Interoperable Internet of Things for Smart Transportation Systems in Circular Cities

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This article discusses recent developments in the area of interoperable Internet of Things, using an example of delivering data-driven transportation services. Initial results obtained by exploiting heterogeneous traffic data streams reveal interesting traffic patterns for different vehicle types.

Population growth in urban areas is adding ever-increasing pressure on already inadequate transportation infrastructure. Governments and city authorities are looking for ways to develop sustainable transport systems. The availability of real-time and open data stemming from various Internet of Things (IoT) devices offers the possibility to improve the performance of intelligent transportation systems (ITSs). Efforts in the research community and industry have led to the developing of several IoT architectures, platforms, and applications. Researchers are exploring ways to integrate the IoT and ITSs in which ITS applications can use IoT data streams to extract meaningful information to enhance mobility management within cities.[1] However, despite extensive research in this domain,[2] mobility-related problems (for example, traffic congestion, fuel efficiency, accidents and safety, and age-friendly mobility) have not been thoroughly addressed. The interoperation among various IoT systems is the next piece of the puzzle for underpinning sustainable solutions to these challenges.

An interoperable IoT facilitates the interconnection among IoT systems and provides information transparency that supports operators with sufficient information for decentralized decisions to achieve common

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objectives.[3] However, harnessing the interoperable IoT for smart transportation is still a challenging problem. The first challenge is to deal with the heterogeneity present at different layers in the IoT. The multitenant IoT devices in smart cities[4] have dissimilar sensing/actuating, processing, and communication capabilities. From a networking perspective, IoT systems use various networking protocols and communication mechanisms to couple their architectural modules. Then, the challenge is to consolidate the understanding of data and services provided by multifarious IoT systems. This can guarantee that the messages shared among different IoT systems do not misplace their actual meaning. It also enhances the interoperation among application services across other platforms and builds up an open IoT environment that can consume multiple heterogeneous data streams. Finally, the integration of legacy IoT devices adds further complications, particularly in the ITS domain, where legacy systems are often an essential part of the transportation infrastructure.

Interoperability in the IoT has been a topic of significance in academia, industry, and standards developing organizations (SDOs) for the past few years. Several SDOs, including IEEE, the Alliance for Internet of Things Innovation (AIOTI), International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T), Internet Engineering Task Force (IETF), World Wide Web Consortium (W3C), and European Telecommunications Standards Institute (ETSI), have been working on defining standards for various aspects of interoperability.[3, 5] The researchers in Palau[6] have proposed solutions typically based on conceptual layered architectures, where semantic interoperability plays an essential role. Several collaborative initiatives have led to the development of frameworks that support IoT interoperability. For example, INTERoperability of heterogeneous IoT platforms (INTER-IoT)[6] is a European Union-initiated project that provides interoperability among heterogeneous IoT platforms through an open cross-layer framework. Similarly, Virtualized programmable InTerfAces for innovative cost-effective IoT depLoyments in smart cities (VITAL-OS)[7] applies semantic interoperability for smart city IoT systems, which enables the agile development of cross-platform and cross-context IoT applications. SemIoTic[8] is a platform that provides users with a semantic domain-relevant view of IoT smart spaces. These initiatives offer promising features to support the development of interoperable IoT applications. Nevertheless, widespread adoption of best practices across domains is still lacking.

This article first discusses the recent developments in the area of the interoperable IoT. Thereafter, a smart traffic use case is presented to deliver data-driven transportation services. Delivering these cross-platform and cross-context data-driven services requires the interoperation of heterogeneous IoT devices and legacy systems deployed by transportation authorities. The main contributions of this article are as follows:

1. detailing the integration and development process to deliver interoperable IoT services for ITSs to overcome the challenges faced by isolated traffic monitoring systems

THE AVAILABILITY OF REAL-TIME AND OPEN DATA STEMMING FROM VARIOUS INTERNET OF THINGS DEVICES OFFERS THE POSSIBILITY TO IMPROVE THE PERFORMANCE OF INTELLIGENT TRANSPORTATION SYSTEMS.

2. designing and implementing ITS services [for instance, origin–destination (OD) estimation, travel time prediction, incident detection, and fault prediction of sensing devices] exploiting the integrated traffic data streams
3. adopting the VITAL-OS platform to materialize semantic interoperability among traffic monitoring systems
4. presenting initial results obtained by exploiting heterogeneous real-world raw data from traffic systems deployed by Transport Infrastructure Ireland (TII).

The remainder of this article is organized as follows. The next section reviews interoperability efforts made by SDOs, academia, and industry. The "Interoperable IoT: The Smart Traffic Scenario" section first introduces our smart traffic use case and its real-world traffic data sources. Then, it describes the data integration and storage stage, followed by defining the ITS smart city services. Next, the initial results acquired from the use case are presented. The final section concludes the article while outlining future research directions.

IoT SYSTEMS MUST BE ABLE TO EXCHANGE MESSAGES WITH OTHER IoT AND GENERAL SYSTEMS THROUGH VARIOUS NETWORKING TECHNOLOGIES TO REALIZE NETWORK-LEVEL INTEROPERABILITY.

CLASSIFICATION OF INTEROPERABLE IoT

Interoperability in the IoT can be defined as the capability and capacity of a wide range of IoT components to communicate, share, and process data effectively to achieve the expected target outcome. This section reviews recent works in the interoperable IoT by grouping them into standardization-, level-, and semantic-based interoperability approaches. Then, it surveys some of the interoperable IoT projects.

Interoperability standards for IoT

Interoperability can be realized by devising standards. SDOs such as IEEE, the IETF, AIOTI, the ITU-T, the W3C, ETSI, and the Open Mobile Alliance (OMA) are engaged in standardizing interoperability approaches for the IoT and machine to machine (M2M) technology. Generally, the IETF focuses on protocols, such as the Constrained Application Protocol and OMA works on Lightweight M2M.[5] The W3C has developed the Web of Things architecture to support semantic interoperability.[9] ETSI is working on the oneM2M[10] initiative and developed the standardized IoT ontology. The oneM2M project provides middleware interoperability solutions between M2M and the IoT, ignoring the underlying heterogeneity aspects of networks, communications, and devices. A recent IEEE standardization effort provisions an IoT architectural framework standard that promotes cross-domain interaction and aids system interoperability.[11] AIOTI (initiated by the European Commission) promotes interoperability and convergence among existing standards and new standardization activities.[5] These interoperability standards are used to address the heterogeneity in the IoT at different levels.

Level-based interoperability

IoT interoperability efforts and standards provide interoperability from different perspectives, such as among IoT devices, networks, and platforms at the data exchange level, mainly achieved via semantic interoperability.

Device-level interoperability. Device-level interoperability enables communication among heterogeneous devices, as the devices have different resources/capabilities (for example, processing, memory, and sensing/actuating), use different operating systems, and are manufactured by different vendors. Device interoperability should support 1) end-to-end seamless data transmission without changing the actual message and data type, 2) the ability to integrate new devices into any IoT platform, and 3) legacy devices. Valero et al.[12] use a set of IoT agents to map standard protocols to address some of these challenges. Device-level interoperability aims to facilitate managing and controlling heterogeneous IoT devices. Some studies recommend a device manager or proxy converter (for example, an intelligent gateway) to control all the network devices.[3] The researchers in Khazael et al.[4] propose a publish–subscribe architecture enhanced by a software-defined network controller to address the coupling between IoT systems and devices.

Network-level interoperability. Network-level interoperability manages the mechanisms to exchange information seamlessly and effectively between (sub)systems through different networks for successful end-to-end wired/wireless communications. Network-level interoperability is challenging because the devices can be heterogeneous in vendors and support dissimilar communication protocols, including Wi-Fi, 3G/4G/5G cellular, low-power wide area network (WAN), long-range WAN, and narrow-band IoT. IoT systems must be able to exchange messages with other IoT and general systems through various networking technologies to realize network-level interoperability. Due to IoT networks' dynamic and heterogeneous nature, this interoperability must handle naming, addressing, routing, resource allocation, energy efficiency, security, quality of service, and mobility issues.[3, 13]

Platform-level interoperability. An IoT platform layer is an intelligent connecting layer that combines the hardware, things, protocols, and applications under one umbrella to empower the services community. In some cases, IoT platforms are also referred to as *middleware solutions* that control data management and visualization. IoT architectures are built on heterogeneous platforms, for example, Cisco IOx, IoT Framework, OpenIoT, ThingSpeak, OneM2M, OpenStack++, Microsoft Azure, Google Cloud, IBM Watson IoT, and Amazon IoT. Platform interoperability aims to enable adaptability, usability, and productivity to facilitate the integration of heterogeneous IoT devices.[3]

Semantic interoperability

Semantic interoperability is the ability to enable different IoT systems, services, and applications to exchange information, data, and knowledge as well as interpret communication interfaces.[14] The meaning and the context of the exchanged data are vital to achieving semantic interoperability. One solution is to use common vocabulary, knowledge, and mapping information that can be exchanged by different applications, services, and devices and that can be represented and integrated by an ontology. In Hazra et al.,[3] the authors clearly stated that even the vertical domain standards had not achieved full interoperability within the domains. Generally, a domain-specific data model is elaborated using JavaScript Object Notation (JSON)-like data structure notations or Web Ontology Language ontology descriptions. Whereas horizontal domains (cross domains) come with different vocabularies and data, the interoperability of various data models becomes a significant problem when the scale of complexity and subsystems increases. Most of the existing real-world application domains use heterogeneous ways to obtain data and/or services from underlying diverse IoT systems that are vertically oriented, mostly closed, and isolated. For semantic interoperability, applications/systems may require the development of any particular domain-specific data models (semantic descriptions).

For example, for the health care-based IoT, interoperability is required for different clinicians, labs, hospitals, and pharmacies to share, use, process, and interpret data, irrespective of sources and vendors. One example of an interoperable system in this domain is ACTivating InoVative IoT smart living environments for AGEing well (ACTIVAGE) IoT Ecosystem Suite,[12] which supports the creation, exchange, and adoption of cross-platform big data services for active and healthy aging. A dataspaces model is proposed in Yus et al.[8] that provides semantic interoperability by utilizing the attention mechanism and pretrained vectors to convert IoT entities into low-dimensional dense vectors for further semantic computation. The manufacturing industry is gaining attention for interoperability as it progresses beyond Industry 4.0. This requires flexible production lines, automated fault detection, and tolerance across systems with the lowest integration costs.[3] Smart and circular cities are under pressure to support a wide range of sustainable services, such as transportation, logistics, buildings, utilities (that is, electricity, sewer, water, and waste management), and more. Such cities need to exchange information across independent systems and correlate operations and information across various city services.[15] The work in Huang et al.[16] introduces an approach to effectively support integrating interdataset queries between IoT resources and open standard-based city models for smart city applications.

Interoperable IoT projects

In the recent past, several collaborative projects have led to the development of interoperable frameworks, highlighting the pressing need for interoperability in the IoT to allow smart cities to share data across devices and systems and coordinate processes across domains to improve sustainability and optimize available resources. For example, BIoTope[15] aims to build an open ecosystem to create ad hoc and loosely coupled information flows in a smart city context. Pilots include electric vehicle charging-related, smart watering-related, and safety of pupils-related use cases. It uses open communication and data standards to realize semantic interoperability. The INTER-IoT[6] platform enables multilayer interoperability (that is, device, networking, middleware, application service, data, and semantics) among IoT systems. It establishes semantic interoperability by developing a generic ontology of IoT platforms. Similarly, VITAL-OS[7] takes a system-of-systems approach to address the challenge of heterogeneity. It offers value-added tools to allow developers to implement new services on top of integrated IoT systems while allowing management of the underlying systems.

Future Internet Core Platform (FIWARE)[17] is a generic platform to facilitate interoperability in city services. It will enable smart city application providers to access real-time information from various underlying IoT systems. The Synchronicity[18] project aims at establishing a reference architecture for bringing an IoT-enabled smart city marketplace with interoperable interfaces and data models for different IoT applications. SemIoTic[8] is a platform that provides users with a semantic domain-relevant view of IoT smart spaces. SemIoTic supports wrappers for IoT devices, consisting of a common interface to communicate with them and device/manufacturer/model-specific code encapsulating the low-level interaction. HayStack is an industry-driven initiative that offers semantic interoperability[19] among building automation systems. This standardizes semantic data models for building equipment, such as lighting; energy; heating, ventilation, and air conditioning; and other building systems. The project provides specifications for application programming interface (API) and serialization formats for data exchange.

The availability of interoperable platforms enables application developers to access a more comprehensive range of IoT data streams and handle heterogeneity at different levels, thereby increasing the scope of potential smart city applications. The integration of IoT systems has a great vision, and several benefits could emerge from the convergence of IoT systems. Consequently, we envisage that integrating data streams from multiple traffic monitoring systems can significantly enhance the spectrum of smart traffic services offered.[5] In the following section, we discuss the smart traffic use case, which demonstrates a unique value proposition concerning the integration, convergence, and interoperability of diverse data streams stemming from traffic monitoring systems.

[THE INTEGRATION OF IoT SYSTEMS HAS A GREAT VISION, AND SEVERAL BENEFITS COULD EMERGE FROM THE CONVERGENCE OF IoT SYSTEMS.]

INTEROPERABLE IoT: THE SMART TRAFFIC SCENARIO

TII is responsible for the transportation infrastructure across Ireland. TII needs to ensure that Ireland's national road network is safe, sustainable, and resilient, facilitating better accessibility and mobility for people and goods. To target these goals, TII has deployed hundreds of different types of traffic monitoring systems under the umbrella of ITSs, including traffic measurement and observation systems (for example, traffic cameras, weather stations, radar-based detectors, and journey time systems) and traffic information systems [such as variable message signs (VMSs) and web and mobile traffic apps] and similar systems. These systems currently operate in isolation, and the acquired data streams are not integrated at any level.

To unearth the potential, a convergence of these traffic systems is needed, which should not be confined to technical integration but extend to data and contextual levels. We use the VITAL-OS platform, which enables semantic interoperability among IoT systems to manage, analyze, and develop smart traffic services on top of multifarious data streams stemming from these fragmented traffic monitoring systems to provide key traffic insights on historical and real-time traffic conditions. VITAL-OS is chosen for the following main reasons:

1. The platform facilitates the development of interoperable (cross-platform and cross-context) IoT applications, particularly aimed at smart/circular cities.
2. In addition to the management and governance of IoT systems, VITAL-OS provides several added-value tools for data discovery, filtering, complex event processing, and service orchestration that can be used to discover, filter, and create events (for example, a sudden decrease in road traffic to detect congestion/incidents) on interoperable IoT data streams.
3. The platform's data model already includes transportation-related ontologies. Therefore, it does not require

any major modification or extension of the existing data model for implementing the smart traffic use case presented in this work.[7] As a result, this approach promotes interoperability through ontology reuse instead of adopting a subjective and case-based ontology (data model) engineering approach.

Utilizing the integrated traffic data streams, the VITAL-OS-powered smart traffic system focuses on providing cross-context data-driven services, such as OD estimation, travel time prediction, incident detection, and the fault prediction of sensing devices.

Data sources

Using VITAL-OS, we integrate the data (and services) from the following systems:

- *Tolling plazas*: Anonymized electronic tolling data from 12 toll booths across Ireland (highlighted in Figure 1) are made available by TII to help understand road network usage and identify interesting traffic flow patterns.
- *Traffic counters*: TII operates and maintains a network of traffic counters on the motorway and national primary and secondary road networks in Ireland. Each counter device captures information about the vehicle type, temperature of the road surface, vehicle speed, lane ID in which a movement was recorded, and other relevant parameters.
- *Weigh in motion*: Weigh-in-motion (WIM) devices are designed to capture and record axle and gross vehicle weights as vehicles drive over a measurement site. Unlike static scales, WIM systems can measure vehicles traveling at reduced and normal traffic speed and do not require vehicles to come to a stop. The WIM dataset contains per-vehicle records capturing the weight, number of axles, and axle loads recorded by WIM sensors.
- *Weather stations*: TII's national network of 80+ weather stations can acquire real-time weather-related data. It includes the air temperature, precipitation, wind speed and direction, and road surface temperature. The weather data are updated at 5-min intervals.
- *Journey times*: TII has deployed a journey time management system (JTMS) in the Greater Dublin area, which provides real-time travel time predictions using automatic number plate recognition cameras. These predicted travel times are then displayed on roadside VMSs for travelers.
- *Automatic vehicle locator*: The automatic vehicle locator system is used to obtain real-time locations of vehicles (for example, buses, trains, and trams), which are then fed to

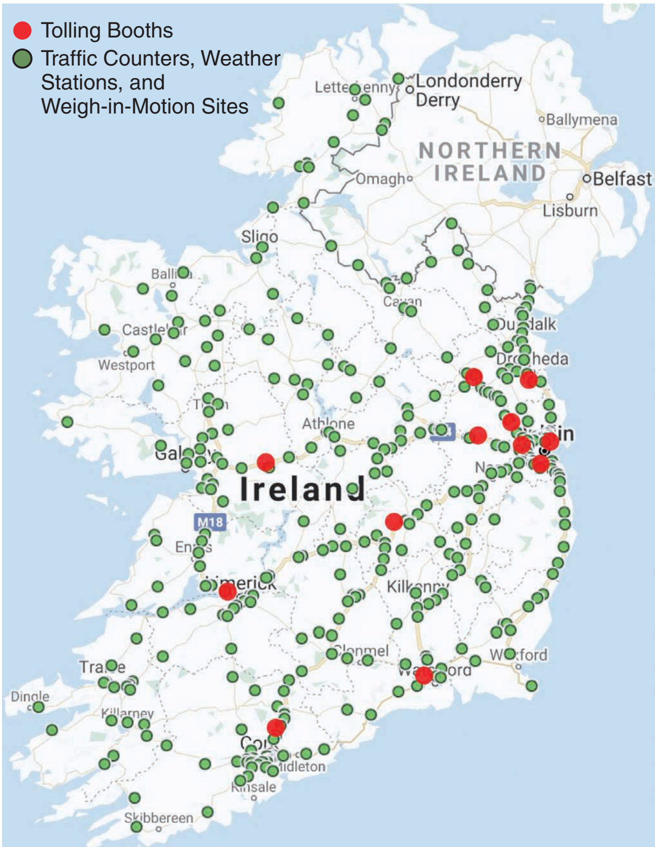

FIGURE 1. TII's deployment of ITS and traffic monitoring systems across the Irish road network. (Source: https://data.tii.ie.)

passenger information systems (stop displays, web portals, and mobile apps).

Data integration and storage

Data from traffic monitoring systems are collected by TII in their original raw form as supported by the manufacturers. These isolated traffic data streams are highly irregular (noisy) and have strong heterogeneous properties, such as their format, structure, temporal frequency, and so on. For example, when processing the tolling data coming from different toll operators, we identified that most of the operators had their own software stack to manage and store the data, resulting in different formats and structures. Similarly, data from traffic counters come at high frequency during peak hours compared to tolling plazas. Furthermore, a malfunctioning monitoring system also leads to data loss and incomplete data transmitted to computational processes. For example, the traffic counters across Ireland could not transmit any data for a few weeks in June and July 2019, due to the failure of the transmission system. Fusing heterogeneous data can uncover important insights, but it is challenging due to heterogeneities that exist within systems. Likewise, for TII, ITS applications must derive actionable information from multiple data streams to improve overall mobility management and make traffic information accessible in an interoperable way for drivers, citizens, and third parties (for example, researchers and developers). We now demonstrate how VITAL-OS enables the platform-agnostic integration of multiple IoT data streams while providing tools to build applications that can exploit underlying data and services.

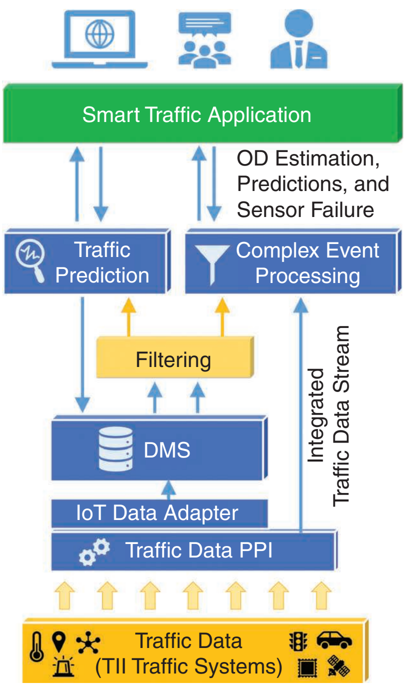

FIGURE 2. The integration and development process model. DMS: Data Management System; PPI: Platform Provider Interface.

Figure 2 provides a high-level overview of the integration and development process. First, integrating TII's traffic systems requires data items and properties to be defined in the VITAL-OS data model relevant to smart traffic systems. VITAL-OS adopts W3C switched service network-compliant semantics to ensure interoperability across diverse IoT streams. VITAL-OS also models transport infrastructure by using a combination of ontologies. The core of these is the ontology of transportation networks.[20] This ontology allows the easy modeling of a transport network graph with connections between infrastructure, such as bus and train stations, as well as events, such as accidents and blocked passages. To model the smart traffic management system, VITAL-OS describes a class *SmartTrafficSystem*, a sub-class of *IoTSystem*. Several additional classes are defined in the existing data model to integrate TII's traffic data. VITAL-OS's data model is not restricted to smart transport scenarios. Users who want to use VITAL-OS for other smart city applications can do so by specifying additional ontology elements. Due to the nature of linked data, these additional elements can be added at any time without redesigning the system. Once all the required entities in the data model are described, the next step is to link TII's data sources to the VITAL-OS platform.

VITAL-OS has published a set of specifications called the Platform Provider Interface (PPI), which defines the interface between VITAL-OS and third-party IoT systems to allow heterogeneous IoT systems to be connected. In its simplest form, the PPI uses popular web standards [for example, Representational State Transfer (REST) and JSON for Linking Data] and is defined as a set of RESTful web services marked as either mandatory or optional. A new implementation of PPIs for TII's traffic systems is carried out to integrate (and map the data of) the traffic systems into VITAL-OS. From a data perspective (when implementing the PPIs), two key requirements must be fulfilled:

1. VITAL-OS must be allowed to periodically pull the updated data via PPIs from the data sources listed in the preceding and convert the information into its own unified data model for storage.
2. VITAL-OS must enable interfaces to allow access to stored traffic data and enable mechanisms to manage the metadata of these systems.

The traffic system's PPI is then registered with VITAL-OS, and the traffic data are stored in the platform's data store, Data Management System, for historical storage and offline processing. By exploiting the integrated data and the added-value functionalities offered by VITAL-OS, smart data-driven traffic services are developed, which are discussed in the following.

Smart traffic services

OD estimation. The origin-destination (OD) demand matrix represents the number of trips from specific origins to specific destinations. Estimating an accurate OD demand matrix produces useful information that can be utilized in different traffic planning phases. Traditionally, surveys are conducted to estimate the OD demand matrix. However, this technique is expensive and inefficient. Hence, we utilize the integrated data collected from different traffic monitoring systems for OD demand matrix estimation.

Travel time prediction. Travel times currently displayed on roadside VMSs, although calculated in real time by the JTMS system, still have an inherent latency (as they are based only upon traffic having already made the journey) and do not consider prevailing and historical conditions, that is, weather, incidents, expected traffic peaks, and so on. The travel time prediction service takes the calculated (JTMS) travel time. It enhances this prediction in real time with data from TII and other sources, including historical journey time data, weather data, incident detection data, and so forth. The travel time prediction service employs data from traffic data sources in the VITAL-OS platform to predict travel times (using machine learning algorithms) for specific times throughout the day.

Incident detection. Traffic incident detection and its impact analysis are one of the major research areas in the ITS domain. Traffic incidents result in nonrecurrent congestion, and they must be dealt with promptly to reduce their effect on road capacity reduction and travel time loss. Incidents occur randomly and may last for different durations, and it is difficult to predict them because of their stochastic nature. However, their impact can be measured using datasets from ITS systems, enabling future incidents to be addressed effectively to reduce consequences and return road traffic to normal conditions. In this context, incidents' duration estimated from different data sources, for example, travel times, traffic counters, and loop detectors (used as part of the Automatic Incident Detection System on the M50 motorway), can reveal interesting and useful patterns. Among others, bad weather and road conditions are two key factors that heighten accident risks significantly. Patterns based on the correlation between incidents and weather and road conditions can be estimated using the data acquired by ITS traffic and road monitoring devices. And to help reduce traffic incidents, such information can be displayed on VMSs and shared with drivers through different means during bad weather conditions.

Fault prediction of devices. ITS systems have thousands of traffic monitoring devices that need to be repaired or replaced when they fail. Currently, a faulty device is identified when it fails by using the Asset and Fault Management System (AFMS) as well as manually. The AFMS provides an inventory of all ITS assets to manage and allows the identification of faulty devices. However, this process causes increased device downtime, as faults are identified only when they

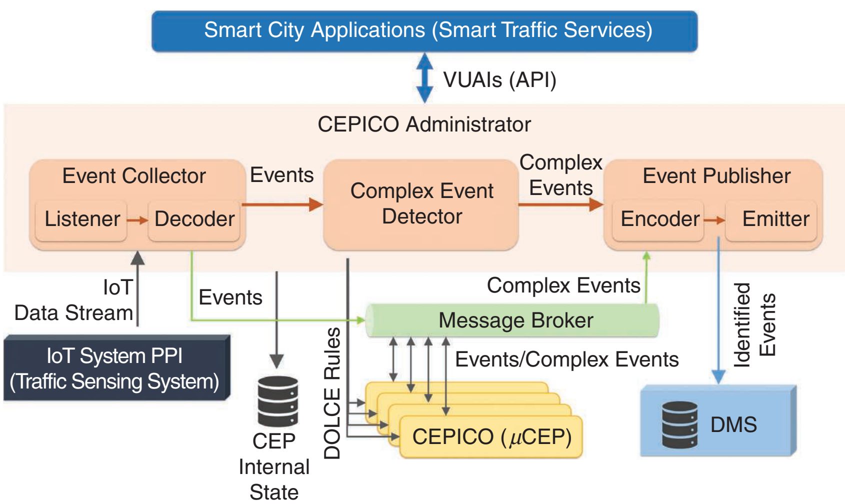

FIGURE 3. The architecture of the VITAL-OS CEP module used for the smart traffic system. µCEP: micro complex event processing; VUAI: virtualized unified access interface.

occur. There is a need for intelligent techniques to identify the system's malfunctions and eventual failures before they occur. A possible technique can use an event detection algorithm on the data stream stemming from a device to detect anomalies that could be caused when the device malfunctions. Another possible method could be to use datasets that give information about environmental conditions (such as weather data) in which the devices fail. This information, combined with other data, such as equipment age and increased usage, can be used to predict faults before they happen.

Initial results

VITAL-OS provides an instance of complex event processing for Internet-connected objects (CEPICO) used to directly analyze the traffic data collected from the smart traffic PPI. Figure 3 provides an architectural overview of the CEP module. CEPICO keeps track of sharp reductions in traffic speeds on different road segments by detecting events that match the specific conditions predefined for a possible traffic incident. CEPICO requests the input observations (traffic speed) from the traffic PPI every minute to collect the latest observations from traffic counters. The Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) rule is specified to trigger a complex event (for example, a traffic incident). The incident detection functionality of the smart traffic system warns traffic operators of any extraordinary situation and accident. Similar to incident detection, the device fault prediction service uses the CEPICO module of the VITAL-OS platform to detect anomalies within the traffic data streams.

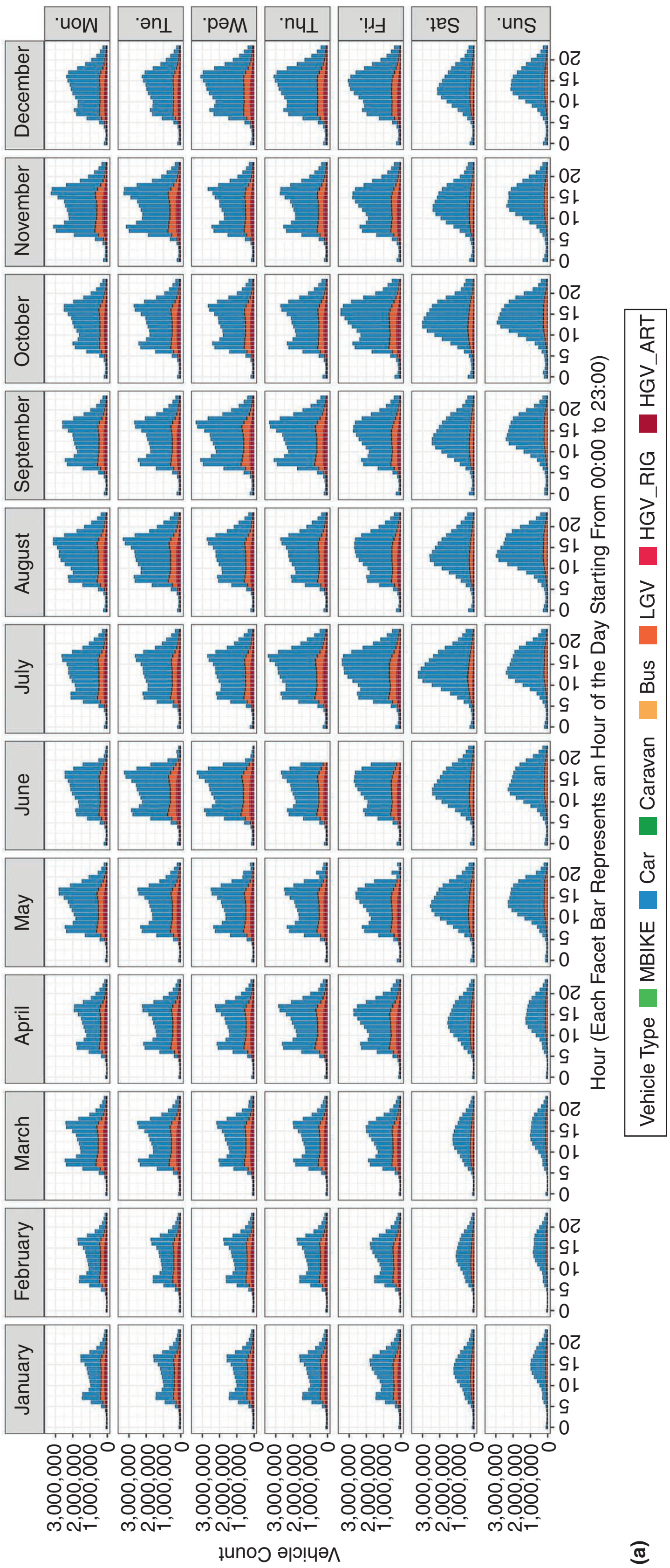

FIGURE 4. The smart traffic services built on top of interoperable traffic data streams. (a) The identified traffic patterns from interoperable traffic data streams (from tolling plazas and traffic counters). *(Continued.)*

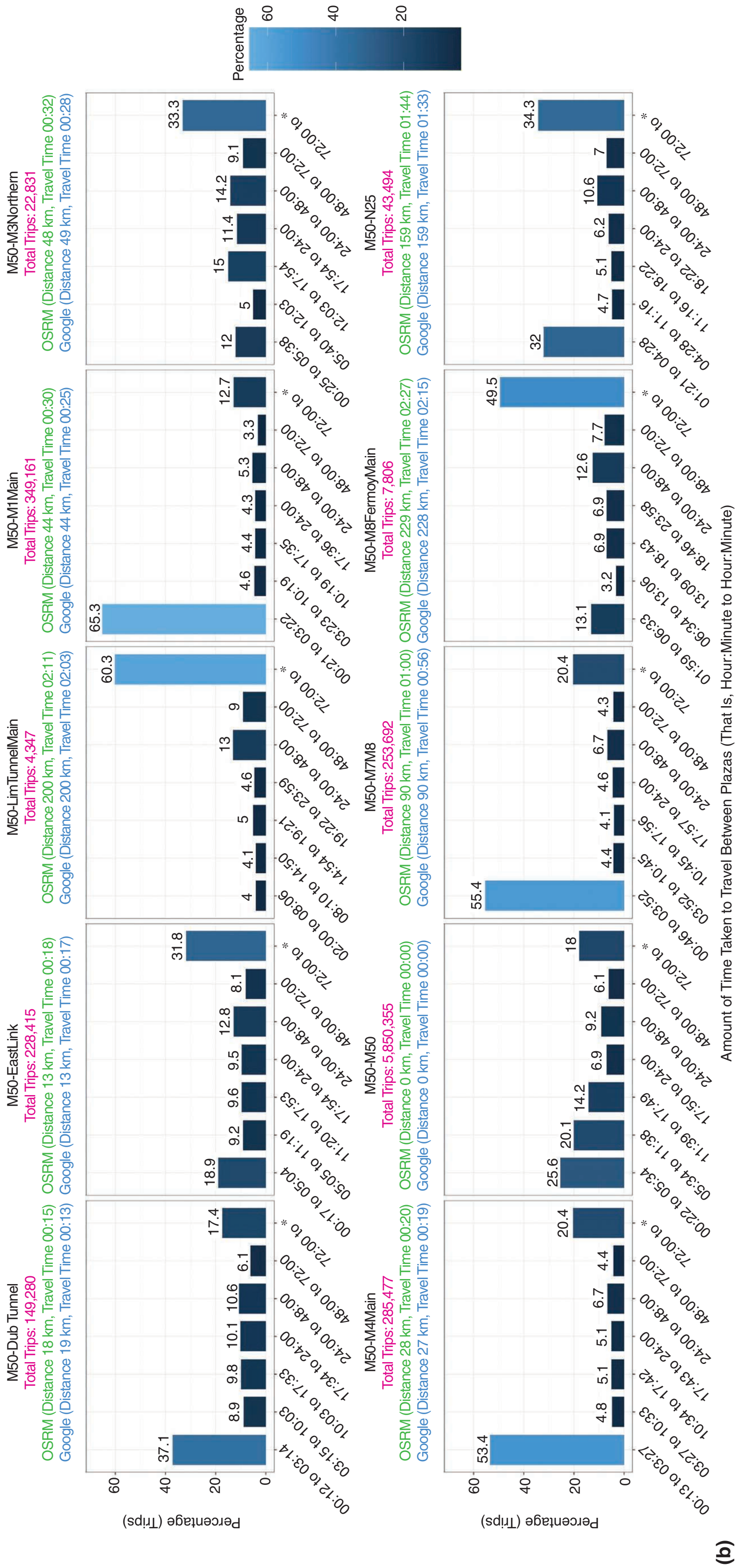

FIGURE 4. *(Continued.)* (b) The journey times estimated using the data from tolling plazas and traffic counters; the comparison is drawn against the Open Source Routing Machine (OSRM) and Google Maps API.

Figure 4(a) highlights interesting traffic patterns across different vehicle classes identified from the integrated tolling and traffic counter data streams for 2021. A significant drop in road traffic volumes in January and February is noted compared to other months, due to the government's imposition of level 5 (the highest) restrictions in Ireland to address the high infection rates of COVID-19. When looking at hourly patterns in each month, almost the same patterns are observed across working days. Weekends have different patterns when compared to working days. Working day morning (7–10 a.m.) and evening (4–7 p.m.) rush hours are caused mainly by motor car and van/large goods vehicle users. Weekend rush hours for motor car users are around noon. There is a significant decrease in the number of trips across tolling plazas on weekends. In particular, there is a sharp decrease in trips associated with goods vehicle classes. In this aspect, future work includes integrating port data to find a correlation among traffic flows on the road network and maritime traffic movement.

Travel times are computed for all vehicle classes with trips between all tolling plaza locations by using the *k*-means clustering algorithm, which is considered one of the most robust and widely used clustering algorithms due to its simplicity. Travel times were first estimated by vehicle types moving between tolling plazas and using the spot speed detected by traffic counters. After that, these travel times were clustered into groups using *k*-means. In this work, we tried different values for *k* and identified *k* = 7 as the best value, providing the lowest error when results were compared with travel times obtained via the Open Source Routing Machine

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(OSRM) and Google Maps API. In addition, travel times are acquired and integrated from the Google Maps API and OSRM for evaluation purposes [see Figure 4(b)]. This work is currently exploring the use of nonparametric models, for example, neural network and ensemble learning, for accurate real-time journey time predictions.

This article discussed the interoperability challenges faced by ITS applications and IoT systems in general. We discussed how different techniques, standards, and platforms propose solutions to the problem of heterogeneity by integrating multifarious systems and making data accessible in an interoperable manner. We then presented a VITAL-OS-powered smart traffic use case to aggregate, store, and process heterogeneous data streams to automate traffic-related operations and provide mobility management services. Initial results demonstrate the usefulness of the interoperable IoT that can further enhance traditional ITS applications. Future work will focus on integrating more traffic data streams to improve smart transportation services.

IoT solutions are expected to be delivered and managed seamlessly, supporting multiple vendors and services behind the scenes to support the sustainable global ecosystem. Derived from the current state of the art, a set of future directions in the domain of interoperable IoT for smart cities is summarized as follows:

- The versatility of data streams from real-time IoT data sources is distributed across a transportation system. Multifarious data streams should be converged to enable a comprehensive, meaningful, and useful view of the data for other relevant transportation services and utilities.
- Current semantic approaches, such as ontology alignment and matching, are created primarily for Internet resources. Instead, there is a need to create a general ontology to cater to various areas of smart cities to address common issues, including city administrative areas, modes of transportation objects, public events, and available services.
- As IoT technology continues to evolve, IoT systems require the development of extensible and flexible data models that enable efficient representation for incorporating future systems and applications.
- There are privacy- and security-related issues in sharing open data across various smart transportation systems while resolving scalability, infrastructure cost and complexity, and data redundancy due to the

exponential growth of connected objects producing big data. The SDOs must consider and publish security-related considerations in technical specifications to enhance secure IoT interoperability across systems. ◼

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