Wireless detection of end-to-end passenger trips on public transport buses

Vassilis Kostakos, Tiago Camacho and Claudio Mantero

Abstract—**An important problem in creating efficient public transport systems is obtaining data about the set of trips that passengers make, usually referred to as an Origin/Destination (OD) matrix. Obtaining this data is problematic and expensive in general, especially in the case of buses because on-board ticketing systems do not record where and when passengers get off a bus. In this paper we describe a novel and inexpensive wireless system that uses off-the-shelf Bluetooth hardware to wirelessly detect and record end-to-end passenger journeys.**

I. Introduction

According to the US Department of Energy, more than 20% of the world's energy is spent on transportation (http://www.eia.doe.gov/oiaf/ieo). At a time when the environmental implications of modern life are scrutinized, reducing the energy spent on transport is a key objective for achieving sustainability for our way of life. With more than 50% of commuters driving their own car to work [4], governments are actively campaigning for the use of public transport. Interestingly, researchers point out that even if more passengers choose public transport, the reduction in energy consumption will not be considerable due to the inefficiencies of public transport:

"Trains and buses are potentially much more efficient than cars, if only they were full. But the way we do public transport at present, trains and buses are not that much more energy-efficient than cars. There remain many other good reasons for encouraging a switch to public transport (for example avoiding congestion and reducing accidents), but don't expect to reduce energy consumption enormously by a switch to public transport. " [11, p. 133].

In Figure 1 we present a summary of the energy cost of various modes of transportation as described in [11]. While developing more efficient bus engines is an obvious way to improve buses' energy efficiency, an orthogonal approach is to consider ways of increasing bus occupancy. Designing a more efficient public transport network, where more seats are occupied more often, can greatly reduce the total energy spent for each passenger and hence bring us closer to achieving sustainable public transport.

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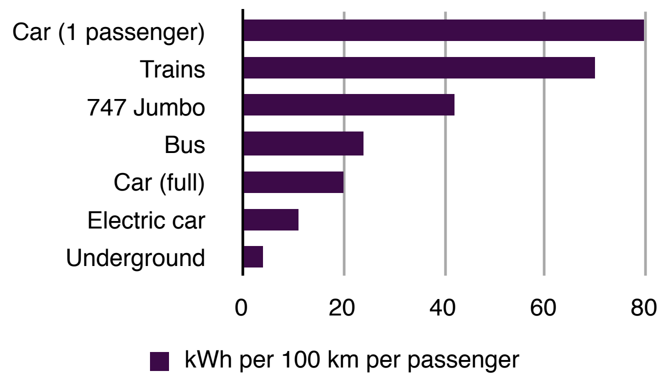

Figure 1. Typical energy consumption of public transport. Notes: Car consuming 33mpg. Trains traveling at 33km/h, and considering energy cost for lighting, lifts, depots and workshops. 747 Jumbo at cruise speed of 900km/h. Underground average speed of 48km/h. [11]. Bus carrying 14.4 passengers at average speed of 18 km/h, distance between stops 0.3 km [13].

A key requirement for designing and improving the public transport network's efficiency is obtaining an Origin/Destination (OD) matrix for passenger movement. Such a matrix is effectively a table that describes the flow of passengers between various points in the transport network (or alternatively between points on a map). In practice, the cumulative OD matrix can be filtered in many ways, e.g. to display the flow of passengers during peak hours or weekends. The design of public transport networks draws heavily on this information, and many decisions such as the scheduling of buses and drivers are directly based on this information [16].

Traditionally, the process of obtaining an OD matrix has been laborious and expensive because it typically involves human observers manually counting the number of passengers over a number of days. More recently, the use of electronic ticketing systems has greatly simplified this process. While some public transport systems such as the underground have an end-to-end ticketing system (i.e. the system records passengers' entry and exit points), others do not. For instance, most ticketing systems on buses record when passengers get on a bus, but do not record when they get off the bus. As a result, bus services still employ manual observation to capture the OD matrix, or rely on expensive sensor systems that can count the number of passengers on a bus at any time without being able to detect the specific origin and destination of any single passenger.

A further complicating factor is that depending on the amount of growth and change within a city the OD matrix changes over time, while in extreme cases (such as the Olympic games) these changes can happen abruptly [14]. Hence, while human observation can be used to capture an

OD matrix, this information may become inaccurate or obsolete within a few months. Depending on the frequency of human observations (typically every 6 months due to high cost), the bus service is expected to operate with a certain degree of inefficiency measured in terms of occupancy (percentage of seats occupied at any given time). An up-to-date OD matrix can help public transport authorities to better allocate their resources (drives, busses, repair crews), develop a more efficient transport network, and to fine-tune the operation of their network, effectively reducing the total energy spent per passenger. Furthermore, authorities can use such information to refine their reward schemes.

II. RELATED WORK

Most research considering OD matrices focuses on deriving accurate estimations from incomplete data (for an overview, see [1]). Typically, human observations and traffic counts do not cover every single segment of the transport network, and hence estimates of the flow of passengers for unobserved parts of the network are statistically derived [8]. Furthermore, some observation schemes do not rely on direct observation but rather on passenger questionnaires, hence introducing unreliability in the data.

In cases where an automated ticket system exists, OD matrices can be captured from ticketing data. It is important, however, to note that not all automated ticket systems are suitable for this task. For instance, in most cases buses do not record passengers' exit points, hence capturing incomplete information about journeys. Furthermore, many ticket systems were not originally designed for data collection [15]. As a result, many lack important information, collect data for specific and limited purposes, and record in a fragmented, intermittent, and difficult-to-use format. Furthermore, different subsystems (e.g. GIS and ticketing systems) may be supplied by different vendors and thus managed in completely different databases, thus making analysis difficult.

The problem of inferring an OD matrix from origin-only data has been addressed by Zhao et al. in their analysis of the Chicago Transit Authority rail system which collects origin-only data [15]. However, their analysis is based on a number of assumptions (p. 381): i) there is no private transportation mode trip segment (car, motorcycle, bicycle, etc.) between consecutive transit trip segments in a daily sequence; ii) passengers will not walk a long distance to board at a different rail station from the one where they previously alighted; iii) passengers end their last trip of the day where they began their first trip of the day. Such assumptions inevitably introduce inaccuracies in the calculated OD matrix, especially when considering a bus-only network. Furthermore, this approach completely fails to take into account one-way tickets, and passengers who do not have a permanent travel card.

Mobile phone tracking has been used as an approach to measure the flows of passengers between parts of a city [4, 6]. Such data, however, has low spatial resolution and is most appropriate for long-distance segments such as highways. This approach cannot be effectively used in a condensed network such as inner-city bus networks. Another approach to capturing passenger trips on busses is to make use of the onboard cameras and apply automated head detection [2], use pressure sensitive carpets, or use infrared sensing for capturing the number of passengers onboard a bus at any given time. However these techniques have the drawback that individual passengers are not detected.

While our use of Bluetooth as a means of capturing OD matrices is novel, Bluetooth has previously been used on public busses for automatic downloading of diagnostics and reports once busses return to their garage. Furthermore, Bluetooth has been considered as a replacements for cables, which can run up to 4 km on a single bus, thus reducing weight and overall petrol consumption [10]. In addition, prototype systems have considered Bluetooth as a mechanism for providing passengers access to the internet [9]. Finally, other systems have considered exploiting passengers' mobile devices for optimizing the transport network, by exploring how passengers' mobile devices can help plan and execute journeys in realtime [7]. This approach, however, requires custom software to run on passengers mobile devices, which introduces considerable development costs and compatibility issues.

The above uses of Bluetooth technology onboard buses are encouraging for us, because we can easily piggy-back our system on top of an existing Bluetooth infrastructure, as described next.

III. IMPLEMENTATION

Our system was implemented for Horários do Funchal, the public transport operator in Funchal, Madeira, Portugal. This organization has over 160 buses serving about 30 million passengers per year, across more than 1400 bus stops. These buses have an elaborate localization and ticketing system, which was in use prior to our study.

Each bus is equipped with an on-board GPS system, complemented by a digital odometer (distance travelled) and door sensor (doors open/closed). These three components are used to determine the bus location at any given moment. Buses report their location using a GPRS connection, and all bus locations are fed centrally into a real-time commercial simulator that estimates when each bus will reach the next bus stop. These estimates are then transmitted to bus stops using GPRS, and each bus stop displays the estimated arrival time of each service on an electronic display.

Additionally, each bus has a ticketing system that records information about the time when passengers boarded the bus, and the type of ticket they purchased. Horários do Funchal uses RFID tickets for all passengers, including those purchasing single trips. This data is stored on-board and transmitted using WiFi each time the bus returns to the central garage.

Our system was developed on a Gumstix Waysmall btx-400, which has a 400MHz processor, a class 1 Bluetooth adapter, and 16 MB of storage. We refer to our system as a "scanner", and for our trials we installed one scanner in one bus. The scanner was installed on the roof inside the main bus cabin, near the exit area located in the centre of the bus

Figure 2. Installation of our system. a: The Gumstix computer (left), along with at 24 to 5 volt converter (right) used to power the Gumstix with the bus' electric circuit. b: a bus being rewired. c: our final installation consisted of a protective plastic case attached to the roof of the cabin. d: the system (indicated with an arrow) is installed near the centre of the main cabin. e: the control centre where real-time data is gathered from the buses' localisation systems and the whole operation is overseen.

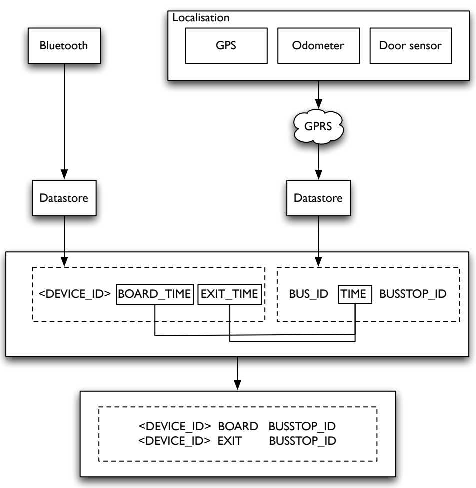

Figure 3. Correlating the Bluetooth data with the bus localization data. From our Bluetooth data we calculate the times when a device boarded and exited the bus. Using the bus localization data, we are able to figure out at what times the bus visited each of the bus stops on its route. Combining these two datasets, we are able to calculate the bus stops where a device boarded and exited the bus.

(see Figure 2).

The scanner software constantly issues a Bluetooth discovery request and records the results. According to the standard Bluetooth protocol, a Bluetooth device set to "Discoverable" mode must respond to the discovery request by transmitting its unique Bluetooth identifier (12 hex digits) and device class (6 hex digits). Our scanner constantly issues the same discovery request, and constantly records the presence of the various devices it encounters (along with the date and time of each distinct instance a device was discovered). Using this approach, we have the additional benefit of not requiring any special software to run on passengers' devices. The only requirement is that passengers set their devices' Bluetooth adapter to "Discoverable" mode. While we had not explicitly measured the proportion of residents in Funchal carrying a discoverable Bluetooth device prior to our study, we expected this proportion to be in the order of 7.5% of the population, as estimated by previous work [12].

IV. DATA ANALYSIS

While our localization and ticketing equipment is in constant use, we deployed our scanner for a period of two week. Single-day pilots where first run to empirically establish the performance of our system. During the actual study the bus covered 4 different routes at different times of the day. This is due to the way buses, drivers and routes interweave in the schedule of Horários do Funchal in order to improve operational robustness. Practically, this means that our scanner collected data for a number of different routes while remaining on the same bus. During our trial the scanner recorded more than 2000 unique Bluetooth devices.

In Figure 3 we present how we correlate the two datasets we have access to: our Bluetooth data and the bus localization data. First, we pre-process our Bluetooth data such that we derive device "trips". A device trip is defined by the unique Bluetooth ID of a device, the time when the device become visible to our scanner, and the time when the device disappeared from our scanner. In practice, our scanner's discovery cycle lasts 10.24 seconds, and no device names are further requested. To derive device trips we accumulate consecutive device discoveries that are less than 5 minutes apart. We set such a high threshold to compensate for instances where standing passengers possibly block the Bluetooth signals onboard the bus.

Having derived device trips, we then correlate these trip times with the bus localization database (Figure 3). By analyzing the localization data, we were able to calculate the exact times when the bus visited the bus stops on its route (with a 10 second error margin). This event is recorded when the bus reaches the bus stop and the driver opens the doors. This way, we were able to identify the exact bus stop when a device first appeared (hence the passenger boarded the bus), and when a device disappeared (hence the passenger exited the bus).

We should note that the correlation process removes a lot of noise from our Bluetooth dataset (approximately 20% of the raw dataset). For instance, our scanner detected devices while the bus was out of service or being repaired. Without the localization data, there is not way to verify if such Bluetooth data reflect passengers or not. With the localization data, however, we know that these devices appeared when the bus was not en-route, hence we can discard this data. Similarly, if our scanner picked up devices from outside the bus (e.g. passengers waiting at a bus stop), then these devices would appear to board and exit at the same bus stop, hence can easily be identified and removed. Finally, if any non-passenger devices where picked up in-between bus stops then our correlation process would not assign them any bus stop at all. We also note that an assumption we make in our analysis is that passengers do not enable or disable their Bluetooth device while onboard a bus.

V. RESULTS

Our equipment collected information about the

- location of the bus at any given time (via localization hardware),
- tickets validated on the bus (via ticketing hardware),
- presence of people on the bus (via Bluetooth hardware).

The number of passenger trips as recorded by our Bluetooth equipment varied each day, depending on the route of the bus. Figure 4 shows the number of trips broken down by hour. Specifically, the top of Figure 4 shows the average number of trips per hour as recorded by our Bluetooth equipment. The bottom of Figure 4 shows the average number of trips per hour, as recorded by the ticketing equipment.

In addition, we examined the correlation between our Bluetooth data and the electronic ticket data (Figure 5). We found a correlation of 0.859 (Pearson product-moment, $p<0.001$) between the number of device trips per hour and the number of tickets validated per hour.

Furthermore, the slope of the regression between these variables is closest to 1 when the number of Bluetooth trips is multiplied by a factor of 10.26. This suggests that about 9.7% of the passengers had Bluetooth-discoverable devices, which is in the same order of magnitude as previous estimates derived from [12].

In Figure 6 we show the number of passengers according to how many times they boarded the bus during our study. It is possible to identify repeated visits since Bluetooth devices have a unique and persistent ID.

Finally, a subset of the derived O/D matrix is shown in Figure 7 as a graph.

VI. DISCUSSION

Certain aspects of our analysis, such as calculating how often passengers use a service, can be carried out using origin-only data. Other aspects, such as trip duration, require both origin and destination data. While only the latter are truly novel in terms of transport engineering, here we discuss all aspects of our results in order to provide a more complete picture about its capabilities and limitations.

A. Passenger behavior

Due to the bus timetable, our equipment covered various services at different times during the day, without following any specific pattern. Equipment installed on a single bus does not provide enough information about the whole transport network, but rather gives discreet snapshots of individual services. This is further evident by the fact that the overwhelming majority of devices we recorded were seen only once (Figure 6), even though one would expect to see multiple commuters making at least 2 trips. An explanation for these results is the fact that our bus alternated between multiple services, even within a single day, hence missing pairs of outward and inward trips of individual commuters. We expect, however, that installing our equipment on multiple buses would enable us to generate results more representative of the activity on the whole network, and help us identify weekly and seasonal

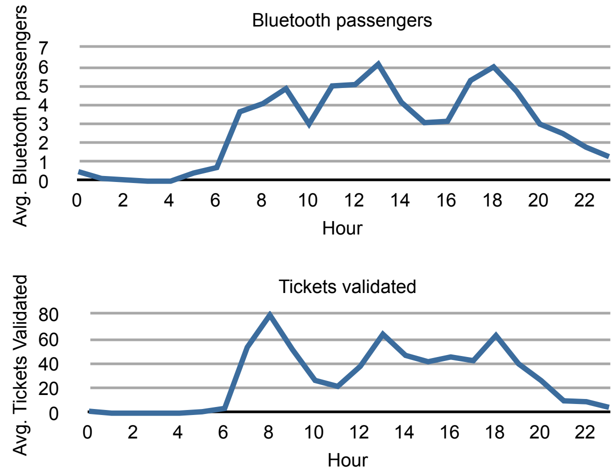

Figure 4. Top: the average number of passengers onboard the bus at any hour during the day, as recorded by our Bluetooth equipment. Bottom: number of tickets validated at any hour during the day on the same bus.

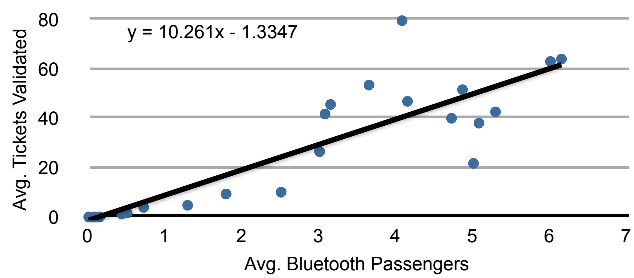

Figure 5. Correlation between the trips recorded by our Bluetooth equipment and the number of tickets validated (ground truth).

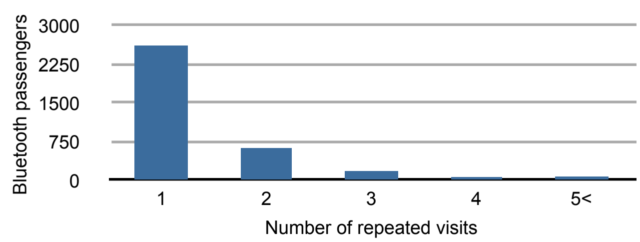

Figure 6. Histogram of the number of trips per individual passenger.

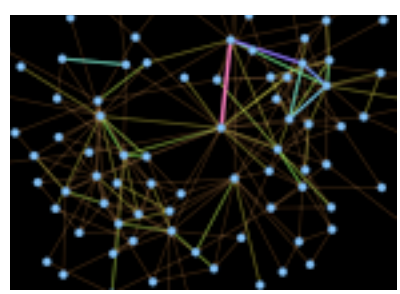

Figure 7. Subset of the O/D matrix shown as a graph where nodes designate bus-stops and connections designate trips (connection color and thickness indicates the popularity of a segment).

patterns.

In terms of temporal activity, Figure 4 (top) correctly highlights the expected morning, mid-day and evening peaks, representing people going to work, to lunch and returning home respectively. These figures accumulate information over the whole period of our study, hence providing more reliable temporal information.

The strong correlation (0.859) between our Bluetooth data and electronic ticket records provide compelling evidence for the accuracy of our technique. Effectively, we regard the electronic ticket records as the ground truth, since every single passenger is required to validate an RFID ticket (even if bought on the bus). While the correlation is quite strong, we feel it can be improved further by understanding an important source of noise currently skewing our results. Notice in Figure 4 that during the morning peak hours (7-9 am) our Bluetooth equipment is consistently under-representing the actual number of people on the bus. A possible explanation for this deviation is that as the bus approaches full capacity of sitting and standing people, Bluetooth signals increasingly decay due to the fact that human bodies act as barriers to electromagnetic signals. Hence, greater number of people on the bus lead to our Bluetooth equipment being able to detect a small portion of those passengers' devices. This can be mitigated by installing multiple Bluetooth transceivers on the bus, hence minimizing the average distance between our equipment and the passengers' devices.

An interesting point to note about the strong correlation of Bluetooth scanning with ground truth relates to identifying which groups of the population can actually be detected with our system. Our assumption is that Bluetooth-enabled devices are randomly among younger passengers, but it is likely that older passengers may not own such a device.

B. OD Matrix

As shown in the graph representation of the O/D matrix (Figure 7), popular segments can be identified by the intensity of their color and thickness, while popular bus stops can be identified by the number of incoming and outgoing links on the graph. The most popular bus stations are near the capital of the island, while the passenger flow captured in this O/D matrix in along a North-South axis. In addition, it is observed that the structure of the network is polycentric, with centers at the south, north, and south-east of the island. Each centre serves as an attractor to nearby regions, resulting in a large number of relatively short trips between each of the centers and nearby regions. This was further validated by directly comparing the recorded data with the routes that the bus served.

An array of tools can analyze an OD matrix and derive network improvements and optimizations, considering the micro, meso and macro scales of transportation (for an overview, see [5]). The OD matrix can be used to optimize network simulators used to predict when buses will reach the next bus stop, as well as optimize the schedule itself, by better allocating buses and drivers to routes [15]. In this sense our system provides rich data about origins and destinations, as we record data on a bus-stop level rather than zone level which can be larger than a square kilometer. This means that our OD matrix can be used to consider bus occupancy for every route in the network. Similar to Figures 4 and 5, each route can be analyzed for occupancy per hour, as well as per day of week. This can help identify under-utilised and over-utilised services, hence guiding decisions on merging or canceling routes, increasing the frequency of existing routes, or introducing new routes.

The low cost of our system (1/20th the cost of commercial passenger-counting systems) makes it possible to install it on more buses. Hence, while our system only detects Bluetooth-carrying passengers, it can do so on more services. Considering the business perspective of Horários do Funchal, let us assume they can afford to install a commercial passenger-counting technology on 5 of their 160 busses, hence recording 5/160ths of their annual passengers. With the same cost, they can use our system to cover 100 busses that record about 10% of 100/160ths of their passengers, or 10/160ths of their annual passengers, which is double the passengers compared to commercial systems. What is likely to be a winning strategy, however, is to use a mixture of the two systems, hence obtaining both fine-grained and high-volume data.

C. Towards Sustainability and New Services

Our system has provided the transport engineers an increased amount of information, both in terms of volume and granularity. One approach is to consider individualized OD matrices, i.e. to generate an OD matrix for each unique Bluetooth device. During our trials we recorded more than 2000 distinct devices. For each device we are able to calculate a customized OD matrix, which helps us predict where each passenger is likely to want to go and when they will get there, given the bus stop at which they are standing, the day of week, and time of day.

Considering individualized passenger information is an approach that can enable new types of services for before, during and after a passenger's trip. Bluetooth-augmented bus stops can use individualized OD data to identify where waiting passengers are likely to want to go. Thus, bus stops can display the time when the next bus will arrive as well as when the bus will reach the bus stops of interest to the waiting passengers. Knowledge of where the waiting passengers want to go can also be used to deliver relevant information about events and attractions.

Finally, our system could be used to provide a reward scheme that compensates passengers for time they potentially lose due to service inefficiencies. Our data already contains information about the exact time and location when a person boarded the bus. This can be cross-referenced with the time that the bus was expected to be at that location (i.e. the bus timetable). This comparison lets us calculate service delays that passengers have to cope with, and such delays could be used as "points" that passengers collect while using the service. An advantage of this scheme is that it motivates passengers to enable their Bluetooth so that they can collect points, as well as the lack of necessity for any specialized software to run on passengers' devices. Points can eventually be exchanged for free tickets or other possible rewards, and will require a booth-like mechanism that can let us verify the person carrying the Bluetooth device that collected points.

D. Limitations

An important issue to note is the penetration of Bluetooth through our passenger community. While we cannot explicitly assess the true distribution of Bluetooth within the community, we can expect that older passenger are less likely to carry such devices. What we do point out, however, is that mobile phones are increasingly commoditised and accessible to larger parts of the populations, with Bluetooth being a technology that is increasingly considered a standard feature of mobile phones. Hence, while at the moment we cannot directly assess which individuals carry (and enable) Bluetooth, our assumption is that in time the portion of Bluetooth-carrying passengers will grow steadily. A further limitation of our system is that it assumes that passengers do not enable or disable their phones while onboard. This could potentially lead to skewing of our data because the system would collect inaccurate information about people's entry and exit from the bus.

E. Privacy

Our use of Bluetooth has privacy implications which are increasingly becoming apparent to users. Our system tracks individual passengers' behavior over time, and by consequence records very precise information about people's location at any give time. Such information, should it fall in the wrong hands, can be used for harmful intents and purposes. For instance, a culprit may use knowledge of the fact that Alice is currently on the bus to infer that she is not at her flat and rob it. Hence, bus companies need to make sure that Bluetooth data is stored securely and is inaccessible to third parties. We should also point out that the same threats are posed by magnetic and RFID tickets, since they can be used in the exact same way to infer the location of passengers over time. In this case, a feature of Bluetooth that works to its advantage is that the Bluetooth ID cannot be linked to users' identity, unlike magnetic and RFID long-term passes which are usually linked to people's identity when they are issued. Furthermore, users can always disable their Bluetooth, thus avoiding detection at will.

VII. 7. Conclusion and ongoing work

We presented a system that can cheaply and automatically collect data about passengers' end-to-end trips. The major output of our work has been the passenger OD matrix, the subsequent graphs and analyses that can be derived from it, as well as the new types of services that our wireless system has enabled.

Fulfilling our goal of improving the transport network and ultimately improve its energy efficiency is a long process involving multiple stake-holders. However, the transport engineers at Horários do Funchal have been very positive about our results, and we are in the process of extending our system to more buses and bus stops. As part of this expansion, we are considering ways of linking our system to the on-board localization system and using its GPRS connection to remotely collect our data in real time. As Bluetooth technology is increasingly being used onboard busses we hope that our system can be used by more transport organizations to collect data about their passengers and eventually optimize their operation by redesigning their network and providing new services.

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