Innovations Deserving Exploratory Analysis Programs

Transit IDEA Program

Development of a Mass-Based Automated Passenger Counter

Final Report for
Transit IDEA Project 84

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Development of a Mass-Based Automated Passenger Counter
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EXECUTIVE SUMMARY

Passenger counting has been an essential part of the transit industry for decades. Automatic passenger counters (APCs) provide passenger boarding and alighting information associated with time and location data. They are a standard tool used by many transit authorities to measure and report monthly ridership to the National Transportation Database (NTD), with resulting federal subsidies calculated solely based on the data they provide. APCs also allow authorities to track ridership changes, calculate performance measures, and adjust schedules. Incumbent APC technologies include infrared (IR) light beam cells, passive infrared detectors, video cameras, infrared cameras, laser scanners, ultrasonic detectors, microwave radars, piezoelectric mats, and switching mats. The cost of current APC systems can be prohibitive for smaller fleets (<250 vehicles) with small capital budgets and integration with existing bus controllers and agency databases is also challenging.

The objective of this IDEA project was to develop an inexpensive passenger counting system that allowed simple integration with existing vehicle information systems to reduce cost. The system relates bus mass to passenger boarding and alighting using pressure transducers located in the air spring suspension system. A micro-controller installed on the bus conducted calculations at the stop event. A feed forward neural network and convolutional neural network algorithm were used to analyze the shape of the signal and predict boarding and alighting at each stop. Built completely using commercially available, open-source software and hardware, this new system is cost-effective, easy to setup and could be integrated with existing transit agency databases.

During the project, the system was integrated on four in-use transit buses around the Minneapolis and Saint Paul metropolitan area. The machine learning algorithms had 91% accuracy for a subset of the data used in training the algorithms. However, testing with the trained algorithms showed that the mass-based APC was 61% and 38% accurate in recording boarding and alighting events, respectively.

Although the algorithms had poor accuracy for alighting events, especially, the system was able to estimate the mass of the bus at each stop accurately. As the project progressed, new, vision-based APC systems were brought to the market by other manufacturers. Based on the testing data collected in this project, the developed APC could not compete with the accuracy obtained by these new systems. Future development work may look to use the mass-based system to augment existing IR-based systems to improve their accuracy to new passenger counting standards.

In an extension of this IDEA project, the University of Minnesota team used instantaneous bus mass recorded by the developed system to estimate the effect of passenger loading on fuel economy and bus energy consumption. A simulation study was done using multiple days of second-by-second bus mass and speed with hybrid and conventional buses to show the effect of passenger loading on the fuel consumption of each technology. The results showed that fuel consumption in hybrid buses are less affected by passenger mass since the additional mass increases the available energy from regenerative braking. Future work in this extended research area will look to better predict the driving range of all-electric transit buses by measuring instantaneous bus mass.

IDEA PRODUCT

In this section, the status of the mass-based APC system at the end of the IDEA project will be described. The key components of the product are the pressure transducers mounted in bus air spring suspension circuits, wiring, and the controller, as shown in the bold outline in Figure 1. The components in the controller are described in a later section of this report.

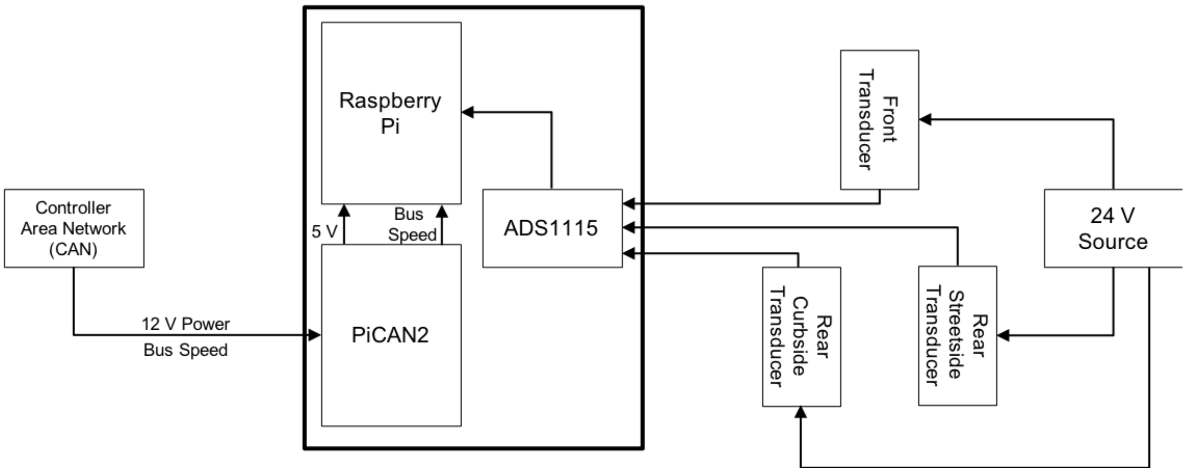

Figure 1: Diagram of the current system as developed in the IDEA Project

The components in the mass-based APC are simpler and cheaper than optical-based automated passenger counter (APC) systems and could be installed at the time of manufacture. Based on the large number of other controllers, for example for fare counting and bus tracking, that are installed on current transit buses, the calculations for passenger count using mass could also be integrated within the overall vehicle controller or other telematics packages provided by third-party developers in lieu of a separate controller, further reducing cost.

The critical determining factor for the commercial viability of the mass-based APC is the accuracy of the system compared to currently available systems. For the mass-based system, relating bus mass on a second-by-second basis to passenger boarding or alighting was the key challenge. A complex machine learning algorithm was developed as part of the product. This algorithm was still in development at the end of the project and could be further refined with additional time and funding.

CONCEPT AND INNOVATION

In this section, the hardware and algorithm development accomplished during the project will be described. The basic concept will be explained, followed by the hardware used in the project, data collection from in-use transit buses, the algorithm used for passenger boarding and alighting detection.

Basic Concept

Modern transit buses are fitted with air suspension systems to ensure a smooth ride and also maintain vehicle ride height. Figure 2 shows the schematic of an air suspension system for one wheel. The leveling valve helps maintain ride height by increasing or decreasing pressure in accordance with passenger boarding or alighting. In case a passenger boards, pressure in the airbag rises. When a passenger alights, pressure in the airbag decreases.

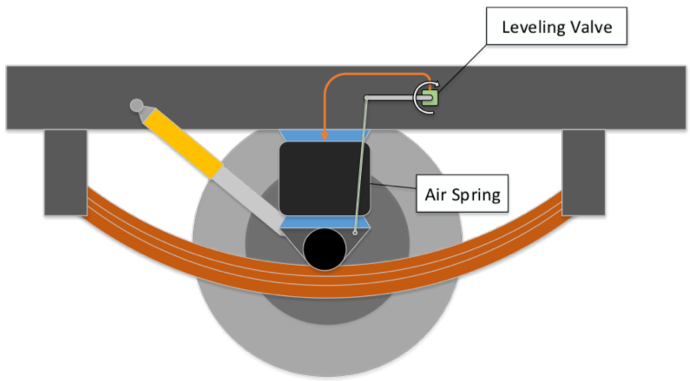

Figure 2: Air suspension system.

The main concept tested in the project was to measure the mass of a transit bus using pressure transducers placed in each air spring circuit and relate it to the number of passengers boarding and alighting. The pressure in each circuit is proportional to the mass of the bus. When passengers board and alight, the pressure transducers see the mass change and relates that to the number of passengers boarding and alighting using a mathematical algorithm. The calculations are accomplished on a microprocessor controller located inside the bus that also measures bus speed and other parameters from the vehicle controller area network (CAN). Bus mass and passenger count information is stored locally on the controller and also communicated via cellular connection to a cloud server.

On a standard 40-foot bus, there are three airbag circuits, as shown in Figure 3. Each circuit comprises two airbags to form the complete suspension system. Articulated buses with more than two axles would require additional transducers but could be used in the same way.

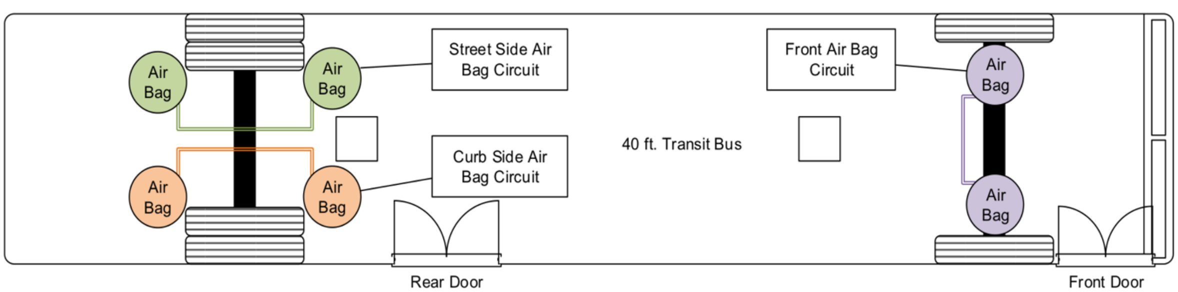

Figure 3: Plan View of Air Suspension System in a 40 ft Bus.

Pressure transducers are placed at each airbag circuit to estimate the pressure in each air bag, which is then used to estimate the total mass of the bus. This is the linear combination of the pressures in each airbag, as shown in Equation 1.

$$m = A_{front}P_{front} + A_{curb}P_{curb} + A_{street}P_{street} \qquad \text{(Eq.1)}$$

Where P_{front}, P_{curb} and P_{street} are the pressures measured by transducers in the air bags on the front, curbside and street side airbags, respectively. A_{front}, A_{curb} and A_{street} are constants found by calibration. Our earlier work conducted before the IDEA project showed that the mass measured by this air suspension system directly correlates with the actual mass of the bus [1].

Hardware Components

The earlier work done before the IDEA project used an expensive National Instruments controller to measure pressure from the air spring suspension system. One of the objectives of this project was to develop an inexpensive microcontroller that could form the basis for a commercial product. A set of cost-effective, easy to source, and easy to assemble hardware was chosen to implement the mass-based APC system in the project. These include a Raspberry Pi 3 Model B, Adafruit ADS 1115 Breakout Board, PiCAN2, Omega PX181B pressure transducers and Honeywell PX3 transducers. The following sub-sections outline the individual hardware components used in the project:

Main Computational Platform

The Raspberry Pi (R-Pi) is a single-board computer initially meant for the advancement of programming and computer science in developing countries. It quickly gained traction for purposes beyond its initial scope to a myriad of other projects, including commercial products. A brief outline of the R-Pi controller is given below:

Physical Resources: The Raspberry Pi is powered by a Broadcom System-on-Chip (SoC) with a 1.2 Ghz quad-core 64-bit CPU and 1GB of RAM. SoC provides ample processing power to perform any computational tasks.

Connectivity: The Raspberry Pi is equipped with Bluetooth 4.1, a 10/100 Ethernet port and 2.4Ghz 802.11n Wi-Fi which allows for flexibility in connectivity while also keeping the device relevant for the foreseeable future.

Storage: The Raspberry Pi uses an external microSD card as the primary storage media. The microSD allows for variable storage sizes to be used as needed and also makes data offline data retrieval easy. Additionally, the storage media can be easily replaced and cards between different Raspberry Pis are interchangeable.

Operating System: The primary OS on the Raspberry Pi is Raspbian, which is a Debian-based OS with a Linux kernel. The OS brings with it the many benefits of a Linux-based OS, which makes programming on any operating system easy to implement on the mini-computer. Many libraries essential for the development of this APC were written exclusively for Linux-based OSes such as socketCAN.

Interfaces: The Raspberry Pi has several interfacing options and relevant ones are discussed below. Serial Peripheral Interface Bus: SPI is a de-facto standard and is used by the PiCAN2 to transmit CAN messages to the Raspberry Pi. Inter-Integrated Circuit: The I2C bus uses two bidirectional lines - the Serial Data Line (SDA) and Serial Clock Line (SCL). The ADS1115 uses I2C to communicate with the Raspberry Pi. I2C supports daisy-chaining so multiple ADS1115s can be added (as done in the articulated bus), in conjunction with other peripherals such as a gyroscope/accelerometer.

Analog-to-Digital Converter

The Adafruit ADS1115 is a four-channel 16-bit Analog-to-Digital Converter with a programmable gain amplifier. The breakout converts the analog signals received from the pressure transducers to digital signals which the Raspberry Pi can record. Adafruit also provides a Python library for the breakout board, which can be used to interface directly with the board without the need for manually accessing registers.

Communication Interface

The PiCAN2 is a Hardware Attached on Top (HAT) developed by SK Pang for the Raspberry Pi, which provides it a Controller Area Network (CAN) interface using the Microchip MCP2515. The PiCAN2 attaches to the R-Pi controller and uses its GPIO pins to interface with the computer.

The CAN network on a Linux-based OS like Raspbian is accessed by socketcan, which is the official CAN API of the Linux kernel. python-can is used to provide a CAN interface for Python and uses socket-can itself on Linux-based operating systems.

A version of the PiCAN2 also comes with a switch-mode power supply that can power the Raspberry Pi directly from the CAN network. The J1939 standard allows for a 12V power line to be carried from the CAN port and is stepped down by the PiCAN2 to power the Raspberry Pi via GPIO. This alleviates the need to supply additional power supply for the Raspberry Pi.

Sensing

Pressure transducers have a digital output, which is converted to analog signals in the controller. The transducers are wired to each of the airbag circuits of the bus (three in a standard bus and five in a 60-feet articulated bus) at the leveling valve.

Omega PX181B: The Omega pressure transducers have an excitation voltage of 9 to 30 VDC and provide an output between 1 and 5 V. They have an accuracy of ±0.3% above 15 psi. However, they are cost prohibitive at over $220 per unit. These transducers were installed on three of the test buses in this project.

Honeywell PX3: The Honeywell transducers have comparable specifications to the ones from Omega, with one notable exception: they have an excitation voltage restricted to 5V. The transit buses used for the development of the mass-based APC did not house a 5V supply and so a buck converter was needed to step the voltage down from 24V or 12V to 5V. Additionally, these were cost-effective at $40 per unit. The Honeywell transducers were installed on Metro Transit buses 1713 and 3300 (stepping down from 24V to 5V) and First Transit bus 3827 (stepping down from 12V to 5V).

Data Collection

Transit Bus Installation

The mass-bases APC system was installed on six buses in total as outlined in Table 1. The table also shows the type of bus and transducers installed on each. Five of the buses were in the Twin Cities Metro Transit fleet and one was a bus owned by the University of Minnesota and operated by First Transit.

Table 1: Buses equipped with the mass-based APC in the project.

Bus	**MT 1503**	**MT 7327**	**MT 7290**	**MT 1713**	**MT 3300**	**UMN Bus**
Manufacturer	Gillig	Gillig	Newflyer	Gillig	Gillig	Gillig
Bus Type	Standard	Hybrid	Standard	Standard	Articulated	Hybrid
Transducer	Omega PX181B	Omega PX181B	Omega PX181B	Honeywell PX3	Honeywell PX3	Honeywell PX3
Wireless Access	No	Yes	No	Yes	No	Pending

Images of three of the buses are shown in Figure 4. Data from bus MT1713 were used in work to develop the neural network model for passenger counting. The data from this bus are given later in this report.

7327 1503 1713

Figure 4: Three buses in the Metro Transit fleet equipped with mass-based passenger counting system.

Logging

Data were logged at 1Hz all times while the bus was running and as fast as possible when the bus was in a ‘stop event.’ A ‘stop event’ is defined as the time when the bus has a velocity lower than 3kmph. This cutoff was chosen after many iterations when it was found that the device would log pressure signals accurately at high speed without missing out information from a stop event.

Each channel was logged separately. ‘Channel’ here refers to the signal from each air spring circuit. There are three channels for each standard bus and five for the articulated bus. Figure 5 shows a sample data record from each transducer during an entire stop event. In this event the pressure of each circuit appears to change independently as passengers board and alight and shift around inside the bus. The APC systems installed in the buses recorded data continuously, and data was retrieved by removing the SD memory card in the controller.

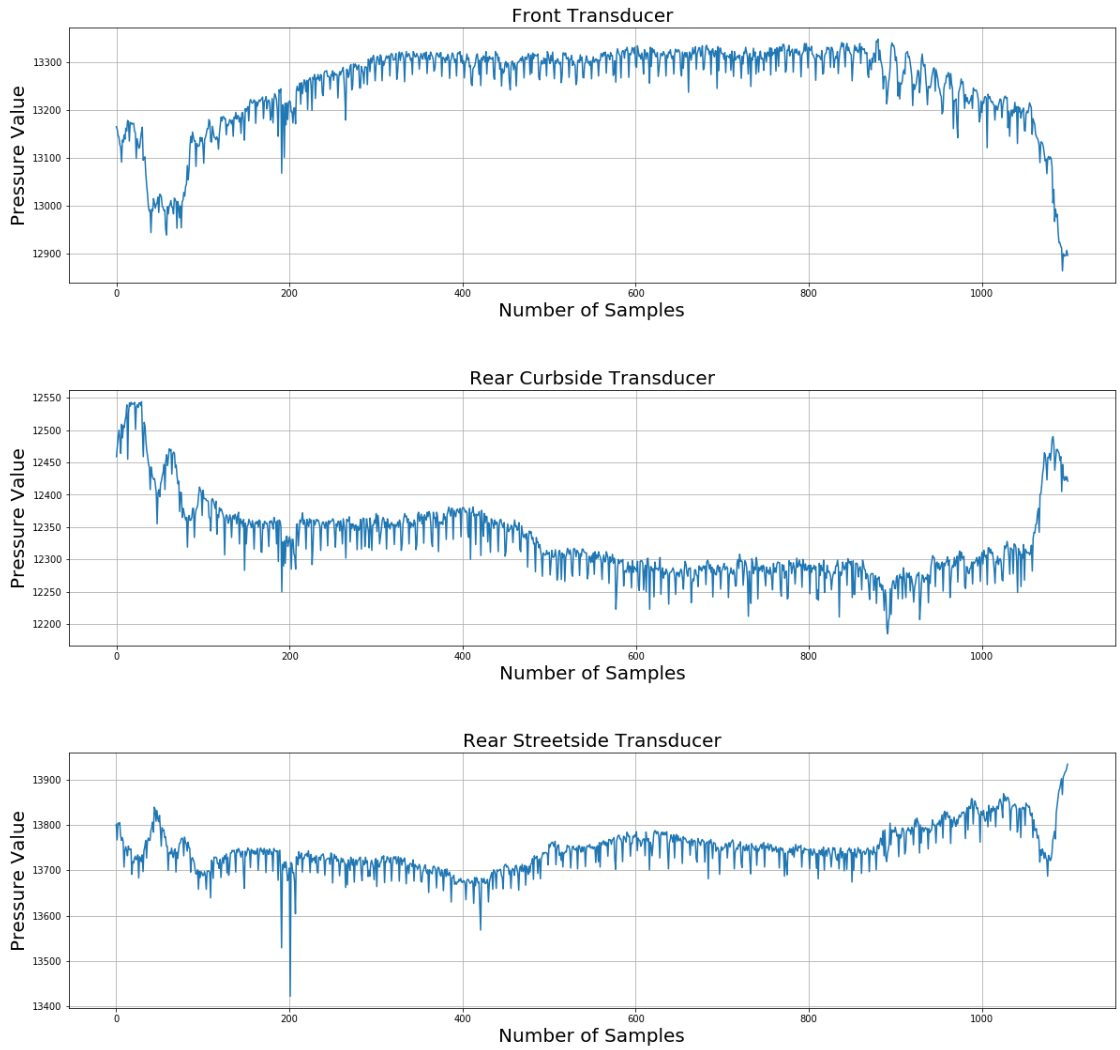

Figure 5: Sample data record from each transducer during an entire stop event for bus MT1713.

Passenger Counting Algorithm

The main effort of the IDEA project was to develop a robust algorithm for accurately estimating boarding and alighting events based on the pressure information from each pressure transducer. In our research conducted before the project started, we developed simple algorithms that used either "mass-based" or "event-based" calculations. Mass-based calculations assumed an average passenger mass and determined boarding or alighting based on the current bus mass. The event-based calculations used the derivative of airbag pressure signals to determine whether a passenger boarded or alighted. The event-based and average mass-based algorithms yielded 72% and 97% accuracy, respectively, as reported in our earlier publication [1]. Although these simple methods were effective, they were confounded by bus kneeling events when the passenger air spring suspension system was "deflated" to lower the bus at stop events and also was inaccurate for heavy or light passengers. The reported accuracy in the earlier work was for trips where kneeling was not used and was dependent on knowing average passenger mass a priori.

To alleviate the inaccuracies of the previously developed algorithms and to predict passengers for all real-world conditions, a machine learning algorithm was developed in this IDEA project. Machine learning algorithms "learn" from previous data to train a set of mathematical equations. The training set is then used to predict the desired quantity by testing a data set that has the same properties as the training dataset.

In this project, neural networks were used to predict passenger boarding and alighting for each stop event. Neuroscientists have been trying to model the brain as a network of neurons, which has inspired computer scientists to build artificial neural networks to solve classic machine learning problems. Neural networks have demonstrated remarkable efficacy in vision and speech problems in particular. In addition to having high accuracy in predictions, neural networks are robust to noise and failures and also enable parallelization of learning algorithms with currently available technology.

In the project, a convolutional neural net model was combined with a cumulative passenger model, as illustrated in the block diagram given in Figure 6. The objective of the cumulative passenger count model shown on the right side of the figure, was to predict how many passengers were on the bus at the end of each stop event. To accomplish this, the air suspension system pressure was recorded only in the last 2 seconds of the stop event before the bus started to move.

The convolutional model was used to predict boarding and alighting as the cumulative model could only predict total passengers on the bus, not how many got on or off during a stop event. The convolutional model required two inputs: 1) The entire stop event data from the pressure transducers on all three air spring suspension channels, and 2) The cumulative passenger count at the end of the stop event as predicted by a cumulative passenger model.

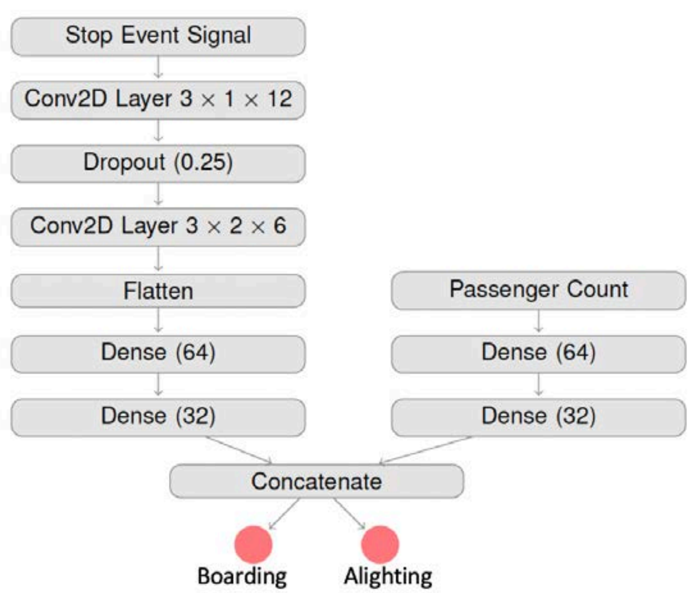

Figure 6: Block diagram of the convolutional neural network and cumulative counting model used to count boarding and alighting events.

Testing Results

To test the developed algorithms, manual passenger counts were recorded from bus MT1713. The neural net model was trained on 80% of the data and tested on 20% of the data collected. The bus operated on the same test route (MT route 14), as shown in the map in Figure 7.

Figure 7: Map of Route 14 used for evaluating the mass-based APC system

First, the cumulative passenger model was trained and showed excellent accuracy (>90%) in estimating the total passenger count on the bus after each stop event, as shown in Figure 8. The model was later improved for cumulative passenger counting and was very accurate in estimating the number of passengers at the end of a stop event. This model and method were later used to extend this research to examine the effect of passenger mass on bus energy consumption.

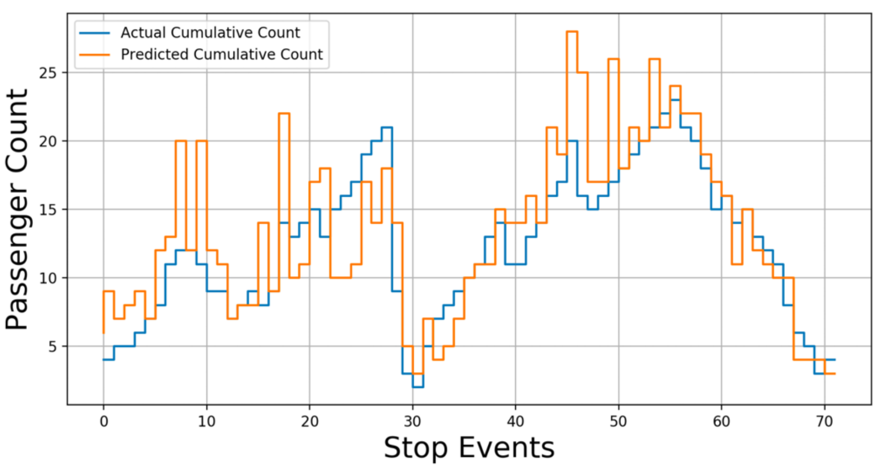

Figure 8: Results of the cumulative passenger count model for bus MT1713.

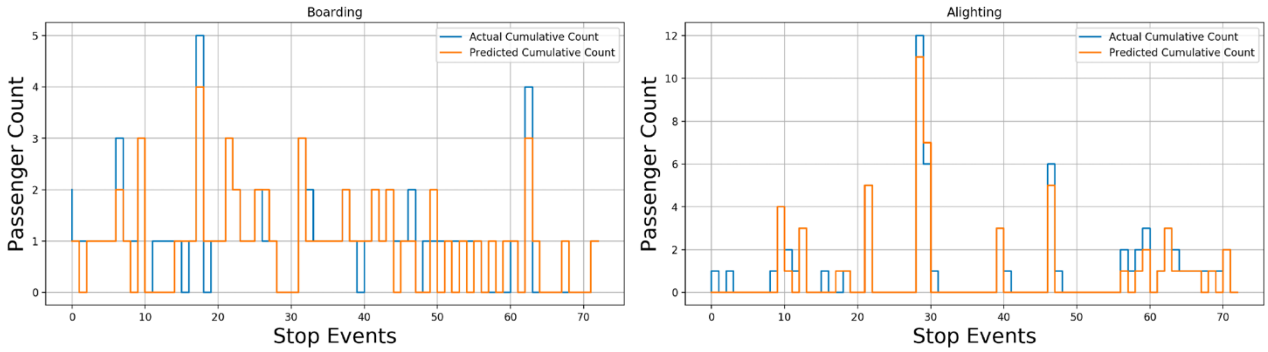

Figure 9: Performance of convolutional neural network prediction algorithm on the training dataset.

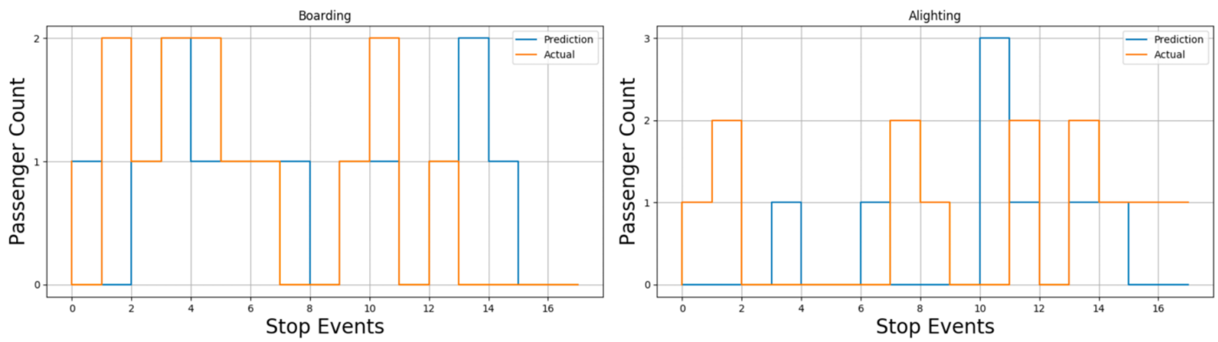

Figure 10: Performance of convolutional neural network prediction algorithm on the test dataset.

Figure 9 provides the performance of the passenger counting algorithms for boarding and alighting for the training dataset. Here, the accuracy of the model was 91%. However, when the trained model was used on the remaining data as the testing dataset, the accuracy for boarding and alighting dropped to 61% and 38%, respectively as shown in Figure 10. More training data may be needed to train the machine learning model properly. Although a large number of pressure data were collected during the project, additional manual counting data was not possible to acquire by the end of the project. The test results clearly show room for improvement, but extremely high accuracies (>98%) were deemed unlikely using the developed technology given the error inherent in the data and the algorithms.

PLANS FOR IMPLEMENTATION

Mass-Based APC

Current Status

Currently, the mass-based APC concept has been proven, though it needs additional refinement before progressing to a commercial product. Since the start of this IDEA project in 2017, new vision-based APC systems have been brought to the market by at least five manufacturers, including Trapeze Group, Eurotech, and Hella Aglaia. These systems use inexpensive cameras mounted in bus entry doors and implement artificial intelligence algorithms to detect passenger boarding and alighting. Vision-based systems can achieve 95-98% accuracy, significantly higher than the accuracy achievable by our mass-based system. Therefore, future work looks to combine the mass-based technique with vision-based

APC systems. Another future avenue of research will examine the use of on-board accelerometer data to determine to supplement pressure-based passenger counting and improve accuracy of developed algorithms.

Commercialization Status

After the IDEA project, the team is looking for industry partners to take on large-scale adoption. A US patent application on the algorithms for mass-based passenger counting was filed through the University of Minnesota's Office of Technology and Commercialization (OTC) to protect the intellectual property [2]. The initial patent office review had required some revisions and the patent is still pending as of the writing of this report.

The team also met with the UMN OTC to determine paths for commercialization. Separate meetings with Janet Hopper from Metro Transit and with John Osumi of Bishop Peak were held where the potential of the mass-based system was discussed. It was in these discussions that the high accuracy vision-based systems were presented, including the new mandate of 98% accuracy. Currently, only two vendors can meet this standard, including APC's from Hella Aglaia (optical) and Iris, Inc (infrared matrix). Procurement is happening only through these two vendors, so industry-wide deployments were down in 2018-2019. Twin Cities Metro Transit and other transit agencies are open to new solutions with integrators, original equipment manufacturers, and APC manufacturers.

Use of Technology for Estimating Energy Consumption in Electrified Buses

Our more recent research work by the project team has pivoted away from using the mass-based measurement system to estimate passenger boarding and alighting, and towards using the pressure measurement hardware and bus mass data developed in the IDEA project to estimate energy consumption in transit buses. This work is summarized in this section and was recently published in the Transportation Research Record [3].

Transit bus passenger loading changes significantly throughout a workday. Therefore, time-varying vehicle mass due to passenger load becomes an essential factor in instantaneous energy consumption. Battery-powered electric transit buses have restricted range and longer recharging time compared to conventional diesel-powered buses; thus, it is critical to know how much energy they require. A shortcoming of previous research is that most use average speed rather than instantaneous speed when calculating fuel consumption. Fuel consumption using average speed is less insightful because it does not capture high or low-speed extremes on a route and is insensitive to the acceleration rate. Also, most fuel consumption research related to vehicle mass has been conducted in large Chinese cities, such as Beijing and Hong Kong. Due to the unusual driving conditions in the urban areas of those cities, results may not apply to less congested U.S. or European cities where vehicles accelerate and decelerate less frequently.

In the work, we applied the cumulative passenger model to determine the impact of time-varying mass from passenger loading on bus energy consumption. Unlike previous studies that use a constant mass or estimate varying mass using average passenger weight, vehicle mass and speed were directly measured from in-use transit buses. The information was then used as input for a vehicle model to estimate the energy use of simulated battery electric buses (BEBs) and conventional diesel buses (CDBs). One valuable use of the analysis presented here is to predict how BEB range is affected by mass changes due to realistic passenger loading. More closely examining the effects of varying mass on fuel consumption can help public transportation companies plan more efficient routes and timetables. The method described in this paper can be adapted to compute the fuel refill quantity in CDBs or recharging time in BEBs that use on-route fast charging. Further, understanding long-term route mass-estimates can inform future infrastructure such as in-ground wireless charging placement or distributed high draw energy storage.

In the research, sixty-five days of velocity and mass data were collected from in-use transit buses operating on routes in the Minneapolis and St. Paul metropolitan area. The simulation tool Future Automotive Systems Technology Simulator (FASTSim) was modified to allow both velocity and mass as time-dependent inputs. This tool was then used to model an electrified and conventional bus on the same routes and determine the energy use of each bus. Results showed that the kinetic intensity varied from 0.27 mile-1 to 4.69 mile-1, and passenger loading ranged from 2 to 21 passengers. Simulation results showed that energy consumption for both buses increased with increasing vehicle mass. The simulation also indicated that passenger loading has a more significant impact on energy consumption for conventional buses than for electric buses due to the electric bus's ability to recapture energy. The work showed that measuring and analyzing real-time passenger loading is advantageous for determining the energy used by electric and conventional diesel buses. Accurate measurement of bus mass could also be used for informing passengers and agencies of overall bus loading independent of bus powertrain type.

Future work in this extended research area will look to better predict the driving range of all-electric transit buses by measuring instantaneous bus mass. The project team has already secured research funding to work on electric vehicle energy consumption optimization for heavy-duty trucks and will incorporate learning from this IDEA project into those algorithms.

CONCLUSIONS

In conclusion, the work conducted under this IDEA project comprehensively evaluated a mass-based passenger counting system for use in transit buses. A low-cost and robust microprocessor-based system was installed on six in-service transit buses. Data were collected from the buses, and a new neural net passenger counting algorithm was developed and tested. The results showed that the accuracy of the mass-based APC was below state-of-the-art systems, and required more research to achieve >98% accuracy for boarding and alighting. Although boarding and alighting event-based algorithms were not accurate, cumulative passenger counting calculations were very accurate. Such total passenger count and mass information could be used in energy management and charge prediction optimization algorithms used for all-electric transit buses in the future.

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