrian information device (PID) (e.g., smartphone that provides Pedestrian-to-Infrastructure (P2I) or Pedestrian-to-Vehicle (P2V) communication) is available to the pedestrian, real-time location information can be extracted, and an alert can be triggered when the pedestrian is crossing in non-designated crosswalks. This application is closely aligned with the development of SAE J3251 Cooperative perception CDA feature: jaywalking pedestrian collision avoidance. This work in progress document will describe the ConOps, system requirements, and a test procedure to evaluate a cooperative automated driving system (C-ADS) use case for jaywalking pedestrian collision avoidance suitable for PoC testing in both virtual and track settings. Additional sensors or cameras that cover the midblock area or in-vehicle sensors are needed in addition to the current infrastructures in the NYC CVPD. Figure 6 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 6: Demonstration of Use Case 1-2: Mid-block Jaywalking

3.2.3.3 Pedestrian/cyclist intention prediction

Application 1-3 aims to predict pedestrian/cyclist intention. As mentioned in section 3.2.1, the intention by each pedestrian orcyclist can be predicted using motion trajectories or social and environmental context. An alert can be triggered when the pedestrian/cyclist intends to travel outside the crosswalk/bike lanes. Since this can occur anywhere on the road, besides the fixed detectors, a VRU device or VRU interaction with external (vehicles & road conditions) system may be needed to implement this application. Figure 7 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 7: Demonstration of Use Case 1-3: Pedestrian/Cyclist Intention Prediction

3.2.3.4 Road obstacle/blind spot

Wide turns and significant blind spots while driving a heavy vehicle around urban streets make it a large challenge to spot obstacles (e.g., pedestrians or cyclists (Eisenstein 2016)). Moreover, pedestrians, cyclists and vehicles may have a limited line of sight with parked heavy vehicles and illegally parked vehicles. This application (1-4) will enable the detection of heavy vehicles by surrounding ACVs and of pedestrian and cyclist presence, and information exchange between vehicles and VRUs. Figure 8 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 8: Demonstration of Use Case 1-4: Road obstacle/blind spot

3.2.3.5 School Zone Crossing

According to a NYC-based study in 2016, children are likely exposed to increased risk of motor vehicle injury as pedestrians when arriving to school. As congestion increases, it becomes more difficult for adult drivers and children to see each other, increasing the likelihood of a collision (Abd el-Shafy et al. 2017). This application (1-5) aims to assist children and parents to safely across the street within the school zone. Besides the pedestrian presence detection described in section 3.2.3.1, this application will also enable communication from and to the school bus with surrounding road users and infrastructure. Status sharing and alerts can be sent to surrounding vehicles when children and parents are crossing the streets in the school zones, or when the school bus is loading/unloading students. Figure 9 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 9: Demonstration of Use Case 1-5: School Zone Crossing

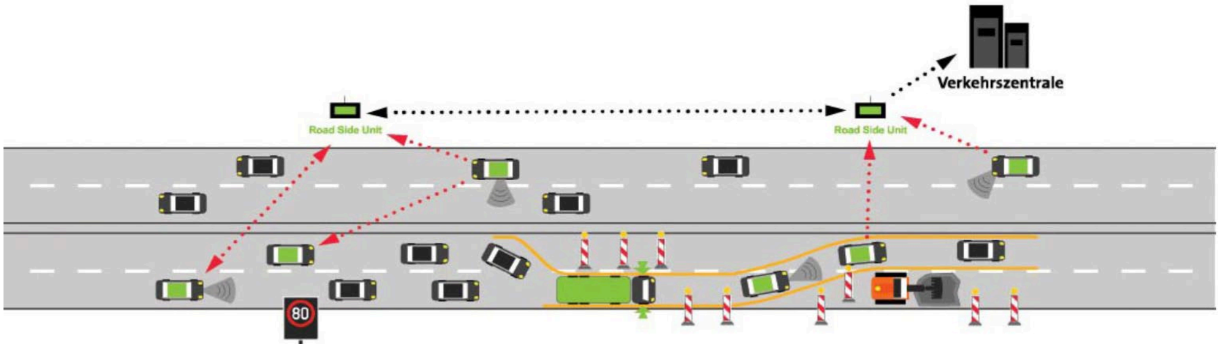
3.3 Cooperative Work Zone

A work zone can be broadly defined as an area where roadwork takes place which usually results in lane closures, detours, and movement of construction equipment. Work zone activities can involve actors such as workers, flaggers, construction vehicles and equipment, and pass-by road users. Work zone safety is of prime importance to NYC. In 2018, there were 701 crashes in work zones on state roads and bridges, resulting in 13 motorist fatalities and 329 injuries to motorists, contractor employees and agency staff (NYS 2018). Protection and efficient management of work zones is essential for the functioning of a 24-hour city like NYC, where permanent closure of roads for construction work is implausible.

3.3.1 Existing Cooperative Work Zone Pilots and Practices

Various projects and research efforts have been conducted to improve work zone safety and capacity in a cooperative manner, including FHWA's CARMA^{SM} (FHWA 2021b), the German Adaptive und Kooperative Technologien für den Intelligenten Verkehr (Adaptive and Cooperative Technologies for Intelligent Traffic) (AKTIV) project (International 2012) and so on. An example of the work zone use case is the German government funding the AKTIV project, which is researching several CD applications (International 2012). The objectives of the project are to optimize traffic at a potential bottleneck, maximize the available road capacity, improve safety in hazardous situations and reduce congestion. Most of the accidents in a work zone occur at the entrance point where vehicles must slow down and merge into a reduced number of lanes but there is also danger within the work zone itself if vehicles do not stay within their (mostly) narrowed lanes and cause spontaneous reactions by other drivers. The drivers entering the work zone receive precise acoustic or optical messages about the upcoming section of the road. At the same time, the system makes driving (speed, maneuvers etc.) recommendations to the vehicles or automatically control following distances and speeds.

Unlike deploying CV without cooperative manners, the benefit of CD in work zone is the ability to optimize the system efficiency (reduce overall travel time) using accurate dynamic information from OBUs and RSUs instead of each vehicle optimizing its individual goals. Lessons learned during the AKTIV project indicate the need to optimize and harmonize the traffic stream at the entrances of work zones and employ measures to improve lane keeping, especially of heavy vehicles, within the zones. Figure 10 illustrates the conceptual diagram of this application.



(Source: AKTIV)

Figure 10: German AKTIV project at a work zone

3.3.2 Infrastructure and Data Needs

The following section maps the NYCDOT CV applications and CARMA CDA features that align most closely to the cooperative work zone use case, and states what efforts are required in terms of infrastructure and data compared to what is already available to NYC.

- Applicable area type: Urban, Rural
- Related NYCDOT CV applications: Speed Compliance in Work Zone, Oversize vehicle Compliance, Blind Spot Warning, Forward Crash Warning, Lane Change Warning
- Can utilize current infrastructure/data NYC has: Partial
- Efforts needed to meet infrastructure requirement: Low
- Efforts needed to meet data requirement: Low
- Related CARMA CDA features: Cooperative Lane Follow (CLF), Cooperative Safety, Cooperative Traffic Management (CTM)

Table 5 goes into greater detail about data requirement and their priority in implementation of this use case.

Table 5. Cooperative Work Zone Data and Infrastructure Needs

Data/Infrastructure Need	Description	Priority	Available in NYC?
In-Vehicle Sensor Data via On Board Units (OBU)	Information such as position, driving direction, hazard warning signal flasher, brake power, deceleration etc.	High	Yes
Vehicle speed	Vehicle speed in variable speed zone areas	High	Yes
Work zone related crash rates	Type of Crash and rate of Crash	High	Yes
Recommended speeds	The speeds recommended to drivers in work zone warning areas	High	Yes
Construction Vehicle safety message and log details	Safety message designed specifically to construction vehicles (e.g., Tractors)	High	No
Basic Safety Messages	A packet of data that contains information about vehicle position, heading, speed, and other information relating to a vehicle's state and predicted path	High	Yes
Mobility Messages	A common set of information at the beginning that includes fixed identifications for the sender and optional identifications for a targeted recipient (either of which could be a vehicle, infrastructure, pedestrian, or cyclist), as well as temporary BSM and plan identifications and timestamps.	High	No
Real-time work zone information (via e.g., Work Zone Data Exchange)	Harmonized work zone data for infrastructure owners and operators (IOOs) and third-party use	High	Partial
Event-triggered messages (e.g., Event-Driven Configurable Messaging (EDCM))	Event-triggered messages broadcast to warn road users about a hazardous event. Delivered to vehicles in a particular geographic region, in the area affected by the event	High	Partial
Road Information	Vehicles can receive road information such as queue information from the surroundings by means of embedded car video cameras and sensors.	High	No
Vulnerable Road User (VRU) device for Workers	The VRU device can be either stand-alone (e.g., a smartphone), or integrated in the VRU vehicle (bicycle) or a tethered device (sensors in the vehicle, communication using smartphone）	High	Partial
Roadside unit sensors	Sensors installed specifically at intersections to improving system communication with vehicles, bicyclists and pedestrians	High	Yes
Work Zone Data Sharing Platform	Providing real-time work zone location information to improve traveler and worker safety and sharing real-time road and weather data from snow-plow operations and other systems	High	No

3.3.3 Use Case and Applications

Figure 11 and Table 6 describe representative CD for ACV applications for the cooperative work zone use case based on stakeholder feedback. While improving work zone mobility through cooperative lane change, merge and speed harmonizing are considered, the focus is on enabling real-time work zone information exchange and ensuring worker safety (Application 2-1 to 2-4). Application 2-5 and 2-6 aim to potentially increase situational awareness by providing risk indicators such as high historical work zone crash locations or high-activity and congestion to areas that may suffer more impacts from work zone activities. Several performance metrics can be used to evaluated applications under this use case, such as queue Length, crash rate, speed and speed variation, surrogate safety measures such as hard braking, TTC or Time to Collision with Disturbance (TTCD), and Deceleration Rate to Avoid Collision (DRAC), and driver response rate. Details of the data related to each application is further explained in Chapter 4.

(Source: NYU C2SMART Center)

Figure 11: Demonstration of Use Case 2: Cooperative Work Zone

Table 6. Use Case 2: Applications - Cooperative Work Zone

Identifier	Scenario	Goals	Description	Related data	SAE Cooperative Class
2-1	Work zone information & presence	Intrusion/Crash prevention, Speed compliance	Provide automated real-time work zone information to road users, current deployment uses data manually collected.	BSM, MAP, CSR,RSM, Camera, TMC work zone data, WZDx, Private Sector/Third Party Data	A, B

2-2	Limited sight/blind spot	Crash prevention	Vehicles entering/turning into a work zone have limited line of sight. Can be blocked by other parked vehicles/HVs in the same road segment of the work zone	RSA, BSM, CSR, Camera	A, B
2-3	Work Zone Lane Change, merge and speed harmonizing	Improve mobility	Vehicle coordination for lane-changing & merging and lane change assignment prior to entering a work zone, thus minimizing traffic jams and limiting back-end congestion from work zones	BSM, MAP, CSR,RSM, Camera, TMC work zone data, WZDx, PSM, Private Sector/Third Party Data	A, B ,C, D
2-4	Worker Safety	Crash prevention	Warnings to workers/flaggers about potential hazards from the construction vehicle and surrounding vehicles	CDD, RSA	A, B
2-5	Risk indication - High work zone crash location	Increase situational awareness	Indicate a high-crash location to vehicles when approaching the work zone	Crash records	A
2-6	Risk indication - High-activity and congested location	Increase situational awareness	Increase situational awareness of locations with high ped/bike/vehicle/on-street parking (low lane occupancy) activities	TMC incident data, Camera, TIM, PVD, Private Sector/Third Party Data	A

These following sections will discuss application 2-1 to 2-4 in greater detail, along with the motivation for their implementation in NYC.

3.3.3.1 Work zone information & presence

By detecting real-time work zone presence by means of RSUs, traffic cameras or embedded ACV video cameras and sensors, work zone information can be shared with surrounding road users directly or via V2X hub (Figure 12). Event-triggered messages will be broadcasted to warn road users about a work zone activity in a particular geographic region or in the area affected by work zone activities.

(Source: NYU C2SMART Center)

Figure 12: Demonstration of Use Case 2-1: Work zone information & presence

3.3.3.2 Limited sight/blind spot

Construction vehicles often create differently sized and shaped blind spots that limit the line of sight of surrounding vehicles. This application will enable communication between the construction vehicle and road users (vehicles, pedestrians etc.) approaching the road segment that has construction activities. The size and shape of the blind spots based on the type of the construction vehicles will be provided. Figure 13 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 13: Demonstration of Use Case 2-2: Work zone limited sight/blind spot

3.3.3.3 Work Zone Lane Change, Merge and Speed Harmonizing

The goal of application 2-3 is to improve traffic congestion and reduce stop-and-go around work zones. To achieve the optimal effectiveness, all four (4) cooperative levels—status sharing, intent sharing, agreement seeking, and prescriptive actions may be needed among vehicles approaching and passing the work zones. Figure 14 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 14: Demonstration of Use Case 2-3: Work zone Lane Change, merge, and speed harmonizing

3.3.3.4 Worker Safety

Each year, over 20,000 workers are injured in road construction work zones. The leading cause of highway construction worker injuries and fatalities is contact with construction vehicles, objects, and equipment (FHWA 2020). This application seeks a new solution to prevent these injuries and deaths. Construction vehicle and passing by vehicles will broadcast safety messages to VRU device for workers to warn them a hazard event (e.g., movement of construction vehicles, or a blind spot). The VRU device can be a personal information device such as smartphone or wearable sensors like a smart watch. Figure 15 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 15: Demonstration of Use Case 2-4: Worker Safety

3.4 Cooperative Intersection Management

Another use case identified for CD is intersection management. Statistics from National Highway Traffic Safety Administration (NHTSA) estimate that 35-40% of all motor vehicle accidents are intersection-related (NHTSA 2010). Moreover, according to INRIX global traffic scorecard (INRIX), the average time spent stuck in traffic was 91 peak hours per year in the year 2017 for NYC drivers, which meant that they spent 13% of their time sitting in congestion. CD has the potential to solve these problems through coordinated efforts between infrastructure and in-vehicle/personal devices. More specifically, CD for ACV data can be used to better estimate the performance of traffic flow states and adaptive traffic control for signal timing as vehicle arrival could be better predicted in advance. CD will also allow ACVs and fully automated vehicles to adapt their driving behaviors and operations to cooperate with signal timing, thereby reducing overall congestion and fuel consumption. This demands motion planning of individual vehicles to be considered together with signal phases, splits, cycle length, and coordination of traffic signals.

Cooperative intersection management requires tighter integration between road users and the traffic control system. This integration brings new challenges and possibilities for different types of signal control strategies, such as actuated signal control, platoon-based signal control, planning signal control, signal-vehicle co-control, driver guidance, multi-vehicle cooperative driving, and intelligent transportation system - intelligent vehicles (ITS-IV) integration in the future. Compared with the traditional intersection management that often requires integration between traffic flow, link travel time, and signal control, intersection management involving CAVs and cooperative driving demands the motion planning and movement of each instrumented vehicle in addition to the traffic control system. Moreover, this integration moves from traffic-responsive feedback control to a more model-based feedforward control with side constraints to guarantee some operational and safety criteria (Guo, Li, and Ban 2019). A comprehensive review of the methods and approaches to estimate traffic flow states and optimize traffic signal timing plans based on CAVs can be found in Guo, Li, and Ban 2019.

3.4.1 Infrastructure and Data Needs

The following section maps the NYCDOT CV applications and CARMA CDA features that align most closely to the cooperative intersection management use case. It states what efforts are required in terms of infrastructure and data compared to what is already available to NYC.

- Applicable area type: Intersection
- Related NYCDOT CV applications: Intersection Movement Assist, Red Light Violation Warning, Blind Spot Warning, Forward Crash Warning, Lane Change Warning
- Can utilize current infrastructure/data NYC has: Partial
- Efforts needed to meet infrastructure requirement: Low
- Efforts needed to meet data requirement: Moderate
- Related CARMA CDA features: Cooperative Right of Way (CRW), Cooperative Safety, Cooperative Lane Coordination (CLC)

Table 7 goes into greater detail about data requirement and their priority in implementation of this use case.

Table 7. Cooperative Intersection Management Data and Infrastructure Needs

Metric/Data Need	Explanation	Priority	Available to NYC?
In-Vehicle Sensor Data via OBU	Information such as position, driving direction, hazard warning signal flasher, brake power, deceleration etc.	High	Yes

Bus/Right turn related crash statistics	Crashes related to right turn or at bus stops	High	Partial
Red Light Violation-Related Crash Rates	Broken down by crossing-path crash type (i.e., straight-crossing versus left-turn crash types)	High	Yes
Red light violation statistics/relationship to crashes	Time-after-red (i.e., violation elapsed time since the onset of the red light) statistics, Signal Violation Rates	Medium	No
Secondary intersection-related crash rates	Intersection crashes not directly related to red light violations (e.g., rear-end crashes), broken down by crash type	Medium	Yes
Dynamic Traffic Signal Information (e.g., SPaT)	Signal Phase and Timing/pedestrian sensor data that is provided to each driver in real-time, time to signal, possibility of maneuver	High	Yes
Geofence messages	Each message is applied to part of a single traffic lane and designed to communicate traffic control updates to CAV/CARMA vehicles via cloud services (e.g., CARMA cloud)	Medium	No
Basic Safety Messages	A packet of data that contains information about vehicle position, heading, speed, and other information relating to a vehicle's state and predicted path	High	Yes
Mobility Messages	A common set of information at the beginning that includes fixed identifications for the sender and optional identifications for a targeted recipient (either of which could be a vehicle, infrastructure, pedestrian, or cyclist), as well as temporary BSM and plan identifications and timestamps.	Medium	No
Event-triggered messages	Event-triggered messages (e.g., Traveler Information Messages (TIM)) broadcast to warn road users about a hazardous event.	High	Partial
Dynamic Lane Assignment	Vehicle accepts a request from the cloud regarding which lane plan to be in, and if necessary, calls for the lane change to be executed.	Optional	Partial
Geometric Data	Intersection geometry	High	Yes
Traffic and crowdsourcing data (e.g., travel time data from local agency or third parties)	Data transfer to a data sharing platform and special app-providers. Data transfer to backend server will be via a connected device such as smartphone, to be used by the pedestrians and bicyclists involved	Medium	Partial
Traffic Signal Data Exchange	Installing signal equipment to improving system communication with vehicles, bicyclists and pedestrians	Medium	Partial
Roadside unit sensors	Sensors installed specifically at intersections to improving system communication with vehicles, bicyclists and pedestrians	High	Partial
Collision Detection	Messages exchanged contain accurate data to estimate the trajectories of the different road users, to make a risk assessment of	High	Partial

	potential collision. To avoid a high number of "nuisance" warnings, high positional accuracy is required.		

3.4.2 Use Case and Applications

Figure 16 and Table 8 describe the representative CD for ACV applications for cooperative intersection management use case based on stakeholder feedback. CD for ACV provides a new opportunity for improving intersection safety and communication, including better conflict avoidance (use case 3-1) coordinated traffic signal timing for synchronizing traffic movements and managing traffic progression (use cases 3-2 and 3-3), and offers novel solutions to identify irregularities that interrupt traffic movement at the intersection (use case 3-4). Several performance metrics can be used to evaluated applications under this use case, such as corridor/network travel time and travel time reliability, traffic throughput, fuel consumption, crash rate and surrogate safety measures such as hard braking, TTC or TTCD, and DRAC. Details of the related data of each application are further explained in Chapter 4.

(Source: NYU C2SMART Center)

Figure 16: Demonstration of Use Case 3: Cooperative Intersection Management

Table 8. Use Case 3: Applications - Cooperative Intersection Management and Signal Optimization

Identifier	Scenario	Goals	Description	Related data	SAE Cooperative Class
3-1	Conflict avoidance	Crash prevention, mobility improvement	Vehicle turning left at a signalized intersection with opposing left-turning and through-moving vehicle.	BSM, ICA, SPaT, MAP, SSM	A, B, C

3-2	Signal Timing Optimization	Mobility improvement	Enhance the current MIM adaptive signal system in NYC with ACV data and detections of pedestrian and vehicle flows for a single intersection.	BSM, ICA, SPaT, MAP, SSM, SRM	A, B
3-3	Key corridor/grid area coordination	Mobility improvement	Utilizing CD for intersection communication, including signal timing and demand coordination for key corridor(s) or a grid network. CD for ACV will be used to notify the demand and help the decision-making process on metering or releasing the demand.	BSM, SPaT, MAP, SSM, SRM, Camera, FLIR, travel times from Wi-Fi and third party	A, B
3-4	Illegal parking blocking turn lanes	Mobility and situational awareness improvement	Notify vehicles approaching the intersection about vehicles illegally parked on the curb that block the turn lane to reduce lane changes and crash risks	BSM, CSR, Camera, TMC incident data	A

These following sections will discuss all four (4) Cooperative Intersection Management and Signal Optimization applications in greater detail, along with the motivation for their implementation in NYC.

3.4.2.1 Conflict avoidance

Conflict avoidance with CD for ACV operates by sharing the vehicles' status and intention and seeks agreement between vehicles turning left at a signalized intersection and opposing left-turning and through-moving vehicles. Figure 17 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 17: Demonstration of Use Case 3-1: Conflict avoidance

3.4.2.2 Signal Timing Optimization

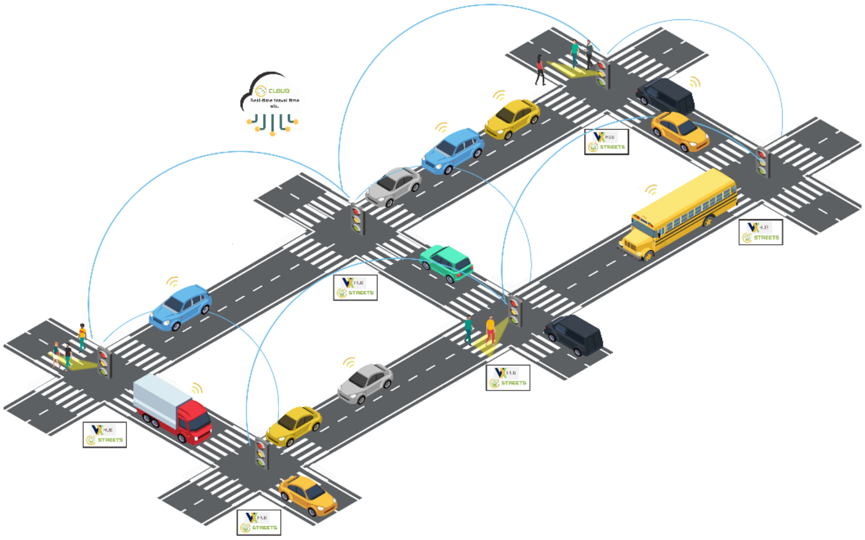
This application concentrates on signal timing optimization at a single intersection. Traffic control such as actuated or adaptive signal timings can be applied or enhanced based on real-time flow and density detection of road users (i.e., vehicles, pedestrians, and cyclists) via RSU, other roadside equipment such as traffic cameras, or status/intension sharing from road users with connected devices. Figure 18 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 18: Demonstration of Use Case 3-2: Signal Timing Optimization

3.4.2.3 Key corridor/grid area coordination

CD for ACV provides a new opportunity for improving intersection communication, including signal timing and demand coordination along with key corridors or a network. In this application, CD for ACV data can be used to provide a better estimate of traffic demand for different types of road users (i.e., vehicles, pedestrians and cyclists) to the TMC and to help its decision-making process on metering or releasing traffic demand. Figure 19 illustrates the conceptual diagram of this application.



(Source: NYU C2SMART Center)

Figure 19: Demonstration of Use Case 3-3: Key corridor/grid area coordination

3.4.2.4 Illegal parking blocking turn lanes

Illegal parking is a common occurrence in dense urban areas. It routinely causes danger for cyclists and pedestrians and disrupts traffic flow. Furthermore, illegally parked vehicles, especially trucks, at the corner of an intersection can partially block turn lanes. This may cause spillover to the upstream intersection, create blind spots for pedestrians and other vehicles, and result in network-wide impacts in terms of traffic congestion (Gao and Ozbay 2016, 2017). This application will broadcast event-triggered messages (e.g., Traveler Information Messages (TIM)) to warn road users about illegal parking events that block a turn lane. Such events may be identified by nearby ACVs, roadside sensors, or agency/third party data (probe data) and shared with V2X cloud and surrounding vehicles. Figure 20 illustrates the conceptual diagram of this application.

(Source: NYU C2SMART Center)

Figure 20: Demonstration of Use Case 3-4: Illegal parking blocking turn lanes

4 Data-driven Analysis of CD for ACV

This chapter describes the analysis of traffic data in NYC and their appropriateness for USDOT's goals for understanding and enabling CD for ACV in NYC. The data analysis identifies additional data needs and assess the existing agency-owned and third-party data sources available in NYC, especially pedestrian and bike data, alongside potential CAT data that may contribute CD for ACV. CAT refers to the data generated to enable the automation of vehicles and the infrastructure which vehicles share with other CAT users. For each data, its data type, features, coverage, collection and update frequency and data reliability are investigated. Based on this information and its relevance to the three use cases described in Chapter 3, its appropriateness to CD for ACV in NYC is examined. Table 9 provides a summary of the data studied in this research, including existing data that is available to the research team, and other CAT data that is not available yet but may be beneficial to CD for ACV.

Table 9. Summary of Data Examined in This Research

Name	Public/ Private	Data Type	Relevant to CD	Description	Coverage/ Frequency
FLIR Pedestrian Detection Data	Owned by the City	Pedestrian appearance, pedestrian count	High	All-in-one sensor for traffic monitoring and dynamic traffic signal control. The equipment uses thermal imaging to identify pedestrians and vehicles in traffic system.	9 intersections (~120 units)
NYC CVPD Signal phase and timing (SPaT)	Owned by the City	CV Messages	High	Describes the current state of a signal system and its phases and relates this to the specific lanes in the intersection.	NYC CVPD study area
NYC CVPD MAP Messages	Owned by the City	CV Messages	High	Convey one or more intersection lane geometry maps within a single message.	NYC CVPD study area
NYC CVPD Basic Safety Messages (BSM)	Owned by the City, Obfuscated version is public	CV Messages	High	CV Basic Safety Message. Obfuscated NYC CVPD BSM is available publicly via ITSJPO's ITS Data Sandbox.	NYC where V2V or V2I interacts
NYC CVPD Traveler Information Messages (TIM)	Owned by the City	CV Messages	High	Send various types of information (advisory and road sign types) to equipped devices.	NYC CVPD study area
NYC CVPD Personal Information Device (PID) Data	Owned by the City	CV Messages	High	Pedestrian warnings from the portable mobile device for visually impaired pedestrians	NYC CVPD PED-SIG study area
NYCDOT Real-time Travel Speed	Public	Link-based traffic speed, travel time	High	The data comes from a map of traffic speed detectors from various city and state agencies.	NYC / 30s, mostly on major arterials and highways
NYCDOT Remote Traffic Microwave	Owned by/ Accessible to the City	Volume, occupancy	High	Microwave sensor data, maintained by NYCDOT, over 210 sensors available and are	NYC / 30s

Sensor Data (RTMS)				used in Midtown-in-motion project.	
NYCDOT TMC Incident Database	Owned by/Accessible to the City	Event	Moderate	Work zone events extracted by Joint-Traffic Management Center of NYCDOT, including work zone related events.	NYC
NYCDOT Travel Time (via Wi-Fi)	Owned by the City	Travel time	High	Installed at each signalized intersection, some at FDR	-
LinkNYC	Public	Map, Locations	High	LinkNYC is a first-of-its-kind communications network that is replacing pay phones across the five boroughs with new structures called Links. It provides free public WiFi.	NYC
NYC WiFi Hotspot Locations	Public	Map, Locations	High	NYC Wi-Fi hotspot locations	NYC
NYCDOT Traffic Cameras	Public	Video feeds	High	Real-time video feeds from CCTVs	NYC / 2-7 sec / 738 cameras
MTA Bus Time	Public	Travel time	High	MTA bus GPS data	NYC / 30s
NYPD Crash Reports	Public	Crash records	Moderate	The data contain detailed information from all police reported collisions in NYC.	NYC / daily
Taxi Breadcrumb real-time data	Owned by/Accessible to the City	GPS	Moderate	Real-time yellow and green taxi GPS locations	NYC / 2 minutes
NYCDOT Street Construction Permits	Public	Permits	Moderate	The core permit data, including permittee, type of permit, date issued, location. Permits cover activities such as street openings, sidewalk construction and installing canopies over sidewalks.	NYC
511NY	Public	Speed, incident	High	Contain real-time traffic and transit event information provided by NYSDOT, NYCDOT, the New York State Thruway Authority and the Niagara International Transportation Technology Coalition.	NYS / 1 minute
NYCDOT Parking and Camera Violations	Public	Event	Low	Data includes violations of parking, speeding and other traffic violations. Parking violation is labeled by parking tickets and other types of violations are captured by enforced cameras.	NYC / Weekly
MTA Turnstile Data	Public	Transit Volume	Low	NYC subway turnstile counts	NYC / Weekly
MTA Bridges and Tunnels Volume	Public	Volume	Low	Data provide number of vehicles (including cars, buses, trucks and motorcycles) that pass through each of the nine bridges and tunnels operated by the MTA each day	NYC / Daily
MTA Access-a-ride Ridership	Public	Volume	Low	MTA access-a-ride ridership data.	NYC / Weekly

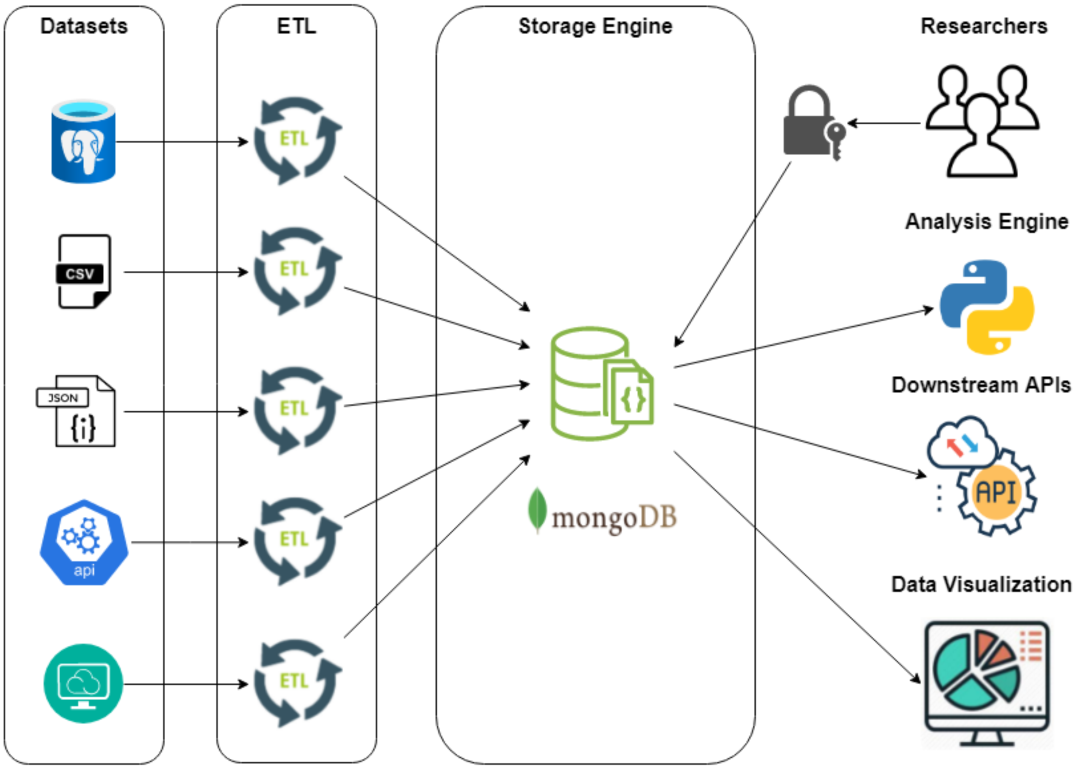
NYC 5G Coverage	Public	Map	High	NYC Verizon & AT&T 5G coverage map	NYC
Citibike Trip Records	Public	Begin-End Location	Moderate	Bike trip data provided by Citibike, including bike trips with specified information such as start and end time / location and trip duration.	NYC / Weekly
Citibike Realtime (GBFS)	Public	Station-info	Moderate	Real-time bike station data, containing bike station information such as available number of bikes in a station and so on.	NYC / 5minute
NYCDOT Bike Counts for East River Bridges	Public	Counts	Low	Daily total of bike counts conducted monthly on the East River bridges.	NYC/ Annually
NYCDOT Bike Counts for Midtown	Public	Counts	Low	Midtown bicycle counts on various avenues at 50th Street, single weekday bicycle count in three separate months (May, July, Sept).	NYC/ Annually
NYCDOT Bike Counts for Uptown	Public	Counts	Low	This count reflects cyclists traveling through Manhattan at on 86th Street along the avenues, in Central Park and on the greenways.	NYC/ Annually
NYCDCP Manhattan Bike Counts - On/Off Street	Public	Counts, helmet usage, use of bike lane, gender, etc.	Low	The counts have been conducted along designated bicycle routes at 10 on-street and 5 off-street locations during the fall season.	NYC/ Annually
Bike Sensor	Private/Not accessible to the City	Location, speed, distance to obstacles, acceleration, and position angle	High	BSafe bike sensor data.	Pilot data
Waze	Third-party, accessible to NY State	Speed, event (Incident, Jams)	High	User-generated data, showing traffic incidents and jams.	NYC/ 1-2 minute
HERE	Third-party, Accessible to the City	Travel time, incident	High	HERE provides travel time and incident data from probe vehicles upon detecting inclement weather conditions, break-down or crash.	Major arterials and highways in NYC
INRIX	Third-party, access by the City	Link travel time, traffic speed	High	Probe data, travel time and speed are aggregated by each link.	NYC major roads / 5min / 15min / 1hour
Transcom Travel Time	Third-party, access by the City	Travel Time	High	Transcom provides fused link travel time data using multiple data sources (Bluetooth, TI-MED, INRIX, NAVTEQ, SENSYS)	NYC / 2 minutes

Nexar in vehicle data	Private/Not accessible to the City	Trajectory, dangerous driving event, work zone, imagery	High	Nexar provides the user's dash cam data include GPS location data and gyro data, and virtual camera data (the screenshots from dash cam)	NYC / Gyro-50 Hz, GPS-1 Hz, Virtual cam-daily~1Hz
Wejo	Private/Not accessible to the City	Trajectory, event data	High	Connected vehicle trajectory and events data. Data come from the on-board hardware monitoring platform and in-vehicle sensors.	US / 1-3s
StreetLight	Owned/Accessible to the City	Volume, Origin Destination (OD) patterns	Low	StreetLight provides location-based service data from smart phones and navigation devices in connected cars and trucks.	NYC / 1 month
Connected (Mobile) Devices Data (CDD) and Personal Safety Message (PSM)	Not Available yet in NYC	CV message	High	Broadcast safety related data for vulnerable road users (like pedestrian, cyclists, and road worker)	-
Common Safety Request (CSR) Messages	Not Available yet in NYC	CV message	High	Provides a method for vehicles to request for additional safety applications related information from surrounding vehicles and embed them into appropriate position in BSM part II	-
Cooperative Intersection Collision Avoidance (ICA)	Not Available yet in NYC	CV message	High	Broadcast to other V2X devices in the area a warning of a potential collision with a vehicle that is likely to be entering an intersection without the right of way	-
Probe Vehicle Data (PVD) Messages	Not Available yet in NYC	CV message	High	Exchange information between a vehicle with other V2X device to collect it status	-
Roadside Alert (RSA) Messages	Not Available yet in NYC	CV message	High	Alerts to warn nearby hazards to traveler and it is transmitted by V2X	-
WZDx	Not Available yet in NYC	Work zone info	High	produce consistent and unified open real-time work zone data feeds	-

The sample data collected for this white paper was stored in a MongoDB database. Its data management framework, as outlined in Figure 21, is a confederation of open-source products and scripts. Each component in the framework is isolated and customizable. The framework provides great flexibility for New York University (NYU) researchers to add new datasets or modify existing ones. MongoDB, as an open-source not only structured query language (NoSQL) database software, is capable of handling various data formats, such as javaScript object notation (JSON) (semi-structured data), comma-separated values (CSV) (structured data), spatial data, and time-serious data without additional infrastructure maintenance. It is optimized for big data processing and has a better performance on the geospatial data analysis comparing to the traditional geographic analysis software like PostGIS. By implementing a MongoDB cluster, it supports terabyte-level data analysis and has the scalability to increase its functionalities and capacity based on the data analysis requirements and further integrations.

There is a data pipeline for each dataset which executes the Extract, Transform, Load (ETL) operations in a fixed interval and dumps the JSON data to the MongoDB database. Unlike the traditional structure data, JSON data allows for flexible and dynamic schemas, which is more practical for modern transportation data requirements. It also reduces the coding complexity for researchers and maintenance workload.

On the other side, the Python analysis scripts will be executed according to the given coordinates and geometry. It will aggregate all the related data within the range for future analysis. It can also be expanded as downstream APIs for communicating with other applications. In the meantime, researchers can use data visualization tools such as Tableau and Apache Superset to show the analysis in an interactive way.



(Source: NYU C2SMART Center)

Figure 21: Data Management Framework

This chapter is organized according to the following sections. Section 4.1 presents and evaluates the data collected by pedestrian detection equipment deployed as part of the NYC CVPD. Section 4.2 introduces the available bike data in NYC and section 4.3 describes the existing traditional NYC traffic data, such as remote traffic microwave sensor data, real-time travel speed data, incident and work zone databases, and bus and taxi data. Section 4.4 briefly discusses some of the cooperative automated transportation data (e.g., BSM) other than the automated pedestrian detection data presented in Section 4.1. Section 4.5 highlights private sector/third party traffic data that can be potentially used for CD for ACVs. Section 4.6 shows the NYC Wi-Fi hubs and 5G network coverage. Finally, section 4.7 summarizes the appropriateness of each data type/dataset for the proposed CD for ACV use cases. A few existing datasets were not fully explored as the NYC team did not have access to the full data details at the time the report was written.

4.1 Pedestrian Detection Data

This section provides brief descriptions of the data provided by pedestrian detection equipment deployed as part of the NYC CVPD. Detected objects at the intersection as contact closures in the detection zone can be used for CD for ACV to improve situational awareness at the intersection, especially for pedestrian and bike safety.

4.1.1 Data Overview

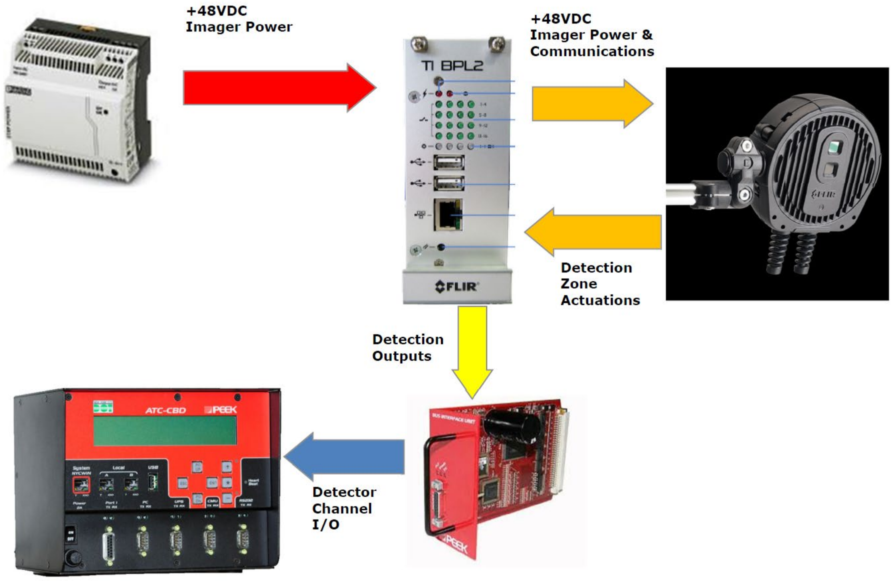
Ten NYC intersections were outfitted with pedestrian detection equipment capable of detecting objects in the configured zones to provide an input to the traffic controller for the Pedestrian in NYC CVPD's *Signalized Intersection Warning (PEDINXWALK)* application to inform the RSU at an equipped intersection of the presence of pedestrians in the crosswalk. Nearby vehicles equipped with an Aftermarket Safety Device (ASD) will receive this information from the infrastructure. The application will then, as appropriate, warn the driver of the pedestrian's presence.

Pedestrian detection is achieved via thermal cameras that operate similarly to passive infrared sensors, generating infrared images by detecting body temperature. This positioning allows thermal devices to detect the movement of pedestrians as well as count the number of pedestrians in the detection zones. The current NYC CVPD uses a commercial product FLIR "TrafiOne", an all-around detection sensor for traffic monitoring and dynamic traffic signal control. It combines the FLIR Lepton thermal imaging sensor with embedded thermal video detection algorithms to provide detection data and streaming videos on vehicles, bicycles, and pedestrians. It can be used to detect pedestrians and bicyclists at the curbside and/or on the crossing. TrafiOne supports various system architectures for stand-alone and network-based applications. Integration with the TrafiOne is achieved by using powerline communication through TI BPL2 EDGE, Ethernet (ETH) communication or direct output contact closures. Table 10 presents the device features.

Table 10. Pedestrian Detection Device Features (FLIR Intelligent Transportation Systems 2018)

Features	TrafiOne 195 and TrafiOne 156	TI BPL2 EDGE	ETH interface
US Federal Regulations	FCC Title 47	FCC Title 47	FCC Title 47
Product Standards	N/A	NEMA TS2	N/A
Temperature	• Operating: -40°C to +55°C • Storage: -40°C to + 80°C	• Operating: -34°C to +74°C • Storage: -34°C to + 74°C	-40°C to + 74°C
Mechanical integrity	• NEMA TS2 : Shock immunity 10G • NEMA TS2 : Vibration immunity	• NEMA TS2 : Shock immunity 10G • NEMA TS2 : Vibration immunity	
Electrical integrity	• NEMA TS 2 : EM Immunity • FCC Part 15 : EM Emission Class B	• NEMA TS 2 : EM Immunity • FCC Part 15 : EM Emission Class B	• FCC Part 15 : EM Emission Class B
Product safety	• EN62368–1 : Safety • EN60950-22 : Outdoor usage	N/A	N/A

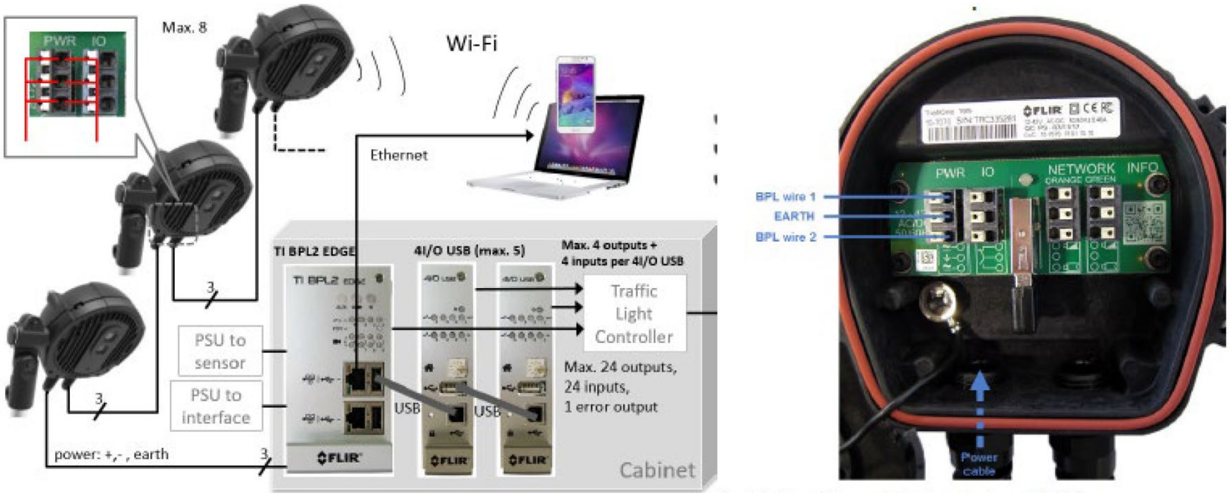
NYC CVPD currently is using the BPL2 interface card in the traffic controller cabinet. TrafiOne sends the detection result over its power cable to a TI BPL2 EDGE board. The interface board then generates output contact closures and provides an RJ-45 port for Transmission Control Protocol/Internet Protocol (TCP/IP) communication (Figure 22).



(Source: (Highway Tech 2020b)

Figure 22: FLIR Pedestrian Detection Workflow

The system architecture of a TrafiOne networked installation with powerline communication via TI BPL2 Interface is presented in Figure 23.



(Source: (Highway Tech 2020a)

Figure 23: TrafiOne System Architecture

PSU = Power Supply Unit

4.1.2 Data Collection

Performance metrics, such as pedestrian presence/count detection and detection latency, were evaluated based on different scenarios with different days of the week, times of day, traffic demands, and light conditions for two instrumented intersections: 1) Site A - High pedestrian density location: Flatbush Avenue and Pacific Street, Brooklyn; and 2) Site B – Low pedestrian density location: 47th Avenue and 34th Street, Queens. Site A as shown in Figure 24 has an hourly pedestrian flow around 150-500 per hour per crosswalk and Site B as shown in Figure 25 has an hourly pedestrian flow less than 50 per hour per crosswalk. Live videos of the east crosswalk at Site A (with two thermal cameras to cover the entire crosswalk) and south crosswalk at Site B (with one thermal camera) were recorded.

(Source: NYU C2SMART Center)

Figure 24: Site A Flatbush Avenue and Pacific Street, Brooklyn (High pedestrian density location)

(Source: NYU C2SMART Center)

Figure 25: Site B 47th Avenue and 34th Street, Queens (Low pedestrian density location)

A dry run for collecting FLIR data was scheduled for June 9-10, 2021. This effort included field video recording at the two study sites, video recording from nearby NYCDOT traffic camera, TransSuite (NYCDOT's central system for Integrated ITS devices such as signal control devices) and PEDINXWALK application data. However, the dry run failed because the pedestrian presence detection files cannot be pulled locally from the FLIR cameras. The camera models used for NYC CVPD are FLIR TrafiOne 156 and

FLIR TrafiOne 195. None of these was able to generate a pedestrian presence log output. In addition, although real-time pedestrian presence information could be monitored through the Advanced Solid-State Traffic Controller (ASTC) front panel in TransSuite, it did not log the pedestrian presence calls and the data could not be retrieved from the software. Changing the input-output (I/O) map to bring the pedestrian presence inputs to the actuation inputs or programing new Simple Network Management Protocol (SNMP) traps to report the changes to pedestrian presence inputs will be needed as a long-term solution to record and retrieve such information.

FLIR unit supports a network interface (Figure 26) to configure the units, detection zones, administration settings (e.g., system logs), and display the live views. Therefore, an alternative method that connects to FLIR network interface and retrieve the JSON outputs and live view videos was tested and used for the final data collection.

(Source: NYCDOT)

Figure 26: FLIR Web Interface

From August 16 to August 21, 2021, a total of 20 hours of detection videos were collected for the two study sites for the following scenarios:

- Weekday morning (8am - 9am)
- Weekday midafternoon (2pm-3pm)
- Weekday afternoon peak hours (5pm - 6pm)
- Weekday nighttime (9pm-10pm)
- Saturday morning (8am - 9am)
- Saturday midafternoon (2pm-3pm)
- Saturday afternoon peak hours (5pm - 6pm)
- Saturday nighttime (9pm-10pm)

For weekday scenarios, detection data were collected from two (2) different days for each location (i.e., 2-hour data per location). For Saturday morning and midafternoon, 1-hour detection data was collected at the high pedestrian density location. For Saturday afternoon peak hours and nighttime, 1-hour detection data was collected at the low pedestrian density location.

4.1.3 Evaluation Metrics

To measure the appropriateness of this data for potential CD for ACV usage, the evaluation metrics in Table 11 were assessed at two (2) instrumented locations.

Table 11. Pedestrian Detection Evaluation Metrics

Identifier	Criteria	Description
PDE 1-1	Pedestrian presence detection	Detection accuracy, precision, recall, F-1 score and false negative rate for pedestrian appearance in the detection zone
PDE 1-2	Pedestrian counts	Counting accuracy, precision, recall, F-1 score and false negative rate for number of pedestrians appear in the detection zone
PDE 1-3	Detection latency (in-time delay)	The in-time delay between the time when a pedestrian walks into the detection zone and the time when the pedestrian is detected by the pedestrian detection equipment
PDE 1-4	Detection latency (out-time delay)	The out-time delay between the time when a pedestrian walks out of the detection zone and the time when the pedestrian is no longer detected by the pedestrian detection equipment

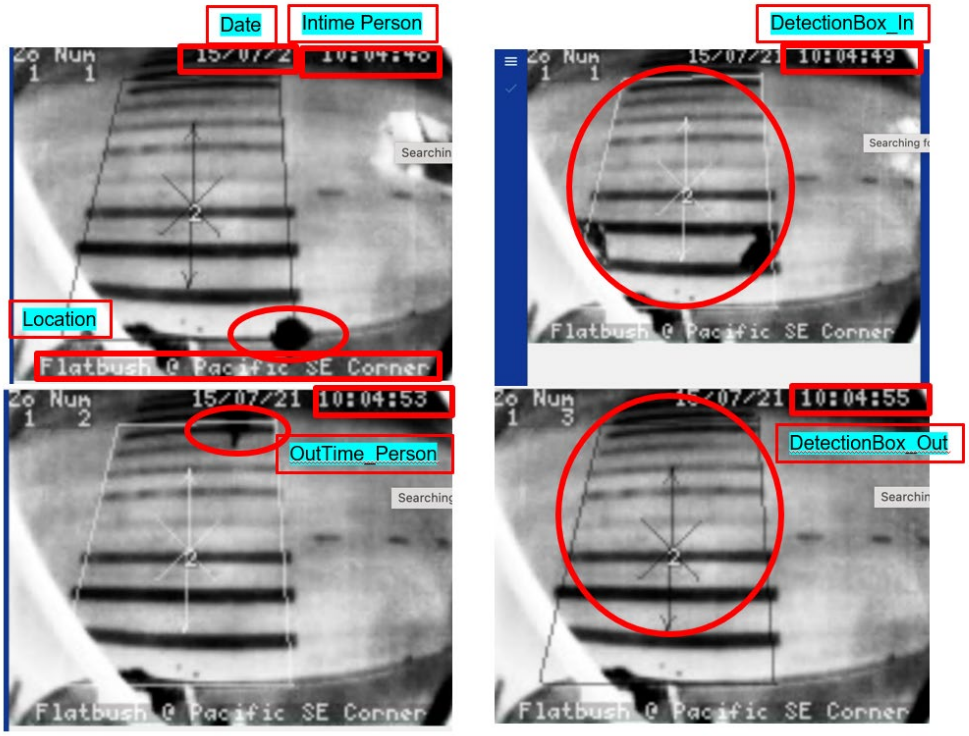
Accuracy, precision, recall, F-1 score, and false negative rate are used as performance metrics for pedestrian presence detection and pedestrian counts. If an instance is positive and classified as positive, it is called a true positive (TP); if that instance is classified as negative, it is called a false negative (FN) (Fawcett 2006). Similarly, if an instance is negative and classified as negative, it is called a true negative (TN); if that instance is classified as positive, it is called a false positive (FP) (Fawcett 2006). Type II error (the false negative rate) is considered (a negative result corresponds to failing to reject the null hypothesis, in this case, fail to detect/count the pedestrian) to account for undetected pedestrians. Precision represents exactness - the percentage of detected pedestrians that are actual pedestrians - while recall represents completeness - the percentage of actual pedestrians which are captured by the detector. The F1 score is the harmonic mean of the precision and recall. The equations of these metrics are presented as follows:

Accuracy (ACC) = (TP+TN)/(TP+TN+FP+FN)
Precision = TP/(TP+FP)
Recall or Hit Rate or True Positive Rate = TP/(TP+FN)
F-1 Score = 2 (precision x recall)/(precision + recall)
False Negative Rate (FNR) or Miss rate = FN/(TP+FN)

Table 12 lists the data attributes used for evaluation, and Figure 27 illustrates how the data is extracted from live-view videos.

Table 12. Pedestrian Detection Evaluation Data Attributes

Data Attributes	Description
Location	The location of the pedestrian detection devices
Date	The date of the live-view video
InTime_Person	The time the person enters the crosswalk
DetectionBox_In	The time the white detection box is activated
OutTime_Person	The time the person leaves the crosswalk
DetectionBox_Out	The time the white detection box is deactivated
Detection_In_Delay	The time difference between DetectionBox_In and InTime_Person
Detection_Out_Delay	The time difference between DetectionBox_Out and OutTime_Person
Ped_Atually_Presence	Actual number of Pedestrians on the crosswalk
Ped_Detected	Number of Pedestrians detected by the detection device



(Source: NYCDOT)

Figure 27: Information Extracted from Live Views in FLIR Web Interface

4.1.4 Evaluation Results

Table 13 and Table 14 show the evaluation results for pedestrian detection and counting using FLIR cameras. The detection accuracy varies during different time periods and locations. The summary results show that mid-afternoon and night-time had the highest accuracy rates in terms of pedestrian detection for both intersections. On the other hand, the high pedestrian density site with two (2) thermal cameras detecting the same crosswalk has a higher average detection rate than the low pedestrian detection site with one thermal camera. For Site A, while the morning period also had a detection accuracy rate larger than 80%, accuracy rate dropped to 68% during the PM peak hour where about 500 pedestrians walked on the crosswalk. For Site B, although the system had a low detection rate for morning and PM peak period, the results may be more random due to the small number of pedestrians. The precision among all time periods for both locations is very high (~1.00), which indicates that the FLIR equipment's accuracy is high once it can detect an object. False negative rates ranged from 10% to 43%, and missed detection was mostly observed during PM peak hours. FLIR counting accuracies were generally lower than detection accuracies. Counting a group of people crossing the street using thermal sensors was found to be challenging. Site A has a similar detection performance among weekdays and Saturdays. Site B has very limited pedestrian volume on Saturdays, thus it was determined not to be included in the final evaluation.

Although other cities claimed a high detection accuracy and low false detection of FLIR thermal sensors (Lin et al. 2019) based on the evaluation results, the FLIR detection accuracy in a complex traffic network with relatively high pedestrian and roadside activities like NYC may not be sufficient for a real-time CD safety application. However, thermal sensors are not affected by changes in ambient light, and the evaluation and validation results showed an acceptable detection accuracy rate during nighttime. Therefore, additional detection technologies such as computer vision or on-board cameras on probe vehicles along with thermal sensors is suggested to achieve a satisfactory detection accuracy to fulfill the safety goals for deploying CD for ACV in NYC. Using FLIR sensor for nighttime detection may still be the most ideal approach.

Table 13. Pedestrian Detection Results Using Thermal Cameras

Site A: High-Pedestrian Density Site				
Performance Metrics	**Morning** (~180 peds/hr)	**Mid-Afternoon** (~280 peds/hr)	**PM Peak** (~500 peds/hr)	**Night** (~170 peds/hr)
Accuracy	0.81	0.83	0.68	0.87
Recall	0.81	0.83	0.68	0.91
Precision	1.00	0.99	1.00	0.96
F1_score	0.89	0.91	0.81	0.93
False negative rate	0.19	0.16	0.32	0.09
Site B: Low-Pedestrian Density Site				
Performance Metrics	**Morning** (~14 peds/hr)	**Mid-Afternoon** (~13 peds/hr)	**PM Peak** (~21 peds/hr)	**Night** (~3 peds/hr)
Accuracy	0.57	0.85	0.63	0.90
Recall	0.57	0.88	0.63	0.90
Precision	1.00	0.96	1.00	1.00
F1_score	0.73	0.92	0.77	0.95
False negative rate	0.43	0.11	0.37	0.10

Table 14. Pedestrian Counting Results Using Thermal Cameras

Site A: High-Pedestrian Density Site				
Performance Metrics	**Morning** (~180 peds/hr)	**Midafternoon** (~280 peds/hr)	**PM Peak** (~500 peds/hr)	**Night** (~170 peds/hr)
Accuracy	0.72	0.60	0.55	0.62
Recall	0.74	0.63	0.56	0.69
Precision	0.96	0.95	0.99	0.87
F1_score	0.83	0.75	0.71	0.77
False negative rate	0.25	0.36	0.44	0.28
Site B: Low-Pedestrian Density Site				
Performance Metrics	**Morning** (~14 peds/hr)	**Midafternoon** (~13 peds/hr)	**PM Peak** (~21 peds/hr)	**Night** (~3 peds/hr)
Accuracy	0.50	0.81	0.55	0.80
Recall	0.52	0.85	0.55	0.89
Precision	0.93	0.96	1.00	0.89
F1_score	0.67	0.90	0.71	0.89
False negative rate	0.46	0.15	0.45	0.10

In addition to detection accuracy, detection latency is also key to achieve safety goals of CD for ACVs. The summary of detection latency tests is presented in Table 15. The average in-time detection delay (the time the pedestrian walks into the detection zone and the time FLIR detects the pedestrian) is around 1.33s and the average out-time detection delay (the time the pedestrian walks out of the detection zone and the time FLIR stops detecting the pedestrian) is around 0.94s for the two (2) tested intersections. While the out-time delay may not affect CD safety applications, the impact of in-time delay should be considered when designing safety applications for CD for ACVs.

Table 15. Pedestrian Detection Latency Using Thermal Cameras

Site A: High-Pedestrian Density Site								
	AM Peak		Midday Off-Peak		PM Peak		Night	
	Mean	Conf. Int.	Mean	Conf. Int.	Mean	Conf. Int.	Mean	Conf. Int.
In-time Delay (second)	1.10	[0, 2]	1.22	[0, 2]	1.50	[0, 3]	0.92	[0, 2]
Out-time Delay (second)	0.49	[0, 1]	1.11	[0, 2]	0.89	[0, 2]	1.12	[0, 2]
Site B: Low-Pedestrian Density Site								
	AM Peak		Midday Off-Peak		PM Peak		Night	
	Mean	Conf. Int.	Mean	Conf. Int.	Mean	Conf. Int.	Mean	Conf. Int.
In-time Delay (second)	1.75	[0, 3]	1.35	[0, 3]	1.16	[0, 3]	1.60	[0, 3]
Out-time Delay (second)	0.62	[0, 1]	0.96	[0, 2]	1.10	[0, 2]	1.20	[1, 2]

FLIR can be used to detect vehicles and bicycles, and the data extracted from detectors and its API is appropriate for various CD for ACV use cases, such as detection of pedestrians in crosswalk and blind spot detection, to improve safety (especially for vulnerable road users). It is worth noting that the current FLIR deployment in NYC only supports pedestrian detection. Therefore, additional configurations may be needed when using FLIR for bike and vehicle detections. Based on the evaluation results shown in section 4.1.4, additional technological solutions (such as computer vision or data sources like closed-circuit television (CCTV) camera) are recommended to be used together with FLIR data to improve detection accuracy, especially for CD SAE cooperative level B, C, D safety applications that need higher level of timely and accurate detection.

4.1.5 Lessons Learned

Several lessons learned were captured during the evaluation of FLIR pedestrian detection:

- The detection accuracy of FLIR thermal sensors varies under different demand scenarios and cities. Local validation and evaluation of this technology is needed, especially for areas with complex traffic condition and road user activities. Using thermal sensors for automated pedestrian counting remains a challenge.
- Thermal sensors are not affected by changes in ambient light, so they can be used to capture pedestrians at night.
- FLIR often requires a pre-configured “direction” of walking (e.g., North to South or South to North) to trigger the detection and achieve higher detection accuracy. However, in a city like NYC, pedestrians may cross the street more freely. Although these scenarios were not counted as miss detections in the evaluation process, they should be considered when developing a CD pedestrian safety application.
- Initialize and synchronize the FLIR card's time during the initial configuration. In addition, a 6-second delay was found three days after synchronizing the FLIR card clock with the clock on a

local laptop with the LFC time. There is an option to synchronize the time of the FLIR card with the clock of an NTP server, but that option is not currently set up.

- Real-time evaluation and monitoring of pedestrian detection devices should be considered. Feasible evaluation methods (e.g., local printouts vs network portal) are suggested to be identified at the time the devices are purchased and installed. Not every FLIR device has the same functionality and running "/api/events/supported" can print out a list of events that is actually supported by the specific device.

4.2 Available Bike Data in NYC

NYC has several sources of bicycle data. NYCDOT has a dedicated website **(https://www1.nyc.gov/html/dot/html/bicyclists/bikestats.shtml)** for bicycle statistics and reports. This website includes statistics reports on ridership, cycling risk, bicycle crashes and bikeshare ridership. As NYCDOT update its reports either yearly or quarterly, the data is not the most up to date. However, other sources can be found to get bicycle data. These include bikeshare data, bicycle count data, crash data, bicycle infrastructure network data, and data from emerging technologies (e.g., BSafe-360 multi-sensor device for collecting bicycle trajectory and distance from vehicles).

The company responsible for the bikeshare in NYC, Citi Bike, makes their station-based historical data available monthly on their website (**https://ride.citibikenyc.com/system-data**) and their real-time availability data in *General Bikeshare Feed Specification (GBFS)* format. The station-based historical data contains data on each trip made by users, including ride ID, type of bicycle, timestamp of start and end of the trip, start and end stations' names, IDs, and geographical coordinates, and type of member (casual or membership). They used to have data on the bicycle ID, trip duration, gender, and birth year. However, the fields were removed in 2021 due to privacy concerns. This dataset is useful for getting an estimate of overall trends and patterns for bicycle ridership in the city.

While Citi Bike's station-based historical data offers data on each trip made in the system, the real-time availability data offers data on the quantity of bicycles and docks available at each station of the system at a specific timestamp. This dataset contains station ID, total number of physical bicycles available, number of bicycles disabled, number of docks available, if the station is currently installed on the street, if the station is currently renting bicycles, if the station is currently accepting bicycles to be returned, and the last time the station status was reported to backend. To get access to this data, a script should be created to fetch the data from their server at predetermined time intervals. This type of data is useful especially for optimizing the balancing of bicycles in the stations and for understanding supply and demand for each station at a granular level.

NYCDOT also provides data on bicycle ridership throughout the city, the bicycle count data at (**https://data.cityofnewyork.us/Transportation/Bicycle-Counts/uczf-rk3c**). Monthly bike count data is collected at 14 (as of 2019) inductive loop counters around NYC at key locations. Although the spatial coverage is limited, it allows us to gather data not only on shared bicycles, but also on privately owned ones. The dataset provides the counter's location ID, name of the street where the counter is located, name of the counter, counter's geographic coordinates, type of count it is conducting (e.g., bicycle, pedestrian, car, etc), the time zone of the region where the counter is located, the data recording interval (e.g., 15 or 60 minutes), direction of travel, when the counter was installed, and serial number of the individual counter. Some of the issues to be careful when first working with this dataset include the existence of more than one (1) counter per location, hardware failures that lead to missing readings for direction of travel or incorrect volume readings, and the removal of existing counters throughout the years.

Bicycle crash data can be obtained by filtering New York Police Department's (NYPD) Motor Vehicle Collisions – Crashes dataset (https://data.cityofnewyork.us/Public-Safety/Motor-Vehicle-Collisions-Crashes/h9gi-nx95). This dataset contains data on all the crash events in NYC involving different types of vehicles, and it is updated daily. They have three sub-datasets for this data: MV-Collisions – Crash, MV-Collisions – Vehicle, and MV-Collisions – Person. The most relevant for safety studies is the MV-Collisions – Crash, from which we can determine the number of crashes involving cyclists. Each row of the MV-Collisions – Crash dataset represents a crash event and contains data on the date and time it occurred, the type of the vehicles involved, address and geographical location, the number of persons, pedestrians, cyclists, and motorists injured or killed, and factors contributing to the collision. This dataset is filled by reports coming from officers, which may lead to some inconsistencies in the notations used for vehicle type and contributing factors. Therefore, when filtering for bicycles, one should try to find all variations of notations used for bicycles (e.g., BK, bicycle, bike, bik, etc). Moreover, the actual number of collisions involving bicycles provided by the dataset might not cover all of them, as the ones in which the police were called only get reported. Some collisions involving bicycles might occur but not be reported due to the cyclist getting up and leaving before anyone can call the police. This leads us to believe that this dataset might be biased to include mostly collisions in which there were severely injured or killed cyclists and not from ones involving non-injured cyclists.

The city also provides information on the bicycle infrastructure network. The NYCDOT provides a map containing all the existing bicycle routes in the city (https://data.cityofnewyork.us/Transportation/Bicycle-Routes/7vsa-caz7). The map is updated annually, and it contains data on the street where the route is located, the LION segment ID, the borough, the facility type (e.g., protected, conventional, signed/marked route, or link), the street where it starts and ends, if on or off the street (e.g., greenways), facility class (e.g., facility type, link or stairs), installation and modification date and times, direction of travel, number of lanes, and type of facility in the directions of start and end streets.

Lastly, the use of emerging technologies has shown potential for acquiring new key data for bicycle studies. For instance, Bernardes, Kurkcu and Ozbay (Bernardes, Kurkcu, and Ozbay 2019) developed a portable multi-sensor device called BSafe-360 that can collect data on the distance between the bicycle and obstacles positioned to its sides (e.g., parked and passing vehicles), the bicycle trajectory, and the speeding and braking behavior of the cyclist. Though in its initial stages, this type of data can provide key information on how cyclists react when interacting with traffic, determine what can be considered a safe distance between themselves and vehicles, and identifying any near-misses.

While none of the current bike data provides sufficient coverage and real-time features that the proposed CD use cases require, emerging sensor solutions such as the portable multi-sensor bike device (Bernardes, Kurkcu, and Ozbay 2019) may be expanded to be tested at a pilot site to improve situational awareness.

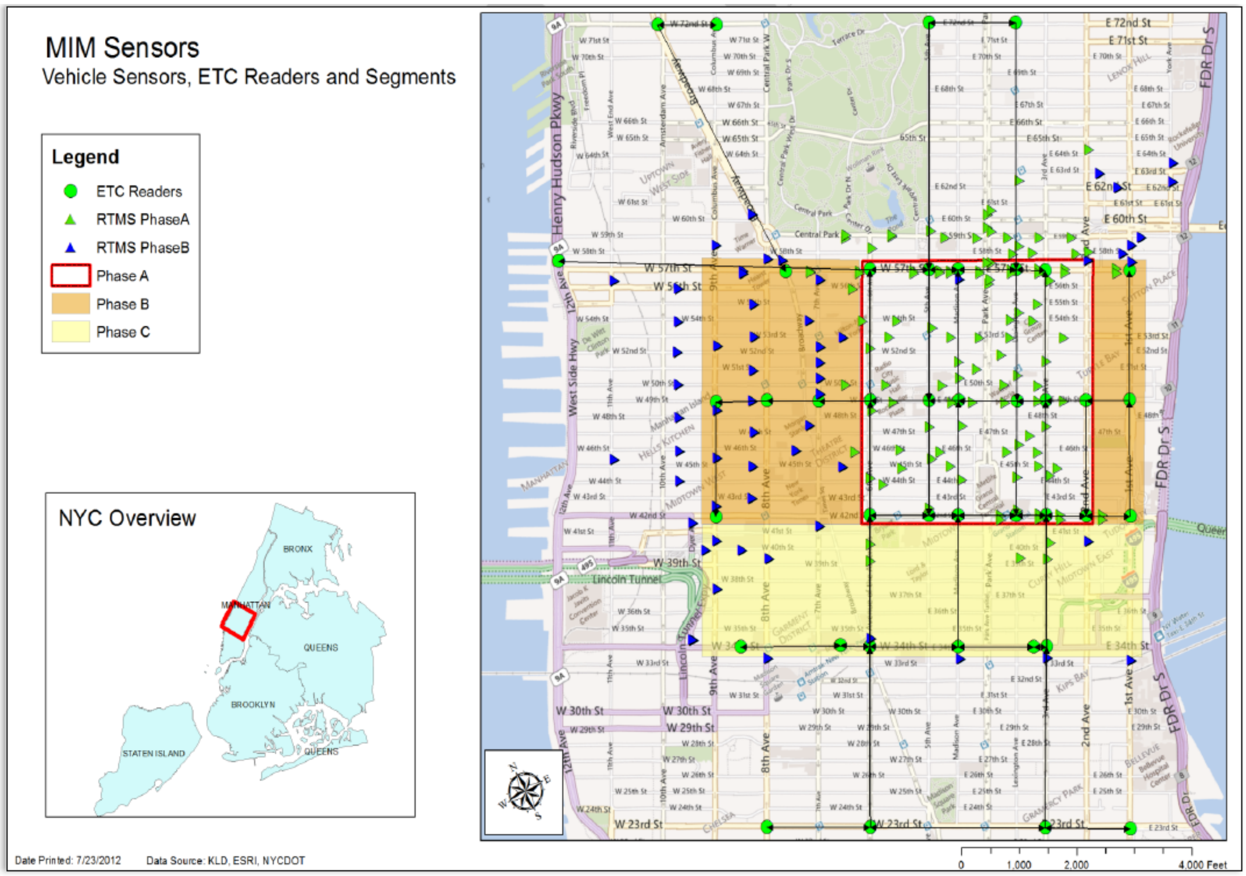
4.3 Traditional Traffic Data

This section provides brief descriptions of traditional traffic data owned or accessed by local agencies and how the data is used in the current traffic operations in NYC. Specifically, several real-time and non-real-time data from NYCDOT such as data extracted from microwave sensors or Wi-Fi are examined.

4.3.1 NYCDOT Remote Traffic Microwave Sensor (RTMS) Data

The NYCDOT ITS infrastructure for the initial Midtown in Motion (MIM) deployment in 2011 includes 103 advanced solid-state traffic controllers, 32 video cameras, 100 RTMS sensors, and 23 electronic toll collection readers at intersections within a 110 square block area from 2nd to 6th Avenues, and 42nd to 57th Streets (KLD Engineering 2013). MIM is a large-scale active traffic management system that uses travel-time-based adaptive control for congestion management in an urban grid network (Xin et al. 2013). The system was expanded in 2013 to include a total of 146 RTMS sensors and covering more than 270 square blocks of Midtown Manhattan, from 1st to 9th Avenue, and from 42nd to 57th Street.

Figure 28 illustrates the MIM implementation and locations of the RTMS sensors. The RTMS detects flow and occupancy information based on the presence of moving vehicles using radar technology. The RTMS data is being transmitted on a zone/lane basis. The system is currently configured to collect data for selected locations every 5 minutes, but it can be configured and return the data back to the TMC with a shorter interval (e.g., every 30 second interval).



(Source: KLD Engineering 2013)

Figure 28: MIM Zones and Sensors

Typically, microwave sensors are affected by problems such as decorative flags and banners being placed in front of or near the detectors or construction and repair work that places metal structures in the field of view (for instance, scaffolding) (KLD Engineering 2013). NYCDOT has been monitoring the state of these detectors and has a system monitoring tool that automatically generates daily reports that investigate detection zone changes, travel time segment changes, and detector health status to monitor RTMS sensor reliability and “up time”. In general, 80% of the sensors are performing well, with 6% intermittent and 14% of the unit’s needing investigation (KLD Engineering 2013). The average speed can be estimated from the flow and occupancy information provided by the microwave detectors, and it was found to have a good match with speed from other data sources (KLD Engineering 2013; Morgul et al. 2014).

RTMS is one of the critical data sources for near real-time traffic flow information and can provide presence indication with a lane-based resolution. Current RTMS sensors are configured to detect vehicles, but additional configurations may be made to detect bike presence. The data update interval used in TMC can be set to 30 seconds; however, the feasibility and reliability of having a lower data transmission interval needs to be investigated if this data is used for certain CD for ACV safety applications.

4.3.2 NYCDOT Real Time Speed Data

NYCDOT's traffic speed detector feed (NYCDOT 2021c) is an open-sourced service that allows various user groups to download real-time traffic speed information on a regular basis. This data feed contains 'real-time' traffic information that is updated several times per minute from locations where NYCDOT picks up sensor feeds within the five boroughs, mostly on major arterials and highways. NYCDOT uses this information for emergency response, management and so on. The traffic speed information is encoded based on a link-based system and contains real-time traffic conditions collected from installed traffic detectors that belong to various city and state agencies. This data only covers major arterial roadways within the five (5) boroughs. The speed information is reported by physical traffic detectors, which will highly depend on the status of the detectors themselves. The speed information is aggregated in specific time periods. Considering the spatial coverage, missing values, and reliability issues, this data is suggested to be fused with other speed or travel time data sources.

4.3.3 NYCDOT TMC Travel Time Data

NYCDOT real-time travel time data is collected by TMC via its Wi-Fi sensors. Currently, WiFi sensors are installed at every signalized intersection in NYC and can be configured to “active” mode to collect travel time data. After examining a sample of the data, the research team found that the data transmission/update frequency is not uniform (often vary from 2s to 82s). Depending on the use case, the NYCDOT TMC travel time data can be a good real-time data source to provide driving environment information to the vehicles but may be insufficient for CD safety applications that requires immediate actions (e.g., work zone safe merge) due to its data granularity and resolution. It can be useful for certain CD use cases (e.g., high-speed locations or signal optimization) that do not require high data frequency. Sharing the travel time information and use it as a data input to identify hazard events when an anomaly is found can increase situational awareness of drivers and VRUs.

4.3.4 NYCDOT TMC Incident Database

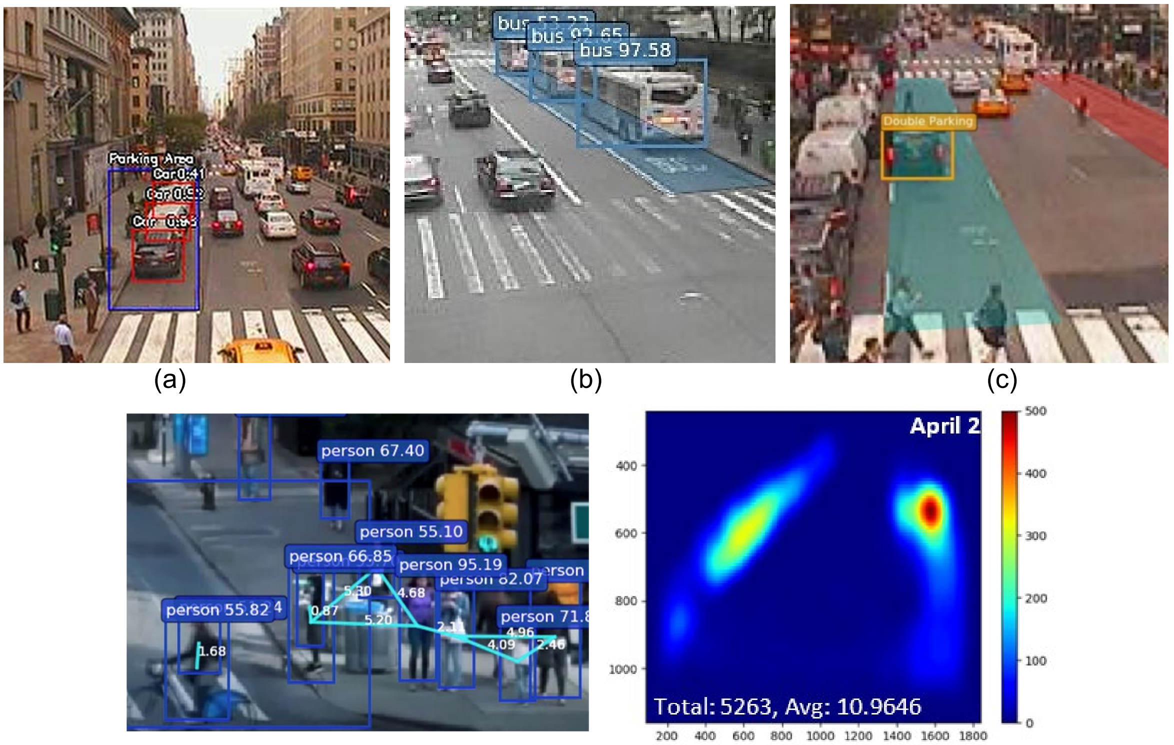
The NYCDOT TMC incident database contains incident information. Incident information is also collected from other sources and partner agencies, including CDOT TMC, SDOT JTOC, SDOT JTMC, Transcom, NYPD (TMC), CDOT OER, PANYNJ, MTA Bridges & Tunnels, NYCEM, PA Alert, PANYNJ CCTV cameras and others. For each traffic incident, incident type, source agency, affected lanes and direction, traffic condition, severity level and actions taken are recorded. Since incident information is entered manually, values in certain features do not have a unified format. The incidents are either identified by monitoring system like MIM or reported by agency partners or emergency management personnel. Therefore, not all incidents occurred in the area may be captured, with some incidents experiencing delays during the reporting process. Although the TMC incident database may not be exhaustive, it can be fused with other incident data source such as NY511 or Waze for real-time work zone or road obstacle information to share hazard event status and increase the general situational awareness for certain CD use cases (e.g., work zone information and presence).

4.3.5 NYCDOT Street Construction Permit Database

NYCDOT Office of Construction Mitigation and Coordination (OCMC) issues over 150 different types of sidewalks and roadway construction permits to utilities, contractors, government agencies and homeowners (NYCDOT 2021b). Permits are required for construction and other work that impacts the quality of pavement or blocks lanes of traffic. This data has been made public since 2018. The database is updated daily and includes core permit data, such as permittee, type of permit, date issued, and locations. The permits cover but not limited to street openings, sidewalk construction and installing canopies over sidewalks. Although this database is not updated in real-time, it is the most comprehensive and up-to-date work zone database in NYC to obtain street construction information. It is worth noting that the start and end date in the database do not necessary represent the actual working dates/times. If the location is on a street segment, this data does not reveal the exact location and length of the work zone. Moreover, since the street information is in plain text, additional efforts will be needed to convert or align them into geographic coordinates. Also, in the current NYC CVPD all work zone information is hard coded and there is a need to have a unified database or standard for real-time work zone information. Fusing work zone data in agency owned data sources such as NY511 with third party event data (e.g., Waze, Here) may provide valuable real-time work zone presence information for CD for ACV and specification such as Work Zone Data Exchange (WZDx) is suggested to allow harmonized work zone data.

4.3.6 NYCDOT Traffic Cameras

The CCTV system is a valuable source of traffic condition information for many transportation systems. Traffic video data can provide rich information, such as traffic volume, travel speed, curb activities, and incident information, to facilitate traffic operations and management. NYCDOT traffic cameras (https://nyctmc.org) provide frequently updated still images from 731 locations in the five (5) boroughs. The TMC often uses these traffic cameras as part of their traffic monitoring and incident response system. The live stream of the traffic camera data is not fully utilized but it has a lot of potentials to be used in variety of CD for ACV use cases. Leveraging computer vision techniques, the research team tested the feasibility of using the exiting NYCDOT CCTV cameras for real-time pedestrian detection (Zuo et al. 2021), curb/bus lane occupancy, and traffic incident such as double parking. This data can be used together with other data sources like FLIR to increase the reliability of the detection or be used to increase the data availability and coverage to enhance shared perceptions. Examples of using the CCTV camera footages based on computer vision are shown in Figure 29 below.



(a) (b) (c)

(d) (e)

(Source: NYU C2SMART Center (Gao et al. 2021))

(a) detecting parking occupancy; (b) monitoring bus lane usage; (c) identifying illegal parking/double parking, (d) detecting pedestrian, and (e) using pedestrian density information at bus stops to assess transit demand. (Source: C2SMART (Gao et al. 2021))

Figure 29: Example of usage of the traffic cameras based on computer vision

4.3.7 Metropolitan Transportation Authority (MTA) Bus Time

MTA Bus Time uses GPS hardware and wireless communications technology to track real-time location of buses. Service Interface for Real Time Information (SIRI), a standard covering a wide range of types of real-time information for public transportation, is adopted for MTA Bus Time project. One of the key datasets that can be extracted from MTA Bus Time is the travel time information. Travel times can be collected from many potential sources. Conventionally, fixed detectors such as inductive loops embedded in the roadway have been used to measure vehicle flows and estimate speeds. Recent technological advances and the widespread deployment of GPS in consumer devices make mobile data sources a promising and potentially cost-effective way to monitor the congestion in a transportation system. MTA Bus Time data provides real-time vehicle monitoring and bus stop monitoring information about buses tracked by the system and buses serving a particular stop. MTA Bus Time also supports GTFS-Realtime that provides TripUpdates, VehiclePositions, and Alerts (MTA). The spatial coverage of MTA Bus Time data includes the entirety of NYC where bus routes or activities are available. According to MTA, the data update frequency is every 30 seconds. However, the actual interval observed from the dataset collected turns out to be approximately 60 seconds in most cases. In addition, this interval gets longer when scheduled activities increase (Silva and Ozbay 2017). The reliability of MTA bus data largely depends on locations and arterials with more bus routes and frequent bus activities. When used appropriately, it can provide accurate lane-specific information (i.e., for road links with a dedicated bus lane) or areas with bus stops or transit hubs. This data source should be considered if the CD for ACV deployment is nearby a bus stop or has high bus activities.

4.3.8 Taxi Breadcrumb Data

New York City Taxi & Limousine Commission (TLC) provides publicly available taxi trip records that include fields capturing pick-up and drop-off dates/times and zones, trip distances, itemized fares, rate types, payment types, and driver-reported passenger counts. This data is currently updated every few months. TLC also collects taxi breadcrumb data recorded by technology service providers (TSPs) in real time. Each taxi pings its location to the TSP it contacts every 120 seconds and sends the time, date, and driver's hack number to TLC. In combination with start/stop points from the trip record data, these breadcrumbs can be used as waypoints in the driver's path to generate a more reliable route (NYC TLC 2018). Although this data is collected in real time, it is not readily available in real-time. The granularity of TLC taxi breadcrumb data (~120s) may not be sufficient for all CD safety applications that requires immediate action but can potentially share travel time, speed and trip-based information along with other data sources to improve situational awareness for proposed CD use cases 1-5, 2-6 and 3-2 if the data is reported in real-time.

Other non-real time data examined includes crash records, parking and camera violations, MTA turnstile data, ridership and bridge and tunnel volume data, and 311 services requests. Details of the data can be found in the technical memorandum on cooperative driving for advanced connected vehicle: data analysis (NYCDOT and C2SMART 2021).

4.4 Other Cooperative Automated Transportation (CAT) Data

This section discusses the CAT data other than the automated pedestrian detection data presented in Section 4.1. CAT data refers to the data generated to enable the automation of vehicles and the infrastructure which vehicles share with other CAT users (Cohan et al. 2020) and is fundamental to "achieve a connected vehicle ecosystem that enables reliable, secure V2I data exchanges in order to support cooperative automated transportation to improve traveler safety, mobility, equity, and efficiency." Currently, NYC uses BSM, SPaT, MAP, and limited TIM and CDD data in its CVPD project. Other CAT data, such as the new CARMA CDA messages, listed in this section are not available to NYC yet but can be potentially beneficial to the three CD use cases identified.

4.4.1 Basic Safety Message (BSM)

BSM is a standard message protocol mainly used in safety applications. In V2X Equipped Object (including V2I and V2V application) (SAE International 2020), its functionality is being broadcasted to surrounding vehicles with a frequency of 1/10th second to ensure the surrounding vehicles have basic safety knowledge about the vehicle who send this message. The BSM message contains two parts. Part I is necessary for the data to be valid because it contains core information about basic safety, and Part II is optional because it is used to enhance various other applications. Field-collected data, including BSM from the three (3) CVPD sites selected by USDOT, have been made publicly available through the USDOT ITS DataHub (www.its.dot.gov/data). Many other publicly available field-collected, simulated, and emulated BSM datasets can also be found through the ITS DataHub.

NYC obfuscated some BSM data fields like *Time, Latitude,* and *Longitude* for privacy consideration. A sample of NYC CVPD EVENT Data that includes the EVENT meta data, BSM, MAP, TIM and SPaT data can be found at (USDOT 2021a). The BSM data can serve as a complementary information for traditional data. Many of the data elements, such as event trigger flags, cannot be measured by tradition traffic data collection approaches. The V2I information also increases the geographic breadth and granularity of data to traffic operators and managers. The optional feature of the BSM can assist new applications other than the ones deployed in NYC CVPD and allows for more information to be communicated. The Part II of the BSM is flexible, and features such as path prediction and *CrumbData* can be used in CD for ACV to further improve safety and mobility.

4.4.2 MAP and Signal Phase and Timing (SPaT) Messages

The MAP message is a DSRC standard message protocol intended to communicate various types of geographic roadway information (SAE International 2020). Typically, a MAP message is static message that contains relevant geometry information about multiple lane details. This static feature leads to many strengths of MAP message, such as high accuracy, great reliability and low latency (Sumner et al. 2018). MAP messages are often used with a Signal Phase and Timing (SPaT) message using the intersection ID data element. Most existing MAP data in NYC CVPD is event-specific, and a potential weakness can be the lack of coverage/availability due to the need for being broadcasted by RSUs. The information transferred via SPaT includes the geometric layout of the intersection, current phasing information and next expected phase information (SAE International 2020). The information includes only active signals; the inactive ones will be omitted. Besides these information, signal preemption and priority status values could be included. However, these are not implemented in NYC CVPD. The SPaT message is included in the NYC CVPD EVENT data as a feature. The Reliability of SPaT dataset is relatively high because the information recorded are mostly static feature and the transmission rate is relatively high (can be used in real-time application). However, even though most of the geographical information and active phase information is accurate in SPaT, the prediction of next phase information may be inaccurate if the intersection is controlled adaptively (Ibrahim et al. 2018). This can be a challenge in NYC as the MIM system is an adaptive signal system. Some recent efforts aim to improve the prediction accuracy of SPaT using different methods such as machine learning (Genser et al. 2020).

4.4.3 Traveler Information Messages (TIM)

TIM is a US standard message protocol that intends to communicate important traffic information to travelers via equipped devices (SAE International 2020). This includes location-specific and time-specific data such as advisory information for specific geographic areas and time periods via V2I communication or satellite communication if equipped devices are out of range of an RSU (Zumpf et al. 2020). Advisory information may include inclement weather warnings and advisories, recommended speeds, road closure notifications, parking/services information for trucks, vehicle restrictions, etc. The NYC TIM data is also recorded in the EVENT dataset in 'timList' feature. The data information includes the road signal information, SSP Index for message content, SSP Index for location content etc. The TIM data frame information is relatively sparse. As TIM can be delivered from satellites that allows this message to be sent to road users who are not within the RSU or V2V communication range, it enables sending, relaying and receiving perception data about the driving environment (i.e., what the driver and other road users see) for improved situational awareness and fits into the cooperative perception (CP) concept.

4.4.4 Connected (Mobile) Devices Data (CDD) and Personal Safety Message (PSM)

Connected device are defined as wireless electronic devices (e.g., tablets and smartphones) that can communicate sensor data with other entities through embedded operation systems and communication technology. The communication technologies include cellular, satellite, Wi-Fi, Bluetooth, Near-Field Communication (NFC), and DSRC. The data collected by the entity (e.g., agency, third-party) can be traffic flow, traffic density, etc., and the data collected by smartphone can include pedestrian speed, pedestrian intention, etc. The Personal Safety Message (PSM) message is used to broadcast safety related data for vulnerable road users (like pedestrian, cyclists, and road worker). The message is not being used in NYC CV Pilot project. With that said, it is still under development but can be very useful for proposed CD use case 1 pedestrian and bike safety and use case 2-4 worker safety. One potential advantage of this dataset is it contains the VRU data feature which can be used as a complement to other datasets which are mostly vehicle oriented. However, the amount of VRUs in can be much larger than vehicles, therefore, the potential high latency should be considered when designing an operational scenario using this message.

SAE International developed the standard of PSM (SAE J2735) and minimum performance requirements of the PSM transmission from VRUs (SAE J2945/9). FHWA examined the system architecture and design of PSM (Valentine et al. 2017). Moreover, The Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle (CV) Pilot, industries and a few researchers also have been looking into different approaches in generating PSMs, such as vision-based (Islam et al. 2020) or LiDAR (THEA 2021).

4.4.5 Other CAT Data Currently Not Available in NYC and CARMA CDA Message Set

CDD allows for a broader coverage of data collection, which leads to increased reliability. The data can serve as a connection between VRUs such as pedestrians/cyclist/workers and intersections. From a feature perspective, this dataset can be useful in safety related application and intersection management. The reliability mainly depends on the data accuracy. This type of data is key to certain proposed CD use cases such as work zone worker safety. For example, a prototype wearable sensor (i.e. smart watch) was developed to provide visual and audible alarms to workers about the surrounding environment (i.e., what I and others see) and can be used for improved situational awareness (Zou et al. 2020).

CAT data is currently not available in NYC but can be useful for other CD for ACV use cases including Common Safety Request (CSR), cooperative Intersection Collision Avoidance (ICA), Probe Vehicle Data (PVD), Roadside Alert (RSA) messages and Work Zone Data Exchange (WZDx) and so on. They are also briefly discussed in the data analysis technical memorandum (NYCDOT and C2SMART 2021).

In 2021, CARMA also added six (6) new message types the CDA Message Set to enable V2X communication between vehicles and other entities for various CDA cooperation classes, as defined in SAE J3216, for enabling true cooperative behavior (Lochrane 2021). The goal of creating these new message types is to address the needs for intent sharing, CDA agreement seeking, traffic control information, and maneuvering recommendations. Four (4) out of six (6) new message types (mobility path, mobility request, mobility response, and mobility operation) fall under the mobility messages category. Each message has a common set of information at the beginning that includes fixed identifications for the sender, optional identifications for a targeted recipient (either of which could be a vehicle, infrastructure, pedestrian, or cyclist), temporary BSM identifications, plan identifications, and timestamps (Lochrane 2021). The other two (2) fall under geofence messages (traffic control request and traffic control message) category, in which each message is applied to part of a single traffic lane and designed to communicate traffic control updates to CARMA vehicles via CARMA Cloud (Lochrane 2021). These messages on mobility and geofence are highly related to CD for ACV and need to be further explored.

4.5 Third-party Traffic Data

A growing number of private sector/third party data brings lots of opportunity and can provide insights for designing and operating CD for ACV. Although using these data sources effectively and getting an exhaustive list of efforts can be challenging, the following section looks at many third-party data that are available to the research team. These include endeavors that collect driver behavior data such as dangerous driving or using computer vision for work zone operations (e.g., Nexar) and those which utilize connected mobile device applications or connected infrastructures to collect map-based data (e.g., Waze, Google Maps, INRIX, StreetLight).

Waze *(https://www.waze.com)*, primarily used for navigation guidance, also provides information about traffic jams and events that affect road conditions, either from drivers using Waze or from external sources. Waze actively partners with agencies to both provide and receive traffic data through its Connected Citizens Program (CCP). Waze traffic data consists of the following information: 1) *General information*: timestamp of the file, geographic area from which the data was retrieved, etc; 2) *Traffic alerts*: traffic incidents reported by users; 3) *Traffic jams*: traffic slowdown information generated by the service based on a user's location and speed; 4) *Unusual Traffic (Irregularities)*: alerts and traffic jams that affect an exceptionally large number of users. The New York State Department of Transportation (NYSDOT) has a data exchange agreement with Waze and is currently establishing a data lake for this data. Waze real-time incident, jam and irregularity alerts can be good supplemental information for all three (3) CD for ACV use cases, especially for providing real-time work zone information. Historical Waze data can also be used in off-line evaluation (e.g., high accident locations) or as training data for real-time anomaly detection (Gao 2020) that can provide predictive traveler information.

HERE (https://www.here.com**)** provides real-time traffic data using multiple data sources including probe data and sensor data. HERE provides real-time service that matches the probes to the HERE map in order to recognize the current traffic conditions on the road. It integrated the readings from probes and sensors to provide aggregated traffic mobility information such as traffic speed and link travel time. NYSDOT has this data exchange agreement with HERE and accessing the real-time HERE mobility data for NYS, including NYC can be accomplished using the direct HERE data feed.

INRIX (https://inrix.com) reports historical traffic state information via multiple data portals. The most accessible one is with the National Performance Management Research Data Set (NPMRDS) data. This dataset contains historical speed and travel time data of roadway links (e.g., freeways, highways, major and minor arterials) nationwide, which is mostly collected by probe vehicles. The speed data is calculated from current road conditions and is reported at the segment level for roadways that INRIX covers, including comparisons to typical and free-flow speeds. INRIX data covers freeways, highways, arterials nationwide in the U.S.

TRANSCOM (**https://data1.xcmdata.org/DEWeb/Pages/index.jsp**) is a coalition of sixteen (16) transportation and public safety agencies in the New York – New Jersey – Connecticut metropolitan region. It maintains a multi-source data fusion platform, which integrates data sources such as Bluetooth, loop detector, TomTom, traffic camera data and so on. TRANSCOM has their own data reliability metric and identifies the current traffic conditions using the most reliable data source at the time.

Nexar collects crowdsourced data through consumer-grade dash cams and phone-based sensors (such as accelerometer, gyroscope, and GPS), anonymizes and aggregates the data, and provides vision-based data services (Nexar 2021). It generates a fresh, high-quality, street view of the world and transient changes based on vision data that is approximately 130 million miles of road data per month worldwide (Lawton 2021). Nexar has developed AI algorithms to automatically extract road features from dash camera video data that are expected to be used to model city activity for civil engineering management (Lawton 2021). Based on this, Nexar provides services such as querying street current images and monitor changes, detection, monitoring, and mapping of traffic signs and signals, and detection, monitoring, and mapping data for work zones in areas of interest (Nexar 2021). Accompanying the phone-based sensor data, the Nexar dash cam can capture a 40-second clip of an incident (such as hard brake) or collision (20 seconds before and after the event) that is automatically saved to the cloud (Ariella 2019). Nexar also has detected incident and dangerous driving event data in NYC including time, location, direction, observed behavior (swerve, hard break, etc.) and G-force that may be beneficial for safety applications.

One safety-oriented usage for Nexar data is in the work zone. The Ohio DOT (STONE 2020) and the Regional Transportation Commission of Southern Nevada (RTC) (Nexar 2019) have launched a pilot using the work zone function (namely CityStream Road Work Zones) to improve work zone safety. It enables agencies to access real-time updates of work zones remotely; ensure compliance with work zone standards; detect and enforce unauthorized lane closures and monitor which sites are regularly causing traffic congestion. Nexar's dangerous driving event data and work zone application can be used as a supplemental data to contribute to the proposed CD for ACV use cases, especially for the cooperative perception of work zone.

Wejo (**https://www.wejo.com**) collects probe vehicle data from multiple OEM data sources globally. The data contains 11.3 million active vehicles, a 50 million vehicle supply base, 391 billion curated miles, 10.1 trillion data points, and 48.4 billion journeys reported (Wejo 2021). Across the USA, Wejo states that their data covers 1 in 28 vehicles and covers 95% of U.S. roadway networks (Wejo 2019). Wejo provides four products that are journey intelligence, traffic intelligence, vehicle movements and driving events. Wejo vehicle movements product provides location and journey information for vehicles. The company states that it has coverage of up to 95% of U.S. roadway networks and that the data is accurate down to three meters and the data update frequency can be every 3 seconds or less. Aggregated based on the vehicle movement data from probe vehicles, Wejo extracted event data such as harsh braking, speeding occurrence, parking, as well as traffic flow and travel patterns such as traffic volume, speed, travel time. The frequency of traffic data is available daily, weekly, monthly and it also provides hour-by-hour traffic trends (Wejo 2021).

StreetLight (**https://www.streetlightdata.com**) data is mainly based on navigation-GPS and location-based services (LBS). Streetlight offers traffic and trip data such as annual average daily traffic (AADT), various vehicle miles traveled (VMT), and trip metrics such as origin-destination (OD) data, trip route, trip purpose (StreetLight 2019). StreetLight currently uses one major navigation-GPS data supplier, INRIX, and one LBS data supplier, Cuebiq, and updated the data set every month (StreetLight 2019). Once the data is provided to StreetLight, it will go through the process of data cleaning and quality assurance, create trips and activities, contextualize, more quality assurance, normalize, securely stored, aggregate in response to queries and final metric quality assurance. During these processes, other contextual data sets such as road networks, speed limits and directionality, land use, parcel data and census data, were added to improve the accuracy of mobile data (StreetLight 2019). One drawback of the data is that users cannot access data in raw formats and the available aggregated data may have a limited resolution and only particular metrics are available. While this data in its current form may not be appropriate to be used for real-time application in CD for ACV, it is one of the rare data sources in NYC that contains traffic volume information and may be used to calculate exposures.

4.6 NYC WiFi Hubs and 5G Network Coverage

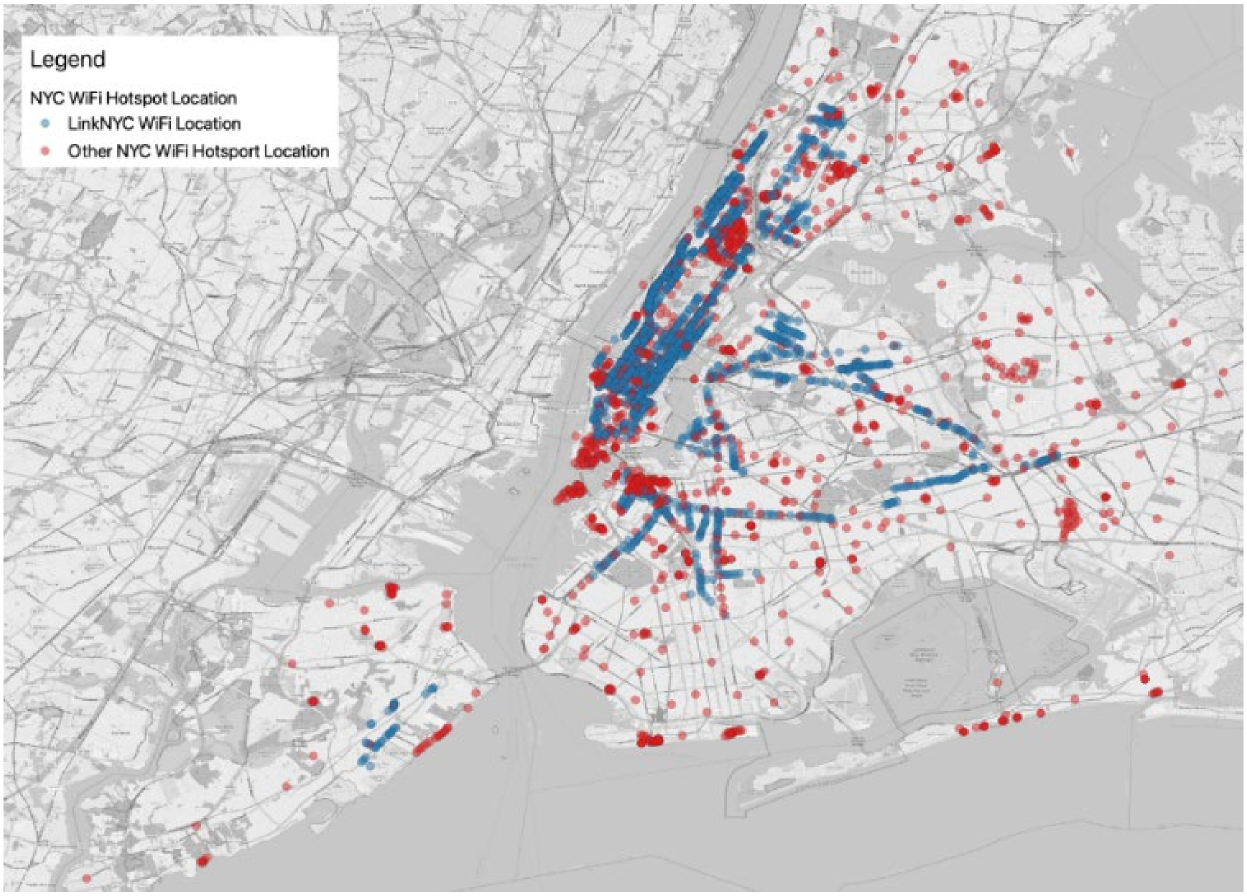
4.6.1 5G Network Coverage

The CD technology requires a reliable, robust, and extended wireless network. As a promising data communication technology, the advantages of 5G include its high-speed data rates and low latencies which enable direct V2V communications or V2X communications. It requires less saturation with a minor increase in latency (Ukkusuri, Satish V., et al., 2019). These communications allow vehicles to interact in real time with their environment to increase road safety, traffic efficiency, and energy savings. The performance of current V2X communication technologies is typically degraded by structures such as buildings and walls that are very common under urban scenarios, which act as obstacles against direct communications. A federal study analyzed latency differences between DSRC and cellular 4G/LTE to assess the feasibility of using these methods for connected and automated vehicle applications (Rayamajhi, Anjan, et al., 2020).

5G-based communication, however, can overcome the problem of local obstacles since the cellular network can establish reliable communications among vehicles with the aid of the base station (Maria et al. 2019). Although the exact communication requirements of CD use cases are still being researched, having low-latency and highly reliable V2X communication will be critical in all cases. This presents a challenge for current V2X technologies, especially in dense traffic scenarios such as a traffic jam on the motorway. In addition, an extended communication range would allow starting the cooperation process sooner. 5G communication promises to enhance the capabilities of V2X communication in terms of latency, reliability, and transmission range, and thus seems well suited to satisfy the requirements of CD (Llatser et al. 2019). In addition, the key advantage of 5G technology is that it will run off existing wireless networks, though upgrades in 5G technology will still need to be made at cellular stations (Ukkusuri, Satish V., et al., 2019). Some state DOTs such as Virginia Department of Transportation (VDOT) are also testing the feasibility of using 5G outside intersections with DSRC deployed at intersections (Ukkusuri, Satish V., et al., 2019). NYC is currently installing 5G antennas across the city and expect to test this communication technology and compare it to DSRC. In addition, National Science Foundation (NSF) supported a part of Harlem as its 5G testbed (**https://www.nsf.gov/news/news_summ.jsp?cntn_id=245045**), and FCC created East Harlem innovation zone for wireless technology and 5G network experimentation. This can advance CD for NYC and potentially enhance the vehicle accuracy for ACVs. Currently, NYC is using RSU triangulation to improve GPS location accuracy and 5G may allow more street-level information exchange with a more redundant network that may provide an additional layer for triangulation. Testing will be needed to confirm this capability in real-world ACV operations.

4.6.2 WiFi Hotspots

As shown in Figure 30 below, there are 3319 NYC WiFi hotspots located in the streets, parks, libraries, subway stations and other places of NYC (DoITT 2020). Most of them are free or free for a limited number of users. Specifically, the LinkNYC program was developed to replace pay phones with new structure called links that provide free high-speed Wi-Fi, nationwide calling, a dedicated 911 button, charging ports for mobile devices, maps and directions (LinkNYC 2021). Currently, NYCDOT has utilized the Wi-Fi hotspots to generate travel time data citywide. Despite lack of current development, 5G and advanced Wi-Fi will eventually benefit CAVs and CD in terms of latency, security, and guaranteed throughput.



(Source: (DoITT 2020), (LinkNYC 2021))

Figure 30: NYC WiFi Hotspot Locations

4.7 Data Appropriateness for CD for ACV Use Cases

Based on the above discussions, Table 16 to Table 18 provide a summary of the appropriateness of data for CD for ACV for the three (3) proposed use cases and their implementation. A more comprehensive review of the data can be found in the data analysis technical memorandum (NYCDOT and C2SMART 2021). It is worth noting that although the six (6) new mobility and geofence messages introduced by the CARMA program (Lochrane 2021) were not included in the following tables, they are highly related to CD for ACV and need to be further explored.

Table 16. Data Appropriateness to CD for ACV Use Case 1: Pedestrian and Bike Safety through Cooperation

(X: Essential or highly related; O: Maybe useful)

	1-1	**1-2**	**1-3**	**1-4**	**1-5**	**1-6**	**1-7**	**1-8**	**1-9**
	Pedestrian /bike presence at the crosswalk	**Mid-block Jaywalking**	**Pedestrian /cyclist intention prediction**	**Road obstacle /blind spot**	**School Zone Crossing**	**Nighttime High-speed Road Link**	**High ped/bike crash location**	**High ped/bike density location**	**Intersection crossing assistance**
Ped Detection (RSU)	X	X	X	X	X				X
BSM	X	X	X	X	X	O	O		X
MAP	X	X	O	O		X	X	X	X
SPaT	X		O						X
TIM				O	X	O	O	O	
Traffic Camera	X	X	X	X	O	O	O	X	X
CDD	O	O	O	O			O	O	X
CSR		O		O	O				
RSA				O					
PSM	X	X	X	X		X	X	X	
PVD				O		O			
ICA	O			O					O
TMC travel time and speed						X			
Crash Data							X		
Private Sector/Third Party Data - Travel Time and Incident					O	X			
Private Sector/Third Party Data - Other (e.g., Dangerous Driving)		O	O	O					O
TMC Incident database				X			X		
TMC RTMS								O	O
Bus GPS data						X			
NY 511						X			
Ped Detection (OBU)	O	X	X	X	O				
Real-time Work Zone Info (e.g., WZDx)				O					

Table 17. Data Appropriateness to CD for ACV Use Case 2: Cooperative Work Zone

(X: Essential or highly related; O: Maybe useful)

	2-1	**2-2**	**2-3**	**2-4**	**2-5**	**2-6**
	Work zone information & presence	**Limited sight/blind spot**	**Work Zone Lane Change, merge and speed harmonizing**	**Worker safety**	**Risk indication - High work zone crash location**	**Risk indication - High-activity and congested location**
Ped Detection (RSU)		O				
BSM	X	X	X			O
MAP	X	X	X		X	X
SPaT			O			
TIM	X		O			X
Traffic Camera	X	X	O	O	O	X
CDD				X		
CSR						
RSA	X		O	X		
PSM				X		
PVD	O	O		O	O	O
ICA			O			
TMC travel time and speed						
Crash Data					X	
Private Sector/Third Party Data - Travel Time and Incident (e.g., INRIX, Waze, HERE)	X	O	O		O	X
Private Sector/Third Party Data - Other (e.g., Dangerous Driving)	O	O	O	O		O
TMC Incident database	O	O	O	O		O
TMC RTMS						O
Bus GPS data						O
NY 511	X	X	O		X	O
Ped Detection (OBU)		O		O		
Real-time Work Zone Info (e.g., WZDx)	X	X	X	X	X	X

Table 18. Data Appropriateness to CD for ACV Use Case 3: Cooperative Intersection Management

(X: Essential or highly related; O: Maybe useful)

	3-1	**3-2**	**3-3**	**3-4**
	Conflict avoidance	**Signal Timing Optimization**	**Key corridor/grid area coordination**	**Illegal parking blocking turn lanes**
Ped Detection (RSU)			X	
BSM	X	X	X	X
MAP	X	X	X	
SPaT	X	X	X	
TIM				O
Traffic Camera			O	O
CDD				
CSR				O
RSA				
PSM				
PVD				
ICA	X	X		
TMC travel time and speed			X	O
Crash Data				
Private Sector/Third Party Data - Travel Time and Incident (e.g., INRIX, Waze, HERE)			O	X
Private Sector/Third Party Data - Other (e.g., Dangerous Driving)				O
TMC Incident database				X
TMC RTMS			X	
Bus GPS data			O	
NY 511				
Ped Detection (OBU)				
Real-time Work Zone Info (e.g., WZDx)				

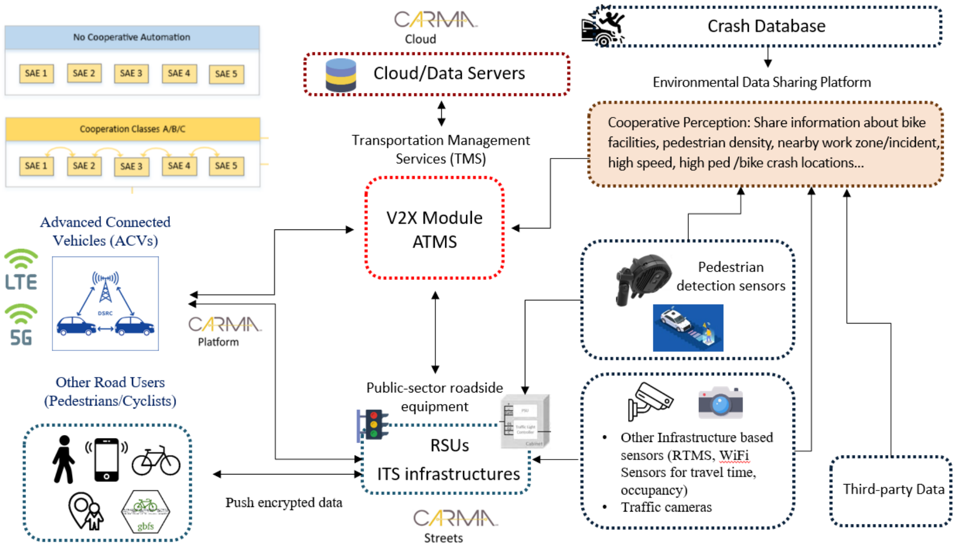
5 Recommendation of Future Needs and Challenges

5.1 Recommendations

5.1.1 CD for ACV Implementation Recommendations

Implementation of the proposed CD for ACV use cases can be piloted in three (3) ways: 1) software simulation, 2) limited real-world environment, or 3) a cyber-physical environment such as Hardware-in-the-loop (HIL) simulation. This section will provide recommendations for piloting/implementing selected use cases identified in Chapter 3.

For pedestrian/bike presence at the crosswalk (use case 1-1) and mid-block jaywalking (use case 1-2), FLIR and traffic cameras are suggested to be used together to improve real-time detection of pedestrians and bikes. Additional CCTV cameras may be installed at current FLIR locations. Installing additional on-board sensor and cameras for ACV can enable vehicle-to-pedestrian (V2P) communication and enhance pedestrian detection. Computer vision algorithms for pedestrian detection are already being developed and customized for NYC by NYU researchers (Zuo et al. 2021). However, integration of the camera detection with FLIR output into the current PEDINXWALK application or a new pedestrian in crosswalk/midblock application is needed to take advantage of this ongoing effort. Moreover, locations with high pedestrian activity and high ACV activities are recommended for piloting since the low market penetration rate of ACVs may result in no events. An example of the flowchart of a centralized CD for ACV application for pedestrian/bike presence is shown in Figure 31.



(Source: NYU C2SMART Center)

Figure 31: Example of a Centralized CD for ACV Application for Pedestrian/bike Presence Workflow

For school zone crossing (use case 1-5), FLIR and traffic cameras are suggested to be used together to enhance the detection of pedestrians. Additional FLIR/CCTV cameras may need to be installed at school zones (I2V). Installing additional on-board sensors and cameras for ACV can enable V2P communication. Current FLIR pedestrian detection and PEDINXWALK application can be directly adopted as part of this use case. New data fusion approaches will be needed if additional on-board sensors and cameras are used for school buses that can be equipped with an ASD. Integrating the computer vision algorithms with FLIR output is also needed if CCTV cameras are used.

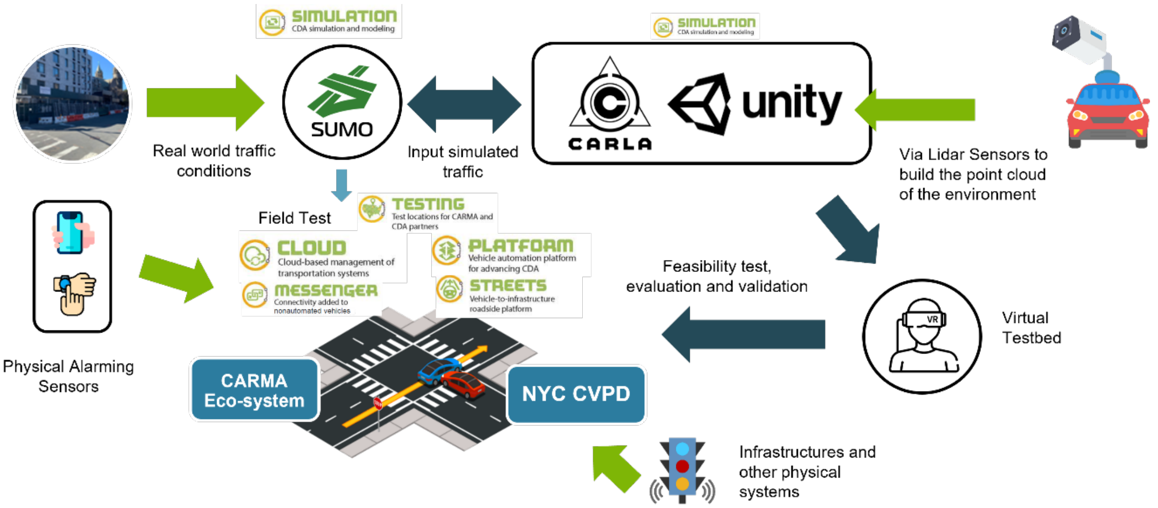
For cooperative work zone use cases, work zone information and presence (use case 2-1), work zone lane change, merge, and speed harmonizing (use case 2-3) and worker safety (use case 2-4), real time work zone data (not readily available) is needed. It is possible to build a real-time work zone database by fusing multiple existing data sources like NYCDOT TMC incident database, permit database, traffic cameras, third-party data or 511, ASD equipped ACVs and CDD/mobile phone apps (if used by workers). This also provides an opportunity to build real-time work zone data from NYC into WZDx specifications (USDOT 2021b). The WZDx program will work alongside CARMA Cloud to share work zone information with equipped vehicles. Computer vision algorithms for work zone detection is also needed in the context of this use case. Work zone lane changes, merging and speed harmonizing (use case 2-3) may require separate or bundled applications. Smartphone-based apps or intrusion alert system can be developed for the worker safety use case.

For cooperative intersection management use cases, both safety and mobility improvements should be considered the main objectives. Multiple data/messages such as BSM, FLIR (for vehicle detection), CCTV, SPaT, MAP, signal status message (SSM) may be used. Signal timing optimization (use case 3-2) and key corridor/grid area coordination (use case 3-3) can be tested as a possible addition to the existing MIM adaptive signal system or other CV pilot area (e.g., intersections among Flatbush Avenue), considering real-time pedestrian and vehicle flows. FLIR can be potentially configured to detect both the pedestrians and vehicles. To achieve the above goal, a new signal optimization algorithm will need to be developed. Key corridor/grid area coordination (use case 3-3) requires considering cooperative perception among vehicles in a network (rather than a single vehicle's communication range). A computer vision algorithm for illegal parking detection is already being developed by NYU researchers who are part of this research project, but it needs to be integrated into TIM/CSR/RSA messages.

For use cases that aim to provide risk indicators to increase general situational awareness (1-5 Night-time High-speed road link, 1-6 High ped/bike crash location, 1-7 High ped/bike density location, 2-5 High work zone crash location, and 2-6 High-activity and congested location), current traditional data sources and infrastructure can also be utilized. The level of computational demand on data fusion will be high for these applications in generating better speed estimation. Moreover, a computer vision algorithm may be needed for density estimation. This information can be converted into TIM messages to be sent to road users including drivers, pedestrians, and cyclists within the RSU communication range, or using other communication means for users that are outside the RSU communication range, to improve their situational awareness.

5.1.2 CD for ACV Co-Simulation Environment Development

Building a cooperative system by combining data from infrastructure-based sensors and in-vehicle devices in the context of improving traffic flow and time sensitive safety applications is a challenging task. It needs to ensure not only the accuracy of the information but also its reliability. Testing CD for ACV only in simulated environments or directly in real-world environments may not always be the ideal approach. Development of cyber-physical testbeds which combine both simulation and the real-world is recommended for better prototype testing and evaluation of novel CAV technologies before an actual full-scale real-world deployment. A cyber-physical testbed allows testing through a HIL set-up, which is a testing paradigm where physical sensors are connected to a virtual test system that simulates reality with high fidelity. A conceptual framework of adopting a co-simulation environment for CD for ACV is shown in Figure 32.



(Source: NYU C2SMART Center)

Figure 32: Conceptual Framework for a Co-Simulation Environment for CD for ACV

Once the developed solution is shown to work in this highly controlled environment, more realistic and larger scale real-world tests can be deployed. Most of the use cases described in this white paper in the context of NYC can be created and tested using this proposed co-simulation methodology. For example, a current C2SMART research project which combines SUMO based traffic simulation around work zones combined with a realistic virtual reality implementation (https://archive.c2smart.engineering.nyu.edu/increasing-work-zone-safety-wearable-sensors-virtual-reality) is being used to test high-tech solutions to warn work zone workers in the presence of intruders (Bernardes et al. 2021). An improved version of this environment can be easily deployed to mimic the conceptual framework proposed in Figure 31.

5.1.3 Utilization of Existing Data for Increased Situation Awareness

While CD for ACV will largely depend on real-time information exchange to achieve actions requiring agreement seeking or maneuvering recommendations, certain existing offline data can also potentially be used to increase situational awareness for class A cooperation, as defined by SAE (SAE International 2021). Knowing the current location of the road user and historical information (such as approaching a high crash intersection) can be a valuable risk indicator and raise awareness of road users.

5.2 Challenges

The concept of CD for ACV can be achieved by building on work being done by agencies, industry, and academia. New standards, ConOps, pilot tests, and implementation projects need to be developed in a coordinated manner. The challenges, requirements, and CD for ACV data and infrastructure needs are likely to change over time as new information and innovations come along. In the near term, testing and deploying CD for ACV may face the following challenges:

- Challenges related to data fusion and message redundancy

- Potential issues related to security, privacy and data trustworthiness

5.2.1 Challenges Related to Data fusion and Message Redundancy

Cooperative perception enables CAVs to exchange data between roadside equipment, in-vehicle sensors, and other mobile and infrastructural sensors to improve driver perception within the environment. This data rich approach can, in turn, generate excessive information in the form redundant messages that increase channel loads and can reduce the reliability of V2X communications, ultimately decreases the effectiveness of cooperative perception applications. Effectively fusing data obtained from different data sources and turning them into reliable and useful information that will benefit cooperative perception remains a challenge. However, this challenge also generates opportunities and new perspectives to develop novel algorithms for data fusion and control redundancy to avoid the generation and dissemination of unnecessary messages.

5.2.2 Potential Issues Related to Security, Privacy and Data Trustworthiness

V2X communication use by connected intelligent vehicles is also exposed to a risk from various malicious cyberattacks. In addition to the communication requirements of AVs, cooperative driving may demand a more frequent or higher rate of information exchange. Vehicles with CD features are vulnerable to security threats in terms of traffic safety and protection of sensitive private information, which may lead to very serious negative consequences. Moreover, the consequences of an attack on CAVs may extend far beyond impacting the vulnerable vehicle itself (Raj and Deka 2018). Thus, CD for ACV data needs to be transmitted and accessed securely. The obfuscation and encryption techniques of current cloud-based propriety solutions incur data losses that are deemed inefficient for accurate usage, particularly in time-sensitive real-time operations. To support accurate usage, raw data may need to be stored in a non-proprietary database (Khan et al. 2021).

Another issue is the data trustworthiness, especially for third-party data. For example, Waze alert data is mainly based on user-generated reports. Although Waze provides reliability and confidence scores based on other Waze users' reactions ('Thumbs up', 'Not there' etc.) and the level of the reporter (Wazers gain levels by contributing to the map, starting at level 1 and reaching up to level 6), it is not clear how these scores are calculated. Trustworthiness of user-generated data may be an issue in the future, creating challenges for sharing accurate information with other users.

To overcome these challenges, emerging technologies such as blockchain, which has been adopted recently as a promising solution towards the distributed storage of crowdsourced data, is recommended when designing the security, privacy and data trustworthiness for CD for ACV. Blockchain-based Distributed Ledger Technology (DLT) can cater the limitations of relying on a single point-of failure centralized cloud-based or otherwise access restricted databases for mobility data storage and retrieval (Khan et al. 2021). Blockchain can also be used as an authentication system for CD for ACV to ensure the integrity of exchanged data and target malicious users and malicious use.

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7 Acronyms

Table 20 below lists the references used for this report.

Table 20. Acronym List

Acronym/Abbreviation	Definition
3GPP	Third Generation Partnership Project
AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ACC	Adaptive Cruise Control
ACV	Advanced Connected Vehicle
AKTIV	Adaptive und Kooperative Technologien für den Intelligenten Verkehr (Adaptive and Cooperative Technologies for Intelligent Traffic)
AO	Agreement Officer
AOR	Agreement Officer Representative
API	Application Programming Interface
ASD	Aftermarket Safety Devices
ASTC	Advanced Solid-State Traffic Controller
ATC	Advanced Traffic Controller
AV	Automated Vehicle
BSM	Basic Safety Message
C-ADS	Cooperative Automated Driving System
C-ITS	Cooperative-Intelligent Transportation Systems
C-V2X	Cellular Vehicle-to-Everything
ConOps	Concept of Operations
CACC	Cooperative Adaptive Cruise Control
CADS	Cooperative Automated Driving System
CAM	Cooperative Awareness Message
CAN	Controller Area Network
CARLA	Car Learning to Act

CARMA	Cooperative Automation Research Mobility Applications
CAT	Cooperative Automated Transportation
CAV	Connected and Automated Vehicles
CCAM	Cooperative, Connected, and Automated Mobility
CCP	Connected Citizens Program
CCTV	Closed-Circuit Television
CD	Cooperative Driving
CDA	Cooperative Driving Automation
CDD	Connected Devices Data
CES	Consumer Electronics Show
CLF	Cooperative Lane Follow
CMV	Commercial Motor Vehicle
CP	Cooperative Perception
CPS	Collective Perception Service
CSR	Common Safety Request
CSV	Comma-Separated Values
CTM	Cooperative Traffic Management
CV	Connected Vehicle
CVIC	Cooperative Vehicle Intersection Control
CVPD	Connected Vehicle Pilot Deployment
DOT	Department of Transportation
DRAC	Deceleration Rate to Avoid Collision
DSRC	Dedicated Short Range Communications
DSS	Dynamic Spectrum Sharing
EC	European Commission
EPC	Evolved Packet Core
ETH	Ethernet
ETL	Extract, Transform, Load
ETSI	European Telecommunications Standards Institute
EU	European Union
EUR	Euro
FCC	Federal Communications Commission

FHWA	Federal Highway Administration
FN	False Negative
FNR	False Negative Rate
FP	False Positive
GBFS	General Bikeshare Feed Specification
GPS	Global Positioning System
GTFS	General Transit Feed Specification
GTFS-RT	General Transit Feed Specification Realtime
HIL	Hardware-in-the-Loop
HMI	Human Machine Interface
I/O	Input-Output
I2V	Infrastructure-to-Vehicle
ICA	Intersection Collision Avoidance
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ITS	Intelligent Transportation System
ITS-IV	Intelligent Transportation System - Intelligent Vehicles
ITSA	Intelligent Transportation Society of America
JSON	JavaScript Object Notation
LBS	Location-Based Services
LED	Light-Emitting Diode
LFC	Line Frequency Clock
LiDAR	Light Detection and Ranging
LIRR	Long Island Railroad
LTE	Long-Term Evolution
MEC	Multi-Access Edge Computing
MIM	Midtown-In-Motion
MSA	Metropolitan Statistical Areas
MTA	Metropolitan Transportation Authority
NFC	Near-Field Communication
NHTSA	National Highway Traffic Safety Administration
NoSQL	Not Only Structured Query Language

NPMRDS	National Performance Management Research Data Set
NSA	Non-Standalone
NSF	National Science Foundation
NYC	New York City
NYCDOT	New York City Department of Transportation
NYCT	New York City Transit
NYPD	New York Police Department
NYS	New York State
NYSDOT	New York State Department of Transportation
NYU	New York University
OBU	Onboard Unit
OCMC	Office of Construction Mitigation and Coordination
OD	Origin-Destination
OEM	Original Equipment Manufacturer
OS	Open Source
OSS	Open Source Software
P2I	Pedestrian-to-Infrastructure
P2V	Pedestrian-to-Vehicle
PANYNJ	Port Authority of New York and New Jersey
PASS	Pedestrians for Accessible and Safe Streets
PATH	Partners for Advanced Transportation Technology
PED	Pedestrian
PEDINXWALK	Pedestrian in Signalized Intersection
PET	Post-Encroachment Time
PID	Pedestrian Information Device
PoC	Proof of Concept
PSM	Personal Safety Message
PSU	Power Supply Unit
PVD	Probe Vehicle Data
RSA	Roadside Alert
RSU	Roadside Unit
RTC	Regional Transportation Commission of Southern Nevada

RTMS	Remote Traffic Microwave Sensor Data
RWTH	Rheinisch Westfälische Technische Hochschule
SAE	Society of Automotive Engineers
SCMS	Security Credential Management System
SIRI	Service Interface for Real Time Information
SNMP	Simple Network Management Protocol
SPaT	Signal Phase and Timing
SPDCOMP	Speed Compliance
SSM	Signal Status Message
SSV	Slow or Stationary Vehicle
SVM	Support Vector Machine
SUMO	Simulation of Urban Mobility
TCP/IP	Transmission Control Protocol/Internet Protocol
THEA	Tampa-Hillsborough Expressway Authority
TIM	Traveler Information Message
TIMS	Traffic Information Management System
TLC	Taxi & Limousine Commission
TMC	Traffic Management Center
TN	True Negative
TSMO	Transportation Systems Management and Operations
TSP	Technology Service Provider
TP	True Positive
TPR	True Positive Rate
TTC	Time to Collision
TTC	Time to Collision with Disturbance
V2I	Vehicle-to-Infrastructure
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VDOT	Virginia Department of Transportation
VII	Vehicle Infrastructure Integration
VMT	Vehicle Miles Traveled

VRU	Vulnerable Road User
VSGN	Vehicle Signage
WLAN	Wireless Local Area Network
WZDx	Work Zone Data Exchange
UC	University of California
US	United States
USDOT	United States Department of Transportation
UWB	Ultra-Wide Band
YCR	Yielding Compliance Rate

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