SIMPLE CAPACITIVE SEAT SENSING FOR OCCUPANCY DETECTION AND PASSENGER COUNTING IN MINIBUS TAXIS

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ABSTRACT

The informal public transportation sector in Sub-Saharan Africa contributes significantly to public transport, and yet little is known about passenger mobility patterns. We propose a low cost system to measure occupancy in a minibus taxi, and to improve understanding of passenger mobility in the taxi industry. A low cost capacitive proximity sensor for seat occupancy detection based on the loading mode capacitive sensing technique is designed and integrated with cellular communications to provide real-time information. The capacitive sensor uses a single electrode to detect an occupant. We use modules for a dynamic wireless system integration where sensors can be added or removed without modifications. A mathematical model of the capacitive sensor is developed to determine the capacitance on the sensor's electrode. The occupied capacitance is double the unoccupied capacitance. Our results show that the proposed capacitive sensor can distinguish clearly between an unoccupied and occupied seat for multiple seats.

1 INTRODUCTION

In Sub-Saharan Africa in general, including South Africa, the minibus taxi sector dominates informal public transport and has grown enormously in the past 20 years (Booysen, 2013). Not only is it the most available mode of transport, but also the most affordable. In 2008 it held 67.9% of the collective transport market share. According to the March 2011 Road Traffic Report (RTMC, 2011), there are 285,858 registered minibus taxis on the road. However, little is known about mobility patterns and passenger occupancy.

This paper describes the design and testing of a sensing and reporting system for the minibus taxi sector. This system consists of seat-mounted capacitive proximity sensors. The sensing system is not designed to detect overloading, but to determine when a seat is occupied. The use of a capacitive sensing technique enables the sensors to distinguish between a human body and a non-human object (luggage for example). The collected data is transmitted in real time, via a cellular carrier service, to a central database. It is then made available graphically on an online platform. The system is illustrated in Figure 1. This paper will only focus on the development of the capacitive sensor. However, the complete system can be seen in (Zeeman, 2013). The expectation is that owners of minibus taxis can use this system to better understand utilisation of their vehicles, and therefore have some understanding of the income generated. The authorities can use the information to improve understanding of mobility patterns and route utilisation.

Capacitive sensing describes a number of techniques to measure the capacitance between an electrode and its surroundings (Wimmer, 2011). Capacitive sensing technology to detect human presence has proven to be a robust and reliable measurement technology with low power consumption that is ideal for the dynamic automotive environment. A number of studies have therefore gone into capacitive sensors for seat occupancy detection with several prototypes developed.

Most of these occupancy detection sensors are developed for smart airbag systems (e.g. George, 2010) and to monitor drivers' vital signs (e.g. Jang, 2012). The focus of the above mentioned sensors are performance (fast response time) and high sensitivity. The above referenced sensors use the shunt mode technique. In shunt mode, the human body effectively becomes grounded, and screens the field, thereby reducing the current measured at the receiver electrode. According to Paradiso (1997) this technique cannot distinguish between a large mass far away and a small mass nearby, but multiple transmitter or receiver electrodes will break this degeneracy. Transmit mode is where the body acts as a virtual extension of the transmitter to the receiver electrode, which is not practical for occupancy detection. Loading mode capacitive sensing measures the change in capacitance between a single electrode and ground.

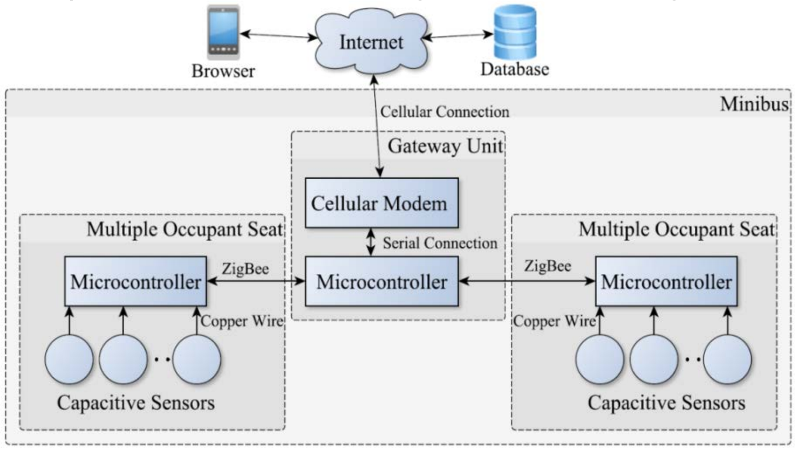

Figure 1 Occupancy detection system with online reporting in real time

Transmit and shunt mode capacitive sensing techniques therefore use multiple electrodes installed on the seat base and backrest for detection of a single occupant. Since this setup only detects a single occupant, the complexity of multi seat vehicles such as minibus taxis with 14 seats would be high. The prototype described in George et al (2010) uses 12 electrodes per seat, thus 168 electrodes would be required for a 14-seat minibus taxi. This sensor system setup is therefore complex and a large number of copper wires are needed to connect all the electrodes with a microcontroller. The distribution of the sensors in the vehicle will cause difficulties when connecting the sensors' microcontrollers with a central microcontroller (collecting all the data) and even more copper wires will be required which increases cost and complexity. We have therefore found that a multiple occupant detection system has two shortcomings when considered for the minibus taxi industry, namely complexity and cost.

2 OCCUPANCY DETECTION DESIGN

The implementation and design of the capacitive sensor's electronic circuit follows in this section. Background on capacitive sensing is given, followed by the implementation in an occupancy detection system in a minibus taxi. This paper is an extension of the work in Zeeman (2013), and the reader is referred to that work for more detailed information on the design.

Parallel plate capacitance can be defined as the amount of electrical charge, which changes with voltage, stored between two non-connected conductive plates. The capacitance depends primarily on the dielectric substrate of the objects, the size of the plates and the distance between them. A dielectric substrate is an electrically isolating material that provides isolation between the conductive plates.

The loading mode capacitor configuration is therefore approximated by the parallel plate capacitor model, since the capacitance is effectively determined between two conductive mediums (that is, the electrode and ground) with a dielectric medium in between (consisting partially of air).

An electronic system that measures the capacitance directly or indirectly, using the loading mode capacitive sensing technique, is simply referred to as a capacitive sensor for the remainder of the paper. The electronic circuit setup can be seen in Figure 2.

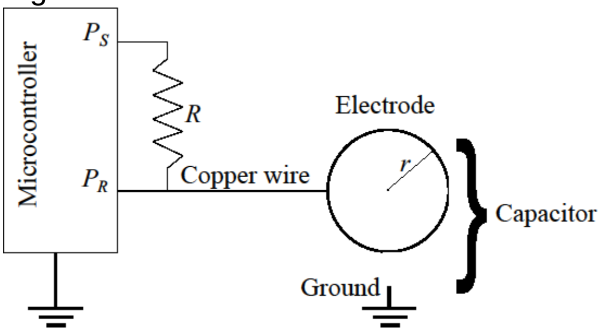

Figure 2 Capacitive sensor's circuit diagram, with $\boldsymbol{P_S}$ the stimulus and $\boldsymbol{P_R}$ and response pin.

The circuit requires a high value resistor (R) between the stimulus pin P_S and the response pin P_R. The high value resistor ($10M\Omega - 50M\Omega$) ensures a sufficient charge/discharge time in the order of $500\mu s$. A higher R will result in a more sensitive capacitive sensor, but more susceptible to electrical interference and noise. The electrode is the sensor component to detect human proximity and is connected with a copper wire to the response pin. The sensor electrode is made from a thin circular metal plate covered by a piece of non-conducting material. This is the sensor component, which is installed on the surface area of the taxi seat, and is occupied by the occupant. The placement of the electrode on the seat can be seen in Figure 3. More information on the process used in the software can be found in the work by Zeeman (2013). The value of the timer is directly proportional to (τ), the RC time-constant.

$$\boldsymbol{\tau = R \times C} \tag{1}$$

Since the resistor value (R) stays constant, the delay depends solely on the capacitance (C).

1.1 Occupant detection

A human body entering the proximity of the sensor, changes the electrical properties between the sensor electrode and ground, which increases the total capacitance resulting in a higher RC time-constant. This will increase the capacitor's charge/discharge time. It is therefore possible to determine if a seat is occupied by interpreting the timer value. The microcontroller monitors the timer and regulates the oscillating frequency at which the voltages changes between the stimulus and response pins.

A multiple occupancy detection system requires multiple sensors since each sensor detects a single occupant. The sensors are installed on the sitting area of the seat as seen in Figure 3.

One sensor is installed on each seat of the minibus taxi, except for the bigger rear seat where an additional sensor is placed.

From collected data, it was seen that the capacitance on the electrode contains a lot of noise. This is expected, since the sensing system is not contained to only detect the capacitance above the electrode (ideal model), but detects the capacitance in the proximity of the electrode. A digital filtering is therefore implemented in the microcontroller to remove high frequency capacitance variations, which influences the output timer value.

The timer value of every charge/discharge cycle is filtered, using a low pass filter (LPF). An exponential moving average (EMA) is chosen as the LPF since it results in shorter effective lag than a simple moving average. The EMA is a type of infinite impulse response filter that applies weighting factors which decrease exponentially. An empirically determined sampling rate of 50Hz is implemented for the occupancy sensor. Other sampling frequencies were tested, but this frequency resulted in good performance, and accurate results. The LPF takes the weighted average of the readings over the last three seconds. The three second weighted average was chosen since this filtering window filters out small manoeuvres performed by the occupant, when moving on the seat, and other external interferences on the vehicle. When the filtered timer value exceeds the occupied threshold, the seat is seen as occupied.

A scenario that frequently occurs is when the minibus taxi stops to pick up or drop off passengers and the passengers move over the seats to make room for new passengers. A detection delay is therefore implemented that accommodates for the occupants moving over a seat, sitting temporarily on the sensor, but not actually occupying it – After the timer value indicated that the seat is occupied, the detection delay waits for five seconds, and then changes the seat status. This applies for a change in state from occupied to unoccupied, and vice versa. This delay was determined empirically from numerous tests.

3 ANALYSIS

In this section a theoretical model, and simplified mathematical representation, of the capacitive sensor is developed to determine the relationship between the capacitance of an unoccupied and occupied seat. The analysis of the minibus taxi and capacitive sensors has indicated that a large number of factors can influence the sensors' capacitance. To determine a theoretical model of the capacitive sensor in a vehicle, some approximations are made.

The minibus taxi chassis is chosen as the common electrical ground (GND) and reference point for the capacitive sensors. A change in capacitance between the electrode and the chassis is therefore determined with capacitive coupling assumed to be only between the electrode and ground. There are 14 or 15 passenger seats in a typical minibus taxi. For simplicity's sake, the seats are assumed to have the same dimensions and material composition. The seat properties will be discussed later on in this section. The charge density distribution is assumed to be uniformly distributed on the electrode for the capacitive sensor to be approximated as a parallel plate capacitor as discussed below.

The simplified model of the sensor in the minibus taxi is illustrated in Figure 3. In Figure 3, S_1 represents a single capacitive sensor mounted in the seat where C_1 and C_2 are the parallel plate capacitances with respect to GND. Each of the seats will have such a sensor, and thus a similar capacitive model. From Figure 2, V_S is the stimulus pin's output voltage, V_R is the response pin's input voltage, and R the resistor that stays constant. C_2 is the capacitance, which changes when a human body enters the proximity of the sensor electrode. The parallel plate capacitance (C) is given by

$$\mathbf{C} = (\boldsymbol{\epsilon}_\mathbf{o}\, \boldsymbol{\epsilon}_\mathbf{r}\, \mathbf{A})/\boldsymbol{d} \tag{2}$$

with: A the plate area in (m^2), d the distance between the plates (m), ϵ_o the permittivity of free space $= 8.854 \times 10^{-12}$ (F/m), ϵ_r the relative permittivity of the dielectric substrate between the plates (dimensionless). Since A and d stays constant, and since ϵ_o is a constant, only ϵ_r can change the capacitance.

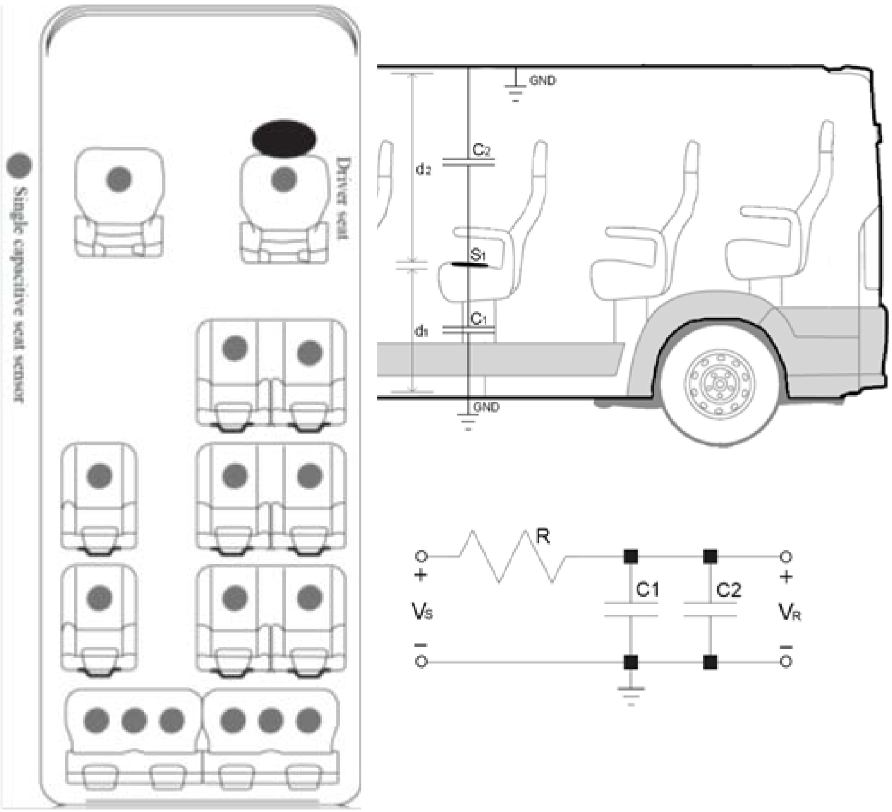

Figure 3 Taxi with occupancy sensors and equivalent electrical model.

With two parallel plates forming a capacitor, the electric field lines are not limited to the sensor, but curves outside the electrode causing the capacitance to be higher than what would have been calculated from the ideal expression (1). This effect is known as fringing. The capacitive sensor's electrode size (A) is therefore increased by 13% to accommodate the fringing effect in this section (Hoch, 1926).

Since a significant part of the dielectric substrate is composed of air, an effective dielectric constant (or effective relative permittivity) is derived by approximating the capacitive sensor as a microstrip transmission line. Microstrip transmission lines constitute of a conductive strip of width (w), and a wider ground plane, separated by a dielectric substrate of thickness or height, h. The effective relative permittivity (ϵ_e) is somewhat less than the substrate's relative permittivity due to the part composed of air (with a relative permittivity of 1) and can be approximated, according to Bahl (Bahl, 1977), with the following expression

$$\boldsymbol{\epsilon}_\mathbf{e} = \begin{cases} \frac{\boldsymbol{\epsilon}_\mathbf{r}+1}{2}+\frac{\boldsymbol{\epsilon}_\mathbf{r}-1}{2}\left[\left(1+12\frac{h}{w}\right)^{-1/2}\right] & \textbf{when } (w/h) \geq 1 \\ \frac{\boldsymbol{\epsilon}_\mathbf{r}+1}{2}+\frac{\boldsymbol{\epsilon}_\mathbf{r}-1}{2}\left[\left(1+12\frac{h}{w}\right)^{-\frac{1}{2}}+0.04\left(1-\frac{w}{h}\right)^2\right] & \textbf{when } (w/h) < 1 \end{cases} \tag{3}$$

As explained in section 2 of this paper, the time constant depends solely on C_{TOTAL} where the total capacitance of two parallel capacitors in a circuit is given by

$$\boldsymbol{C_{TOTAL} = C_1 + C_2} \tag{4}$$

The capacitance under the seat (C_1) stays constant, contrary to the capacitance above the seat (C_2) which can be in either one of states: occupied (occ) or unoccupied (unocc). The total capacitance on the electrode when no human body is in proximity of the sensor, i.e. the unoccupied state, is calculated as

$$\boldsymbol{C_{TOTAL(unocc)}} = \frac{\boldsymbol{\epsilon_0 \epsilon_{e1} A}}{\boldsymbol{d_1}} + \frac{\boldsymbol{\epsilon_0 \epsilon_{e2unocc} A}}{\boldsymbol{d_2}} = \boldsymbol{\epsilon_0 A} \left(\frac{\boldsymbol{\epsilon_{e1} d_2 + d_1 \epsilon_{e2unocc}}}{\boldsymbol{d_1 d_2}} \right) \tag{5}$$

where $\epsilon_{e2unocc}$ and ϵ_{e1} is the effective dielectric constant of respectively the dielectric substrate above and below the sensor electrode. The total capacitance on the electrode with a human body in proximity of the sensor, i.e. the occupied state, is calculated similarly:

$$\boldsymbol{C_{TOTAL(occ)}} = \frac{\boldsymbol{\epsilon_0 \epsilon_{e1} A}}{\boldsymbol{d_1}} + \frac{\boldsymbol{\epsilon_0 \epsilon_{e2occ} A}}{\boldsymbol{d_2}} = \boldsymbol{\epsilon_0 A} \left(\frac{\boldsymbol{\epsilon_{e1} d_2 + d_1 \epsilon_{e2occ}}}{\boldsymbol{d_1 d_2}} \right) \tag{6}$$

where ϵ_{e2occ} is the effective dielectric constant of the substrate above the sensor electrode when an occupant is present.

We have therefore calculated the expected capacitance on the sensor of an unoccupied and occupied seat. The only difference between the capacitance is from a change in ϵ_{e2}.

The main composition of the vehicle's seat material is polyethylene foam, with a relative permittivity of 2.26 (Elert, 2012). The relative permittivity of the vehicle's seat is therefore approximated as 2.26. From (3), the effective relative permittivity (ϵ_{e1}) is calculated as 1.88, since the capacitive sensor electrode has a diameter w of 22cm and substrate height h of 10cm (effective electrical height from the seat surface to the chassis floor), which therefore results in $w/h > 1$. The reason for this low substrate height is because of the metal found in the seat which effectively reduces the distance between the sensor electrode and ground. For the dielectric substrate above the electrode: the relative permittivity ($\epsilon_{e2unocc}$) is estimated as 1, which is the relative permittivity of air, since almost all the whole volume above the seat is air.

An occupant on the seat will increase the relative permittivity of the dielectric substrate above the electrode (ϵ_{er2occ}) substantially, since the human body are comprised of 70.4% water, which has a relative permittivity of 74.1 (Gabriel, 1996). An effective relative permittivity is calculated as 42.91, with w and h as 22cm and 127cm respectively, resulting in $w/h < 1$.

The theoretical model is concluded by calculating the approximated capacitance on the sensor electrode. The unoccupied capacitance is calculated from (5) to be 8.41pF and the capacitance on the electrode when an occupant is present is calculated from (6) to be 22.59pF. The dimensions used during calculations are from actual measurements in a Quantum minibus taxi. The following table is a summary of calculated theoretical capacitance, and includes the values of the two capacitances in parallel (C_1 and C_2) from the simplified circuit diagram in Figure 3.

Table 1 Calculated theoretical capacitance below (C_1) and above (C_2) the sensor electrode.

	Unoccupied capacitance (pF)	Occupied capacitance (pF)	Equations
C_1	8.07	8.07	(2) and (3)
C_2	0.34	14.52	(2) and (3)
C_{TOTAL}	8.41	22.59	(5) and (6)

By comparing the capacitance of the unoccupied state with the capacitance of the occupied state, there can be seen that the occupied state has a significantly larger capacitance. The relationship between occupied/unoccupied is calculated as 2.7, thus more than double. From the theoretical calculations it is therefore determined that an occupant can clearly be detected on the capacitive sensor electrode.

4 RESULTS

In this section the capacitance on the sensor electrode, for an unoccupied and occupied seat, is measured and compared to the expected capacitance calculated with the developed mathematical model.

The capacitance of the sensor electrode is determined by measuring the charge and discharge time of the electrode. The unit has three sensor electrodes connected, and logs the charge and discharge times at a sampling rate of 50Hz. Eight tests were run on the three sensors in the minibus taxi to determine the charge and discharge times for all possible seat-occupant combinations.

The seat-status combinations for the eight tests are illustrated in Figure 4, which shows the capacitances for each of the combinations. These tests are performed since they provide a good indication of the measured capacitance on the sensors. The theoretically calculated capacitances (from Section 3) were calculated as 8pF and 23pF for the unoccupied and occupied state respectively. Figure 4 shows the normalised occupied and unoccupied capacitance on the electrode for the eight tests, and includes the theoretical results.

The experimental results demonstrate that sensor 1 has the highest capacitance readings, with an average of 110pF for the occupied state. Sensor 2 has an average of 86pF, and sensor 3 an average capacitance of 76pF. As previously mentioned, occupant 2 has a small body mass, occupant 1 slightly bigger and occupant 3 the largest body mass. Sensor 1 and sensor 2 behave as expected, with an increase in capacitance with the increased body mass. The unexpected lower capacitance on sensor 3 shows that the sensor is less sensitive than the other two sensors, most likely due to its location in the vehicle.

The experimental results are compared with the expected theoretically calculated capacitance. The measured capacitance is higher than the expected theoretical capacitance. The unoccupied theoretical capacitance has a value of 8pF, compared to the lowest measured capacitance of 27pF. For the occupied state, the expected capacitance is also lower than the measured capacitance. The theoretical capacitance has a value of 23pF, compared to the lowest measured capacitance of 75pF. The difference between the theoretical and the measured capacitance is as a result of the approximations made in the theoretical calculations and external factors (electrical coupling between the sensor and metal objects in the seat) affecting the sensor properties.

Although the results differ, the aim of these tests is to determine if the capacitive occupancy detection system is a viable option for the detection of occupants in a minibus taxi.

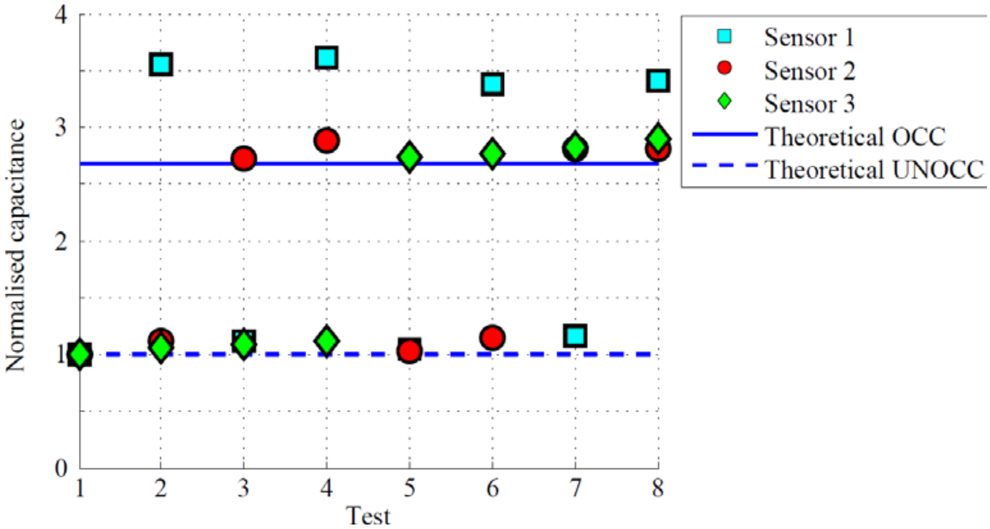

Figure 4 Results comparing the measured capacitance to the expected theoretical capacitance for an occupied and unoccupied seat.

In Figure 4 the normalised results show that both the theoretical and measured capacitance increases significantly from the unoccupied to the occupied state. For the theoretical calculations, the relationship between the occupied and unoccupied capacitance C_{OCC}/C_{UNOCC} is 2.7, and the relationship for the measured capacitance, is 2.8, taking the average ratio from all the tests.

The measurements and ratios therefore prove that the occupancy detection system is a viable option for the detection of occupants in a minibus taxi, since the occupied capacitance is more than double the unoccupied capacitance.

The following tests were also performed with human occupancy correctly detected, as expected: partially sitting on a seat; putting a suitcase on a seat; putting a bag on a seat; occupant touching the chassis of the vehicle; seat partially drenched with water. The result, from a subset of these tests, is shown in Figure 1Figure 5, clearly showing the sensor independence, and also the three second delay introduced by the LPF.

5 ONLINE REPORTING SYSTEM

This section illustrates the online reporting system, which constitutes the top half of Figure 1. Data captured at all the capacitive sensor-enabled seats in the taxi, are reported wirelessly (using a robust Zigbee network) to a central controller, which uses a cellular modem to transmit the status of all the seats in the taxi to the online platform. Trinity Telecoms' SMART platform is used to store and visualise the occupancy and tracking information. This platform simplifies duplication and aggregation of remote data on a large scale, which is suited to the large minibus taxi industry. Moreover, the platform allows a hierarchy of access accounts and browser access, which allows each owner to view their own taxis on their own mobile phones, but also allows the taxi associations and road authorities to view the aggregated information at regional or national level. The online platform is shown in Figure 6. Online tracking is provided as an additional benefit.

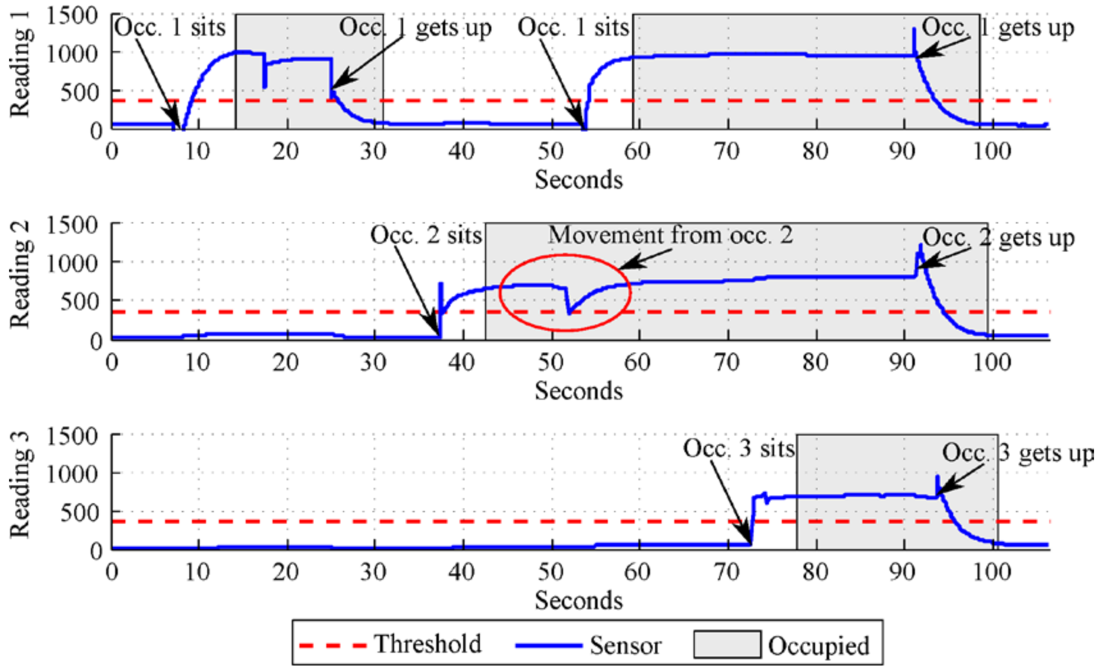

Figure 5 Result showing occupancy movement and resulting detected occupancy.

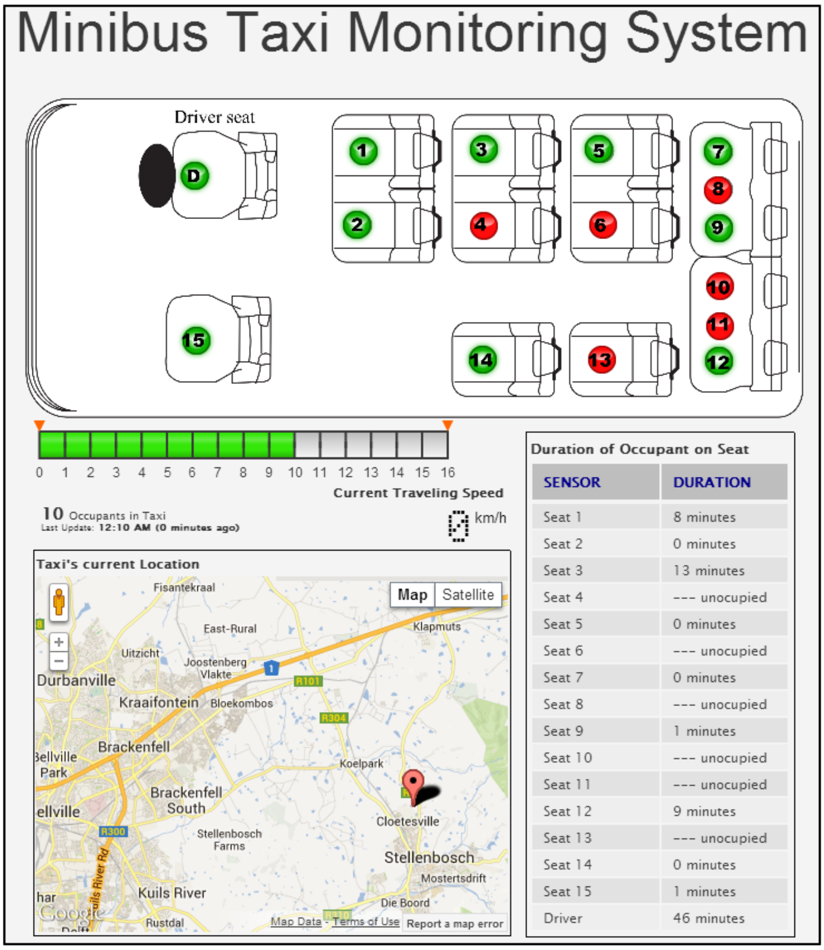

Figure 6 Online minibus taxi monitoring system's online dashboard.

6 CONCLUSION

This paper describes the development of a multiple seat occupancy detection and reporting system for use in the minibus taxi industry. The focus of the work is on the capacitive seat sensor, but the online reporting system is also described. From the theoretical and empirical results, it is determined that the loading mode capacitive sensing technique can distinguish clearly between an occupied and unoccupied seat. The relationship between unoccupied and occupied is approximately double. The simple and low cost capacitive sensor system is ideal for occupancy detection in multiple seat vehicles, because of its low cost design and wireless system integration. Compared to other occupant detection systems, this simple electrode and wireless module configuration reduces wiring complexity, maintenance, cost and ensures greater flexibility for instalment within the vehicle. Collected information can be used by owners, taxi associations, and authorities to improve the utilisation and understanding of this sector of public transport.

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