A Novel LoRaWAN-based Real-time Traffic Analysis Approach for Vehicle Congestion Estimation

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Abstract: In densely populated cities, severe vehicle congestion is an obstacle due to the massive increase of vehicles and bottleneck of roads. Traffic congestion brings severe economic and environmental hazards. Although it is hard to eliminate, it can be mitigated by finding the occurrence of the congestion well in advance to initiate appropriate control measures. Accurately estimating traffic speed, travel time, and other external factors is mandatory for forecasting congestion levels in a dynamic road network. In recent years, sensor-based traffic detection technologies have evolved to achieve accuracy and safety in intelligent transportation systems (ITS). However, some of them need more reliability, have weak usage in different visibility conditions, are hard to set, and have a high cost. Alternatively, modern navigation systems are developed to find the fastest, alternative routes, travel times, and congestion levels for a given source to destination. These systems use Global Positioning Systems (GPS) data to provide the routing information. Due to inaccurate/ inadequate GPS data samples, sometimes these systems may give misleading information. This work presents Long-Range Wide Area Network (LoRaWAN) architecture to overcome the abovementioned limitations. In our proposed case study, we have used the Dragino LoRaWAN GPS sensor (IN865), air quality sensor (MQ135), temperature and humidity sensor (SHT31), and other sensors to extract direct and indirect factors that influence traffic congestion. Haversine formula and hyper-heuristic-based Encoder-Decoder using Gated Recurrent Units with attention mechanism (ED-GRUAT) are used to estimate the segment-based distance, speed, vehicle travel times, and congestion levels. Our case study helps to calculate accurate traffic speed, travel times, and congestion levels.

Keywords: *LoRaWAN, GPS sensor, Speed, Travel time, Congestion.*

1 Introduction

Road networks consist of roads, and their interconnections allow users to select several travel routes between the source and destination. The structure of the road networks can be modeled as a grid, a sparse and dense graph. The vehicular road networks can be classified as static and dynamic. In a static network, edge weights and the topology never changes over time. In a dynamic network, edge weights and network structure changes over time according to the change in vehicle traffic. The last decade has witnessed severe traffic congestion on big city roads [1]. Traffic congestion is characterized by increased vehicular queuing, longer trip time, and slower speed. The root cause of the congestion is an increase in vehicle density due to massive growth in population, the bottleneck of roads, bad weather, Work zones, sudden incidents, and poor traffic signals. Traffic congestion influences the overall travel time increase and impacts losing destinations on time, frequent accidents, generates pollution, wasting time on roads, and waste of fuel. Traffic congestion brings severe economic and environmental hazards.

The Urban Mobility Report 2021 claims that the estimated cost/year for managing congestion in 494 U.S. Urban Areas is $101 billion, with travel delay of 4.3 billion hours, wasted fuel of 1.7 billion gallons, and CO2 emissions of 18 million tons. The 2019 urban mobility report estimated that congestion mitigation costs might rise to $237 billion, travel delays will increase to 10 billion hours, and 3.6 billion gallons of fuel will be wasted by 2025 [2]. The above statics shows a need for reliable and cost-effective solutions.

As a solution, real-time navigation systems [3] (e.g., Google, Apple, and TomTom maps) are developed to provide digital maps with the fastest route, travel time, traffic congestion level, and alternative routes. These navigating systems use Global Positioning Systems (GPS) data to represent traffic conditions and routing information. In these systems, collecting traffic flow data and describing accurate congestion levels from inadequate/inaccurate collected GPS data samples is challenging and may generate many misleading/looping paths [4]. Traffic flow data accurately can be collected using traffic measuring sensors (e.g., LIDAR, microwave radar sensors, loop detector systems) or video detection systems [5]. However, these conventional sensor-based systems face the issues of weak usage in different visibility conditions, hard to set, low coverage, and high cost. This poses a requirement for a large-scale, low-cost, ultra-low-power-consuming network.

LoRaWAN is a standardized and emerging technology for intelligent traffic flow control and management. Some amazing features make LoRaWAN unique and more potent for ITS than other technologies. It has ultra-low-power and low-cost end devices, large-scale network coverage, deep indoor penetration, firmware auto-updates over the air, end-to-end security, license-free spectrum, geolocation, and a larger ecosystem [6]. It also can deploy both public and private networks. Some of the LoRaWAN real-time use cases are the smart city, health, agriculture, metering (air quality, pollution, weather, gas, electricity, and water), natural disaster detection and prevention, supply chain logistics, asset tracking & quality management. In recent years, some reasonable use cases/ prototypes [8]-[15] have been created for intelligent traffic flow management and vehicle traffic clearance using LoRaWAN technology. However, these approaches need more scalability, reliability, and processing accelerators. This motivated us to propose a graphics processing unit (GPU)-based LoRaWAN network for collecting direct and indirect factors in order to estimate vehicle speed, travel times, and congestion levels accurately.

Hence, the followings are the key contributions of the proposal:

1. We are the first to propose a complete LoRaWAN network to capture the spatiotemporal characteristics of the road network and other external factors.

2. We have configured the GPS sensor (IN865), air quality sensor (MQ135), rain sensor, temperature, and humidity sensor (SHT31), and other sensors to the LoRaWAN network for extracting direct and indirect factors which influence the vehicle speed and travel times.

3. Using current and historical traffic information, a hyper-heuristic ED-GRUAT estimates the segment-based speed, travel times, and future congestion levels.

4. A case study was conducted on the LoRaWAN network using the Things Mate and Raspberry Pi4 all-in-one sensor platforms.

Further organization of our article is divided into sections. Section 1 discusses the existing LoRaWAN-based use cases and prototypes. Section 2 elaborates on our proposed LoRaWAN architecture. Section 3 demonstrates the performance analysis and comparison study of our proposal. Section 4 summarizes the conclusion and future research direction.

2 Literature Study

This section presents recent and most relevant literature findings and shortcomings. We discuss the works which applied the LoRaWAN use cases for vehicle traffic flow control and management.

Since road network traffic is dynamic with nonlinear spatiotemporal characteristics, various sensors, and edge Artificial Intelligence (AI) powered cameras are required to capture such features accurately. Recently, sensor-based traffic detection technologies have been developed to achieve accuracy and safety in intelligent transportation systems (ITS) [5]. These technologies use traffic flow sensors such as passive infrared, ultrasonic, LIDAR, magnetic and magnetometer, microwave radar sensors, video detection systems, loop detector systems, etc., for accurate traffic prediction and control. These sensors are used to measure the vehicle speed, count, location, direction, lane occupancy, passage, presence, environmental impact, etc. However, some of them need more reliability, have weak usage in different visibility conditions, are hard to set, and have a high cost. Alternatively, modern navigation systems [3] (e.g., Google, Apple, and TomTom maps) are developed based on GPS data to provide digital maps with the fastest route, travel time information, traffic congestion levels, and alternative routes. These GPS-based systems consume more power and high cost and sometimes need more accuracy. To overcome these problems, one of the promising and emerging technologies is the LoRaWAN network. So, it is a standardized technology used for large-scale, low-cost, ultra-low-power consuming networks that enables sensor nodes for a variety of data collection and exchange in traffic and transportation management systems with end-to-end security [7]. Some of the LoRaWAN-based use cases are early flood detection and warning systems [8], emergency rescue and evacuation [9], smart agriculture, smart cities, smart health, and many more [10]. Recently, it has been applied to intelligent traffic flow control [11]-[14] and vehicle traffic clearance [15]. SalahadinSeid et al. [12] proposed a novel LoRaWAN-based use case for road traffic monitoring. In this use case, Raspberry Pi is used for counting vehicles by capturing the traffic flow videos. A LoRaLoPy transceiver is used to transmit the vehicle count to the LoRaWAN network for traffic analysis. Asiain D et al. [11] developed a LoRaWAN-based network for vehicle speed detection. Ruhaizan F. A. et al. [13] presented a LoRaWAN-based smart traffic light prototype for signalized congestion control. This system uses a magnetic sensor (GY-271) with a SeeeduinoLoRaWAN W/GPS microcontroller to measure the congestion at signalized intersections. SeungByum S. et al. [14] designed a LoRa-based traffic management model to analyze density and travel time. Alokkumar R. et al. [15] demonstrated a traffic clearance prototype for emergency vehicles using a LoRaLoPy sensor device. However, the existing works presented above [11]-[15] need more scalability, reliability, and accurate prediction accelerators. Therefore, we are the first to configure a GPU-based LoRaWAN network with attention-based deep learning (ADL) accelerators to capture and learn appropriate direct and indirect traffic flow factors.

3 Proposed LoRaWAN Architecture

LoRaWAN networks typically consist of gateways that receive signals from end sensor devices and forward them to a central network server. The network server then processes the data and makes it available to application servers to perform analytics, generate reports, or trigger actions based on the data. Fig. 1 illustrates the LoRaWAN architecture we configured for traffic data collection. This systematic configuration captures spatiotemporal vehicle characteristics and other external factors such as weather and air quality parameters. In this architecture, at the bottom right is the DraginoLoRaWAN GPS sensor (IN865) end device we used with microcontroller STM32L072CXT6. It is configured and connected to the LoRaWAN gateways (DL058-EC25) using over-the-air activation. GPS sensor is a location tracker that sends timestamp, latitude, and longitudinal data over long distances to the LoRaWAN network.

GPS sensor also provides interference immunity to minimize battery consumption. GPS sensor consists of a low-power GPS module and a 9-axis accelerometer for detecting latitude and longitude information. GPS sensor is built on top

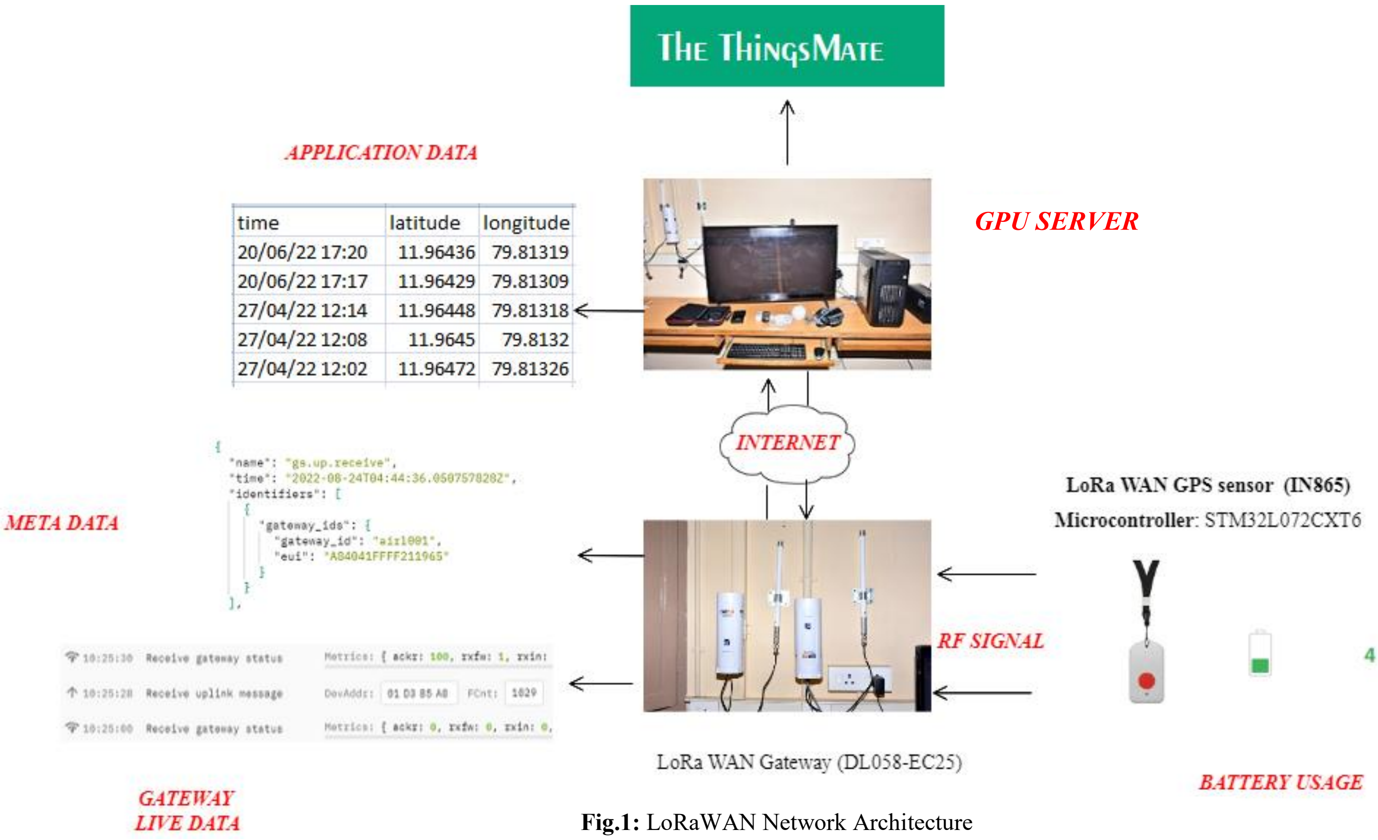

Fig.1: LoRaWAN Network Architecture

of STM32L072CXT6 microcontroller, which has various features like low power and low voltage design. A 1000mA Li-on Battery power powers the GPS sensor with a 2 x AA battery holder. The GPS sensor works on the following frequency bands: CN470, EU868, KR920, AU915, AU923, EU433, CN470, and IN865. The GPS sensor has a flash memory of 192KB, 20KB SRAM, 6KB EEPROM, and an operating temperature of -40 to 85^{o}. During data transmission, the sensor consumes 24 to 150 mA; during sleep mode, it consumes 77 mA, and for operating, it needs 3.5 mA. Some well-known applications are transport, logistics, supply chain, and human tracking.

The gateway receives RF packets that the GPS sensor sends and forwards the same to a network server through the internet. RF packet contains the timestamp, altitude, latitude, and longitude data. In Fig. 1, the gateway live data and metadata are illustrated at the bottom left. The network server identifies the sensor node and communication through security and network management parameters. After successful authentication, the end devices send data to the application server. The application server filters duplicate packets and perform the necessary error detection and correction mechanism. On the top left of Fig.1 is the GPS sensor application data. The security and network management parameters used are sensor ID, Name, DevEUI, JoinEUI, DevAddress, AppKey, and session information, depicted in Fig. 3 and Fig.4. Our LoRaWAN GPS sensor dashboard and session establishment information is presented in Fig. 2 and Fig. 3 respectively. DevAddress (Device address) is the unique address assigned to the sensor nodes. The end device's manufacturer sets the DevEUI. JoinEUI is awarded to the application server.

The main goal of the network session key (NwkSKey) is to prevent message tampering. Payload data encryption and decryption will be performed using the application session key (AppSKey). AppSKey and NwkSKey are unique throughout the session. SNwkSIntKey guarantees the integrity of data for both uplink and downlink. The uplink and downlink payload is encrypted and decrypted with NwkSEncKey. On the top in Fig.1 is the Things Mate platform [16] to manage all the LoRaWAN end devices, gateways, network servers, and applications through secure routing. Things Mate supports all kinds of LoRaWAN versions. In the Things Mate-based application dashboard, the user has a high degree of customization, like adding and removing widgets and other entities. It also provides data visualization features like bar charts, line charts, pie charts, etc. The sensor values are stored in a relational database, like rows and columns. In Fig.1, on the top left-hand, the application data is depicted in .csv and .xlsx formats for traffic analysis purposes.

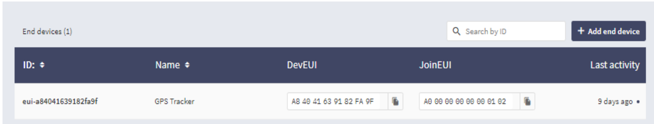

Fig.2. LoRaWAN GPS Sensor Dashboard

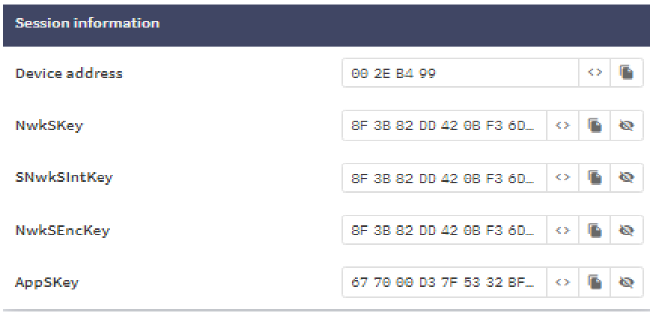

Fig.3. GPS Sensor Session Keys Information

Case Study: In a real-time road environment, vehicle speed significantly depends on spatiotemporal characteristics, road geometry, and weather and air quality parameters. Timely and accurately capturing these parameters is a challenging task. In this case study, we capture vehicle GPS positions, weather, and air quality factors using the LoRaWAN network and Raspberry Pi platform.

Table I: GPS Sensor timestamps, latitude, longitude, and location

Timestamp	Latitude	Longitude	Location
07/02/23 17:25:35	11.9652	79.8148	Pondicherry Airport
07/02/23 17:29:01	11.9549	79.8188	Airport Rd, Lawspet
07/02/23 17:31:40	11.9544	79.8181	Lawspet main Rd
07/02/23 17:33:16	11.9523	79.8184	Krishna Nagar Rd
07/02/23 17:36:19	11.94846	79.8132	Latha Steel
07/02/23 17:39:46	11.94367	79.8087	Kokku Park
07/02/23 17:47:33	11.94172	79.8074	Amutha coffee shop
07/02/23 17:49:49	11.94326	79.8042	Don Bosco Hostel
07/02/23 17:51:55	11.94640	79.7988	Iyyanar Koil St
07/02/23 17:53:05	11.94813	79.80198	K.V.No.1, JIPMER

Table I lists the timestamps, latitudes, longitudes, and locations obtained using a GPS sensor for a route from Pondicherry Airport to K.V.No.01, JIPMER. Fig.4 presents the corresponding PoI icons visualized in Google Maps. For this route, as listed in Table II, we computed segment-based speed and travelled time using a hyper-heuristic-based encoder-decoder using gated recurrent units with an attention mechanism. Haversine-formula [17] is used to calculate the distance between PoI road segments. The latitudes and longitudes plotted in Fig. 5 and Fig. 6 are the point of interest (PoI) visited by the car for February 07, 2023, and February 08, 2023, up to noon. The estimated vehicle speed is illustrated in Fig. 7.

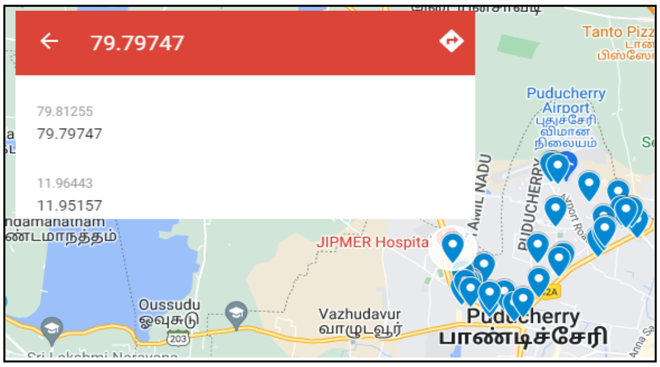

Fig.4. GPS Sensor Tracked Locations

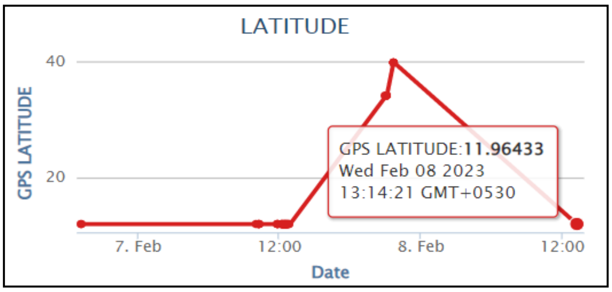

Fig.5. GPS Sensor Latitude Information

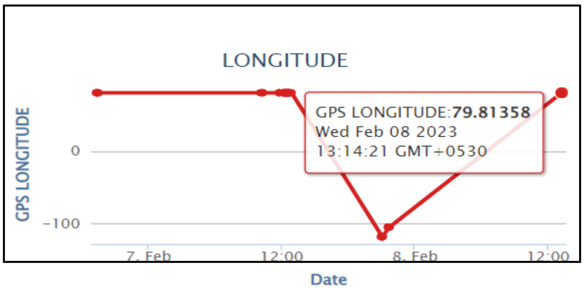

Fig.6. GPS Sensor Longitude Information

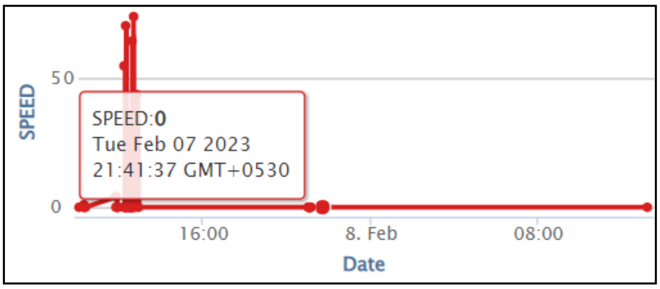

Fig.7. Vehicle Speed Information

Table II: Road Segments Distance, Speed and Travel Time

Road Segment	Distance	Speed	Travel Time (min.)
S_1	1.22518	26.4109	03.26
S_2	0.0942849	2.134752	0239
S_3	0.235779	8.84171	01.36
S_4	0.708742	13.94247	03.03
S_5	0.723421	12.58123	03.27
S_6	0.258875	1.99561	07.47
S_7	0.387959	10.2695	02.16
S_8	0.683378	19.5251	02.06
S_9	0.395828	20.35687	01.10

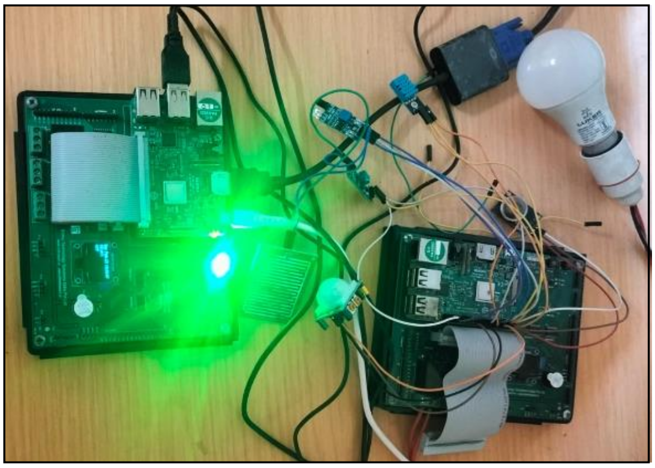

Fig.8. ETS-IoT Raspberry Pi with External Sensors

As shown in Fig. 8, we used the ETS-IoT Raspberry Pi4 platform with External Sensors (MQ135, SHT31) to collect weather and air quality parameters. Table III depicts the samples of temperature (oC), humidity, rainfall (in mm), and air quality parameters. We considered the impact of these parameters into account for predicting traffic speed. Prediction accuracy is improved by paying appropriate attention to spatiotemporal correlations and indirect factors thresholds. We considered that congestion would occur when the traffic speed of a road segment is less than 35 km/hr. The route we have travelled above is experienced with savoir congestion.

Table III: Weather and Air Quality Parameters

Temp	HR	Rain	PM_{10}	$PM_{2.5}$	CO	NO_2	SO_2	O_3
31	69	29	63	68	10	10	24	68
31	68	16	60	63	9	8	19	67
30	70	5.0	68	65	8	9	20	66
30	69	114	62	69	9	12	26	70
31	68	2.0	66	71	9	8	27	65
30	67	104	60	62	8	10	24	69
29	71	148	65	68	10	9	29	70

6 Conclusion and Future Direction

This research presented a LoRaWAN network using the Things Mate and Raspberry Pi4 all-in-one sensor platforms to capture road network spatiotemporal characteristics and other external factors. We have accurately estimated vehicle speed, travel times, and congestion levels using a hyper-heuristic-based ED-GRU with a soft attention mechanism. Prediction accuracy is improved by paying appropriate attention to spatiotemporal correlations and indirect factors thresholds. This approach out performance in accurate vehicle speed and congestion estimation. In the future, we will propose a proactive rerouting approach to analyze the distance, future traffic load, number of intersections, weather, air quality, and travel times on *k*-shortest paths. The rerouting process also determines a dynamic shortest path for vehicle rerouting.

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