Efficient Data Management for Intelligent Urban Mobility Systems

Michael Wilbur 1, Philip Pugliese 2, Aron Laszka 3, Abhishek Dubey 1
1Vanderbilt University, Department of Electrical Engineering and Computer Science
2Chattanooga Area Regional Transportation Authority (CARTA)
3University of Houston, Department of Electrical Engineering and Computer Science

Abstract
Modern intelligent urban mobility applications are underpinned by large-scale, multivariate, spatiotemporal data streams. Working with this data presents unique challenges of data management, processing, and presentation that is often overlooked by researchers. Therefore, in this work we present an integrated data management and processing framework for intelligent urban mobility systems currently in use by our partner transit agencies. We discuss the available data sources and outline our cloud-centric data management and stream processing architecture built upon open-source publish-subscribe and NoSQL data stores. We then describe our data-integrity monitoring methods. We then present a set of visualization dashboards designed for our transit agency partners. Lastly, we discuss how these tools are currently being used for AI-driven urban mobility applications in Chattanooga.

Introduction
With the proliferation of affordable sensor and networking units, urban mobility systems are entering the connected world at a rapid pace. This has led to a proliferation of research related to improving the experience of using public transportation. As use of public transit continues to increase, transit agencies are looking to AI and machine learning to make existing systems more efficient and thus maximize existing infrastructure.

AI methods in this context require data from a variety of real-time streams from a variety of sources. For example, traffic prediction and transit optimization applications require high-resolution traffic, vehicle telemetry, weather, and road network data. As image processing methods have continued to progress, video streams offer potential insights to user behavior and vehicle occupancy.

There are numerous challenges in storing and processing data for AI-driven urban mobility systems. First, these sources present data in domain-specific formats and at irregular intervals that can vary by provider and source, making it challenging to join data streams to be used by downstream AI models (Wang, Zhou, and Lu 2000). Second, the spatiotemporal nature of these data sources presents challenges in efficient storage, synthesis, and data retrieval (Aydin, Akkineni, and Angryk 2016), (Wang, Zhong, and Wang 2019). A third challenge is efficiently presenting the data to AI researchers and transit experts for data exploration (Thudt, Baur, and Carpendale 2013). In addition, there are the typical challenges of working with high-velocity, high-volume streaming data.

Therefore in this work we present an integrated data management and processing framework for intelligent urban mobility systems that is currently in use by the Chattanooga Area Regional Transportation Agency (CARTA). We discuss the available data sources and our experiences with joining the various data streams for our set of AI-driven applications. We also discuss our methods for monitoring the integrity of the data and present a set of publicly available visualization dashboards designed for our transit agency partners. Lastly, we discuss how these tools are currently being used for AI-driven urban mobility applications in Chattanooga. Through our partnership with transit agencies, we are making these tools open-source and providing access to the visualization dashboards and data sets at (sma 2020).

Data Sources
In this section we outline the available real-time and static data sources. A summary of the available data sources is provided in table 1.

Real-time Data
CARTA's vehicle fleet for the fixed-line bus transit system includes 50 diesel, 3 electric and 7 hybrid vehicles. Each vehicle has a telematics kit produced by ViriCiti LLC that provides real-time telemetry data at a minimum of 1Hz resolution of all available vehicle operating parameters. In total, we have already obtained around 32.3 million data points for electric buses and 29.8 million data points for diesel buses. The nature of the telemetry data is dependent on the type of vehicle. For instance diesel and hybrid vehicles include fuel level and fuel rate where the electric vehicles monitor state-of-charge. All vehicles include GPS and odometer data. Each data reading from ViriCiti includes the label (i.e. GPS), a timestamp and a unique vehicle ID. We collect this telemetry data in real-time from the ViriCiti API (vir 2020).

Additionally, each vehicle is equipped with a kit from Clever Devices (cle 2020). This data includes GPS, unique
Figure 1: Data architecture overview - real time data is streamed to an Apache Pulsar cluster consisting of 5 broker/bookie nodes and 5 zookeeper nodes running on-site in VMWare. A MongoDB cluster running in Google Cloud reads from the Pulsar cluster, continuously updating its data view and adding spatial indexing for monitoring and dashboard applications.

Table 1: Data sources.

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
<th>Frequency</th>
<th>Scope</th>
<th>Features</th>
<th>Schema/Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel vehicles</td>
<td>ViriCiti and Clever Devices</td>
<td>1 Hz</td>
<td>50 vehicles</td>
<td>GPS, fuel-level, fuel rate, odometer, trip ID, driver ID</td>
<td>ViriCiti SDK and Clever API</td>
</tr>
<tr>
<td>Electric vehicles</td>
<td>ViriCiti and Clever Devices</td>
<td>1 Hz</td>
<td>3 vehicles</td>
<td>GPS, charging status, battery current, voltage, state of charge, odometer</td>
<td>ViriCiti SDK and Clever API</td>
</tr>
<tr>
<td>Hybrid vehicles</td>
<td>ViriCiti and Clever Devices</td>
<td>1 Hz</td>
<td>7 vehicles</td>
<td>GPS, fuel-level, fuel rate, odometer, trip ID, driver ID</td>
<td>ViriCiti SDK and Clever API</td>
</tr>
<tr>
<td>Traffic</td>
<td>HERE and INRIX</td>
<td>1 Hz</td>
<td>Chattanooga region</td>
<td>TMC ID, free-flow speed, current speed, jam factor, confidence</td>
<td>Traffic Message Channel (TMC)</td>
</tr>
<tr>
<td>Road network</td>
<td>OpenStreetMap</td>
<td>Static</td>
<td>Chattanooga region</td>
<td>Road network map, network graph</td>
<td>OpenStreetMap (OSM)</td>
</tr>
<tr>
<td>Weather</td>
<td>DarkSky</td>
<td>0.1 Hz</td>
<td>Chattanooga region</td>
<td>Temperature, wind speed, precipitation, humidity, visibility</td>
<td>Darksky API</td>
</tr>
<tr>
<td>Elevation</td>
<td>Tennessee GIS</td>
<td>Static</td>
<td>Chattanooga region</td>
<td>Location, elevation</td>
<td>GIS - Digital Elevation Models</td>
</tr>
<tr>
<td>Fixed-time transit schedules</td>
<td>CARTA</td>
<td>Static</td>
<td>Chattanooga region</td>
<td>Scheduled trips and trip times, routes, stops</td>
<td>General Transit Feed Specification (GTFS)</td>
</tr>
<tr>
<td>Video Feeds</td>
<td>CARTA</td>
<td>30 Frames/Second</td>
<td>All fixed-line vehicles</td>
<td>Video frames</td>
<td>Image</td>
</tr>
<tr>
<td>APC Ridership</td>
<td>CARTA</td>
<td>1 Hz</td>
<td>All fixed-line vehicles</td>
<td>Passenger boarding count per stop</td>
<td>Transit authority specific</td>
</tr>
</tbody>
</table>

Vehicle ID (which corresponds with the vehicle ID from ViriCiti) and additionally includes a unique driver ID and the unique trip ID which that vehicle is serving. The unique vehicle ID maps directly to the GTFS schedule produced by CARTA.

We also collect weather data from multiple weather stations in Chattanooga at 5-minute intervals using the DarkSky API. This data includes real-time temperature, humidity, air pressure, wind speed, wind direction, and precipitation. In addition, we collect traffic data at 1-minute intervals using the HERE API, which provides speed recordings for segments of major roads, which provides data in the form of timestamped speed recordings from selected roads. Every road segment is identified by a unique Traffic Message Channel identifier (TMC ID). Each TMC ID is also associated with a list of latitude and longitude coordinates, which describe the geometry of the road segment. Lastly, vehicles are currently being fitted with video equipment that generates real-time video streams to help monitor capacity requirements.

Static Data Sources

Road network map data was collected from OpenStreetMaps (Haklay and Weber 2008), which provides road infrastructure modeled as a graph. In addition, we collect static GIS elevation data from the Tennessee Geographic Information Council (Tennessee Department of Finance and Administration 2019). From this source, we download high-resolution digital elevation models (DEMs), derived from LIDAR elevation imaging, with a vertical accuracy of approximately 10 cm. We incorporated the elevation data in the OSM network by adding the elevation from the GIS data to each node in the OSM network. Lastly, the vehicle scheduling information is provided by the CARTA in GTFS format.

Data Management

Given the volume and the rate of the data being collected, we had to design a custom architecture for the project. The purpose of this architecture is to store the data streams in a way that provides easy access for offline model training and updates as well as real-time access for system monitoring prediction. This architecture consists of a publish-subscribe cluster implemented with Apache Pulsar, which stores topic-labeled sensor streams, and a MongoDB database backend. An overview of the data architecture is provided in figure 1.

This architecture solves two challenges. The first challenge is the persistent storage of the high-velocity, high-volume data streams. The second challenge is that the data is highly unstructured and irregular and different data streams have to be synchronized and joined efficiently. With this architecture, we stream each data source to a topic-based publish-subscribe (pub-sub) layer that persistently stores...
each data stream as a separate topic. Further, we used a
tier represents the name of the data tenant and all authenti-
cation and access is managed at this level. The second tier is
the data category, i.e., vehicle telemetry, traffic, weather,
etc. The third tier is the topic name, which represents
the data source or provider, such as ViriCiti, HERE, or DarkSky.
For ViriCiti, the fleet name is appended to the topic name to
separate electric, diesel, and hybrid vehicles. The tenant, cat-

gory, and topic names together form a topic, which down-
stream applications can use to access the data streams. We
persistently store all messages on each topic in an append-
only ledger. Therefore, the topic can be used to read data
in near real-time or to playback previous data streams to
synchronize new downstream applications. All replication is
handled at the ledger level, which allows downstream stor-
age and applications to adapt and expand without concern
for data resiliency. For this system we used Apache Pulsar
(apa 2019) due to its native support for authentication and
access at the tenant level and high throughput. We run Pul-
sar on-site on a VMWare cluster.

We include two methods for long term, structured access
to the data streams. First, Pulsar includes support for Presto
SQL which is a distributed SQL query engine for big data
(pre 2020). Presto SQL integrates with the Pulsar data stores
to provide an SQL interface on top of the Pulsar topics. This
is useful for analytics teams comfortable with SQL, however
as it is designed for large scale batch queries and does not
support geospatial indexing it is not optimal for user-centric
applications such as visualization dashboards. Therefore, we
implemented a downstream MongoDB (mon 2019) cluster
running in Google Cloud. MongoDB was chosen for its na-
tive support of geospatial, r-tree indexing which optimizes
our system for aggregate geospatial queries for monitoring
and visualization applications discussed in the next section.

**Data Synthesis and Stream Processing**

The various downstream applications such as monitoring
systems, visualization dashboards and energy and ridership
prediction models require data from various streams to be
merged. Typical implementations of stream processing ar-
chitectures require external processing frameworks such as
Apache Spark and Storm. For our implementation we de-
cided to join the data streams within Apache Pulsar. This
process involves designing functions that read from a set of
data stream topics, merge the streams in a series of time win-
dows, and output the joined data on a new Pulsar topic.

As our framework has expanded, we are running numer-
ous streaming join functions within Pulsar. An example is
provided in figure 2, which outputs a data stream that is used
for our energy prediction models and energy dashboard. The
input is the telemetry data from ViriCiti, route, trip and driver
data from Clever Devices, weather from DarkSky, traffic
from HERE and the video feed. Additionally, our predic-
tive models rely road level information from OSM. As this
data is static the latest OSM network is stored in a MongoDB
collection which the function queries each evening to keep
up-to-date. These data sources are merged at 1 second time
windows, which is the resolution required by the predictive
models.

Running our stream processing applications within Pul-
sar has two benefits. First it provides real-time access to
consumers that subscribe to the output topic of these ap-
lications. Second, we include a subscriber that continu-
ously adds geospatial indexing the the streams and writes
to MongoDB. One disadvantage of this approach is that
there is some additional overhead regarding development
time working with the Pulsar API’s instead of more ma-
ture, streaming specific frameworks. However since we do
not require the overhead of incorporating a separate stream
processing framework we are able to reduce complexity of
the overall system and reduce costs that would be associated
with running this external system.

**Data Monitoring**

The incoming data, particularly vehicle telemetry data is
provided by cutting edge telemetry kits from our partner
companies ViriCiti and Clever Devices. These kits are in-
stalled on a variety of fleets bought over the last 25 years,
each with different specifications and requirements. The
challenges associated with this work require careful moni-
toring to ensure the quality of the incoming data. Addition-
ally, it is useful to monitor our data architecture itself to iden-
tify gaps in coverage or failures in the system. Therefore we
implemented a custom monitoring system to notify our data
management team and CARTA of when issues arise.

Our monitoring includes automated programs which send
nightly emails summarizing the state of the system as well
as the incoming data. We use historical data regarding the
number of messages on each topic per day of the week to
compare with the number of messages on that topic over
the previous day. If the number of messages over the pre-
vious day was more than two standard deviations less than
expected, an email is triggered to notify us there was a dis-
crepancy on one of the data streams. This application runs
on all registered topics within Pulsar.

We found that this monitoring application was insufficient

![Figure 2: An example stream data join. Real-time telemetry and routing data from CleverDevices and ViriCiti is combined with weather from DarkSky, traffic from HERE and the video feed. The output stream includes all fields from these sources, as well as static data from OSM, GTFS and elevation. The output stream is a sliding time window at 5 second intervals.](image-url)
regarding the ViriCiti data since failures with the telemetry kits were highly correlated between vehicle models. For instance, early in this project there were issues regarding the kits for the 10 diesel vehicles bought in the late 1990s. Since these had issues immediately, they never showed up in the historical averages and thus were not identified as an issue. Therefore, a second application was designed specifically for the ViriCiti data. This application queries all vehicles, identified by unique vehicle ID, that serviced a trip that day. We then query the ViriCiti data to ensure there was telemetry data on that vehicle during that time window.

Visualization Dashboards

As our framework developed, we also implemented a set of visualization web dashboards using Python, Plotly and Dash. These dashboards are connected to our MongoDB backend to query data for presentation to the user. An example of our energy visualization dashboard is shown in figure 3. In this dashboard, the user can query based on time, fleet and route. The data is presented to the user over the map of Chattanooga as shown in figure 3a and as a series of statistical visualizations, one of which is energy per fleet as shown in figure 3b. This dashboard is used by the data management team and CARTA to monitor the performance of the CARTA fleets over time and is available to the public.

AI Applications

In addition to the visualization dashboard applications, we are currently running a set of AI applications that rely upon the data management framework and data sources discussed in this paper. The first of which is an energy prediction model presented in (Ayman et al. 2020). These prediction models use the output features as shown in figure 2 to train regression and neural network models to predict the energy that will be consumed on a route by the diesel, hybrid and electric vehicles. We are currently working on incorporating these models in the energy dashboard to help CARTA with vehicle scheduling and operational guidance.

Additionally, we are working training statistical models to predict vehicle occupancy to better schedule vehicles in the context of social distancing regulations from COVID-19. In this way we can help to ensure these safety requirements are met and help CARTA better schedule vehicles on popular routes. These models will be incorporated in the ridership dashboards so CARTA operators have real-time access to these models.

Conclusion and Future Work

In this work we presented our integrated data management and processing framework for intelligent urban mobility systems, which is currently in use by our partner transit agencies. We also covered our associated monitoring systems, visualization dashboards and briefly discussed the current AI applications using these tools which we are making open-source and providing access to the visualization dashboards and data sets at (sma 2020).

In future work we are interested in investigating decentralized edge-cloud hybrid architectures for AI-driven urban mobility systems. We have done some work on AI-driven, decentralized routing applications using federated learning (Wilbur et al. 2020) and fog-cloud middleware for smart mobility systems (Talusan et al. 2019), (Talusan et al. 2020). We are interested in studying problems related to data storage and retrieval for these systems in future work.

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