

# SUSTAINABLE BUS DESIGN FOCUSED ON IMPROVED ACCESSIBILITY

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## SUMMARY

The world population is ageing and designing accessible public transport modes is a real challenge for all societies nowadays. The influence of bus movement on the movement of passengers is analysed in this study. Experiments on a static platform and a moving bus were carried out and body motion and foot pressure tracking systems were used to collect information about bus acceleration and the plantar forces of the person. From the experiments it was shown that the movement of the bus does not vary with the vertical position in the bus but it affects a passenger's gait and balance especially whilst ascending and descending the staircase.

**Key words:** moving passengers; acceleration; gait; balance; accessibility; safety

## TERMINOLOGY

*Cadence* is the number of steps per minute.

*Double support time (DST)* in seconds is the time during which both feet are on the ground and relates to a person's stability [Reid et al., 2011].

*Stance time (ST)* in seconds is the time a single step lasts from the moment the foot touches the ground (Heel Strike - HS) until the moment before it is lifted from it (Toe off - TO) and it includes double support time [Khodadadeh et al., 1987; Reid et al., 2011].

*Stride time* is the duration of a complete cycle of the limb measured in seconds.

*Jerk* is the rate of change of acceleration measured in  $m/s^3$ .

*Swing (S)* is the time in seconds between the last contact of the first support of the foot and the first contact of the following support.

# 1. INTRODUCTION

## 1.1. Background

Public transport modes can enable the elderly to partake in everyday life, hence improving their social inclusion and the population of many societies consists increasingly of more elderly than young people [O'Neill & Carr, 2005]. Accessible design of public transport modes becomes more crucial in order to meet the needs of all passengers and provide comfortable journeys.

Buses are the only public transport mode interacting with traffic and hence fore-and-aft acceleration can be at a much higher level ( $2.15 \text{ m/s}^2$  on a bus) than on any other public transport mode (e.g.  $1.5 \text{ m/s}^2$  for metro), decreasing the comfort of passengers [De Graaf & Van Weperen, 1997]. The study will focus on the London double decker bus, as it is part of one of the largest urban transport systems in the world with 2.3 billion passenger journeys in 2010-2011 [Transport for London, 2011].

People of different age groups or characteristics such as obesity and mobility impairments use the London bus service and are likely to face several problems while travelling by bus. A problem shared by all passengers in a moving bus is sustaining their balance whilst trying to find a seat or using the staircase. There are over 800 falls on buses every day in the UK by people over 65 years old who cannot cope with the bus accelerations [Age UK, 2009] with falls from stairs and steps and falls on the same level being reported as the most common types of falls [CIHI, 2011]. Fear of falling is an equivalent problem to falls as it can affect a person's quality of life and health. In the UK, 53% of the total cost of falls is related to falls on or from stairs or steps and 30% to falls on the same level for those over 60 years old [Scuffham et al., 2003]. Older passengers, especially women, are less stable than younger passengers and according to Halpern *et al.* [2005], standing and moving passengers sustain more injuries, especially during sudden acceleration and deceleration. However, acceleration on conventional buses depends solely on the driver's driving skills.

Walking on flat surfaces is influenced by demographic characteristics and the body capabilities of a person [Fujiyama & Tyler, 2010]. In general, men walk faster than women [Tregenza, 1978], older people have a shorter step length [Lockhart et al., 2007] and a person's stride time is affected by their walking speed [Kang & Dingwell, 2008]. Climbing the stairs on the other hand is more demanding as it requires more body capabilities for the centre of mass to be transferred vertically from one step to another [Mayagoitia & Kitchen, 2009]. Even though stair descending is faster than ascending [Reid et al., 2011], descending requires more muscle strength [Salsich et al., 2001; Sowers et al., 2006] and loss of balance is more likely to happen than [Svanström, 1974; Verghese et al., 2008] especially for older adults who have reduced muscle strength [Ewen et al., 2009]. Older people and women achieve lower speeds than younger people and men while climbing the stairs [Fruin, 1971]. Furthermore, people with smaller step length, lower grip strength and shorter unipedal stance have more difficulties climbing the stairs [Verghese et al., 2008].

Comfort and balance were of interest to many researchers aiming at investigating their relationship to the motion of the vehicle. Turner and Griffin [1999] state that the upper and lower deck contribute the same in motion sickness and that the location along the length of the bus results in different acceleration levels. Acceleration in the lateral direction and at the rear of the bus is responsible for the highest discomfort.

When acceleration occurs, the passengers of a vehicle react to the forces applied on them by altering their posture and stiffening their muscles. In most cases passengers are not aware of such events and their ability to stand still depends on their reaction time. The lower the rate of acceleration, the longer the time the passenger has in which to react. According to Dorn [1998] and Vuchic [1981], standing passengers cannot maintain their balance when acceleration is higher than  $2\text{m/s}^2$  and the rate of change of acceleration is quicker than  $0.60\text{ m/s}^3$ .

The studies reviewed above mainly considered either moving passengers in a stationary bus or non-moving passengers in a moving bus. Only Levis [1978] studied the real life situation to some extent by evaluating passengers' comfort whilst walking towards a seat inside a moving bus and found that an increase in acceleration leads to alteration of leg position, arm orientation and hand grip. This reveals that further research is required as most injuries happen during acceleration and deceleration when the bus is leaving or arriving at a bus stop. Hence, it is crucial to examine the changes in passengers walking whilst the bus is in motion.

## **1.2. Purpose of this study**

The aim of this study is to improve the accessibility of the current bus design for all passengers by assessing their ability to cope with the accelerations developed on a bus and to retain balance whilst moving inside or climbing the stairs in a moving bus. This will be achieved by evaluating the current bus design in terms of comfort for the passengers of all age groups, by assessing the differences in passenger's gait when moving inside a moving bus by analysing the effects of the acceleration of the bus on passenger's interactions. There are many technical challenges with conducting such a study and this paper describes an initial set of experiments designed to check whether it would be possible to obtain data to inform the study.

## **2. METHODOLOGY**

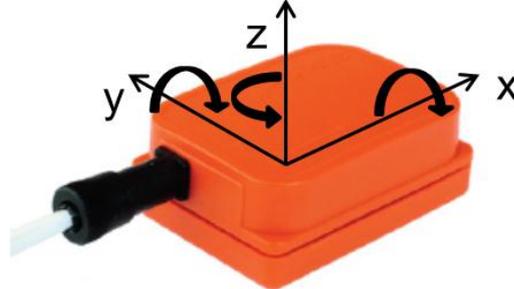
### **2.1. Level of acceleration on a double decker bus**

The aim of this experiment is to define the level of accelerations and the jerk that are being developed when the bus leaves a bus stop and moves around a given route. More specifically, it is important to identify whether the accelerations developed at the top of the staircase of a double decker bus are of the same level as those developed at the bottom and the middle of the staircase.

A route of five right and five left turns was chosen for a normal driving time of ca. 10 minutes. It was repeated 14 times during a low congestion traffic period (10am until 1pm) and the driver was asked to perform his usual driving style. The bus was equipped with a video camera to record the traffic in front of it. In order to measure the accelerations and rotation angles of a double decker bus, a motion tracking system of five tri-axial sensors which consist of an accelerometer, a gyroscope and a magnetometer was used. The X-sens sensor and its coordinate system are shown in Figure 1 below. The rotation angles are calculated in real time by the software and only the acceleration signals were taken into account for the particular experiment.

Three X-sens sensors were placed on the lower floor, midway up the stairs and on the top floor of the bus. The x axis coincided with the direction of movement pointing towards the front of the bus, the y axis coincided with the side along the width of the

bus and the z axis matched the vertical direction. The sensor attached to the upper floor of the bus was chosen to be placed directly above the one attached to the lower floor. Measuring acceleration in such an environment is not very usual, especially when human participants are being involved and hence, the sampling frequency of the data recordings was set at 50 Hz. The fore-and-aft, lateral and vertical accelerations together with the rotation angles were analysed.



**Figure 1: Tri-axial motion tracking sensor. Roll is the rotation around x axis, pitch is the rotation around y axis and yaw is the rotation around z axis. The arrows reveal the positive direction of the axes.**

## **2.2. Passenger movement inside a moving bus**

Events such as walking towards a seat or ascending and descending the staircase when the bus is approaching (decelerates) or leaving (accelerates) a bus stop are considered as crucial and will be examined here. The following experiments were conducted on a single person so as to evaluate the experimental process.

At first, a 27 year old male was asked to answer to questions related to his travelling habits, seat preference and the difficulty of performing tasks such as ascending and descending stairs and walking to a seat. His height and weight, the width of his step and the length of his arms and legs were also measured. So that we could check whether the outcome data might indicate if a person's peripheral vision, grip strength or leg extensor power might contribute to their stability, these were also measured. Various baseline tests were then undertaken by the participant in the static conditions of the PAMELA laboratory (UCL). A unipedal balance test [Steenbekkers & Van Beijsterveldt, 1998] as well as the 'Timed Up and Go' (TUAG) test [Yelnik & Bonan, 2008] were carried out in order to identify the participant's level of balance. The participant's agility and way of walking on a curved and straight line were tested with the 'Figure-of-8' and the 'Ten-steps' tests respectively. For the former, a line in the shape of number eight (8) was marked on the platform whereas for the latter the participant was asked to walk in a straight line at his normal pace and take ten steps. During the tests, pressure insoles of the F-Scan system (Tekscan Incorporated) were placed inside the shoes for the collection of plantar forces. The baseline tests were followed by dynamic tests on a real bus in static and moving conditions. During Condition 1 the subject moved towards a target seat on the lower deck whereas for Condition 2 he was asked to ascend and descend the staircase. These conditions were repeated three times for when the bus is stationary (Task A) and when it is moving on a straight uncongested road (Task B). Six cameras were placed on the lower and upper deck of the bus and a single accelerometer was secured in the middle of the staircase. All devices were recording at 50 Hz. At the end, the subject was given a questionnaire in order to assess each task.

### 3. RESULTS

#### 3.1. Level of acceleration on a double decker bus - Results

Acceleration and rotation data from the lower and upper floor as well as the staircase were captured during an earlier experiment. This aimed to assess whether the rotation angles and the acceleration in three dimensions at all levels of the bus remained the same during a bus journey. The raw acceleration data revealed that the middle of the staircase is vibrating more than the lower and upper floor, especially in the lateral direction of acceleration. Data filtering of 0.2Hz cut-off frequency was then processed which showed that acceleration and rotation angles are identical for the three examined levels.

The maximum fore-and-aft and lateral acceleration was  $1.25 \text{ m/s}^2$  and  $1.08 \text{ m/s}^2$  respectively. Also, the initial fore-and-aft acceleration reached  $1.13 \text{ m/s}^2$  with a  $0.12 \text{ m/s}^3$  rate of change. Both values are much lower than those recommended in the literature but they are highly dependent on the driver's skills.

#### 3.2. Passenger movement inside a moving bus – Results

##### 3.2.1. Baseline tests

The characteristics of the participant (Section 2.2) were collected during the baseline tests and it was revealed that the participant was of a high balance (34.34 sec). Testing his gait pattern and balance mechanisms in different static environments was important and for this purpose three agility tests were performed: 'TUAG', 'Figure-of-8' and 'Ten steps'. Force data were collected throughout the tests and their duration was timed.

Force against time graphs were plotted and it was revealed that the participant's gait mainly consisted of two-peak strides (Figure 2) with the first being related to the force applied on the heel and the second to the force applied on the front part of the foot. The turning point during TUAG and 'Figure-of-8' tests was defined by either a one-peak stride or a three-peak stride where a third area of the plantar was under pressure. This is an indication of the balance mechanism that the subject is engaging when the level of difficulty of the test is increased.

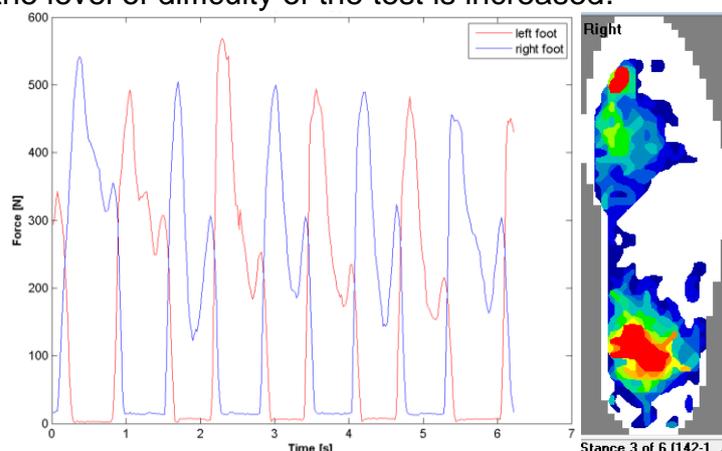
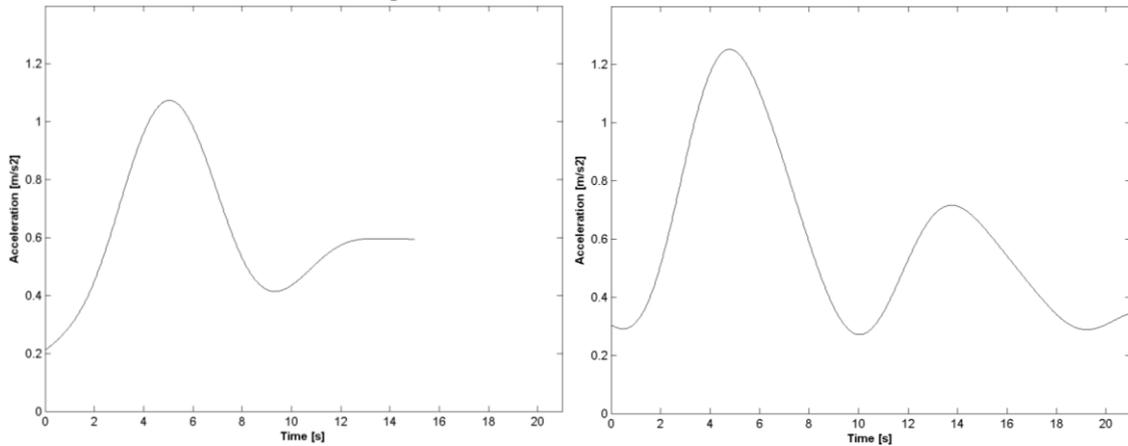


Figure 2: Gait pattern and pressure distribution during 'Ten steps' test

##### 3.2.2. Tests on a double-decker bus

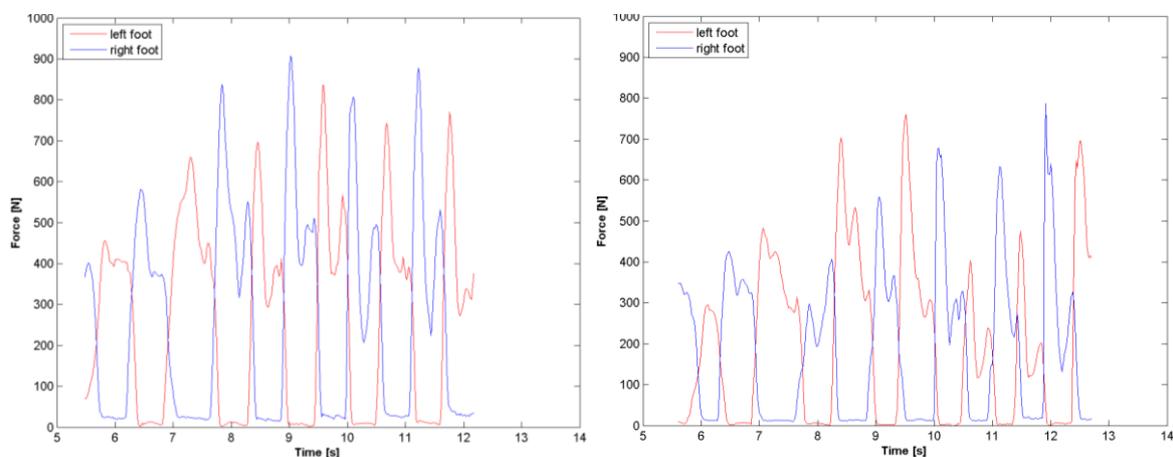
As mentioned above (Section 2.2) the experiment on the double-decker bus

consisted of two conditions for which the participant had to undertake two tasks. For Condition 1, the participant was asked to start from the front door, validate his oyster card and walk towards a target seat. For Condition 2, he first ascended the 8-step staircase, then turned at the top of it and descended and stopped by the rear door. This was repeated three times on a stationary (Task A) and a moving bus (Task B). The longitudinal acceleration of the bus during Task B was measured by one accelerometer (Section 2.1) placed in the middle of the staircase. Only the results of the run during which the highest rate of acceleration was recorded are presented here. The maximum jerk recorded was  $0.28 \text{ m/s}^3$  during Condition 1 and  $0.38 \text{ m/s}^3$  during Condition 2 and the profiles of the longitudinal acceleration of the two conditions are illustrated in Figure 3.



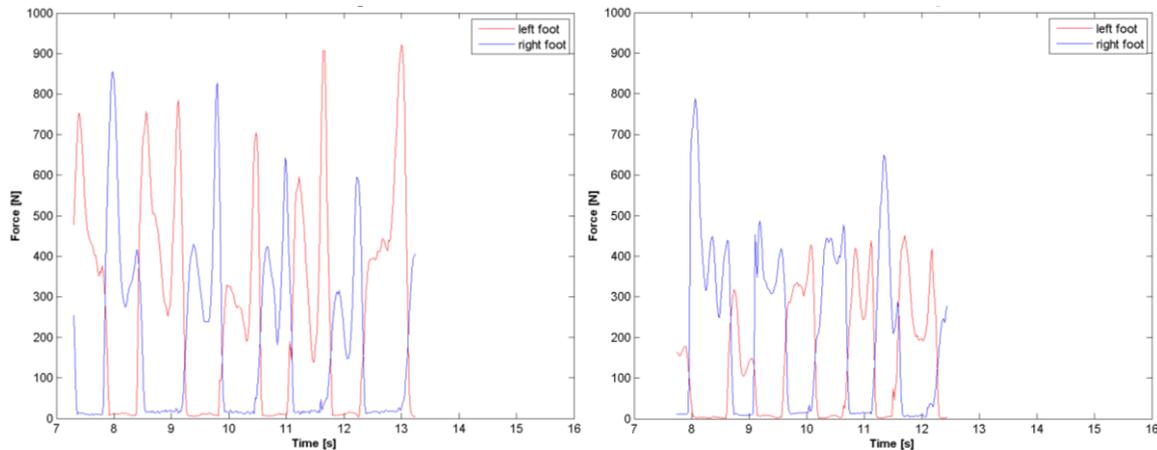
**Figure 3: Longitudinal acceleration of the double-decker bus during Task B of Condition 1 (left) and Condition 2 (right)**

In order to identify whether the participant was performing different gait patterns when the acceleration of the bus was applied, force-time graphs were plotted and analysed. From the synchronisation of the devices it was possible to separate the actual duration of each task and focus on the parts during which the subject was moving. Moreover, the ascending and descending of the staircase were treated as two different cases with the turn at the top of the staircase being excluded from the analysis. All three cases (Condition 1, Condition 2-ascending and Condition 2-descending) revealed that the subject was applying lower force on his feet when the bus was moving.



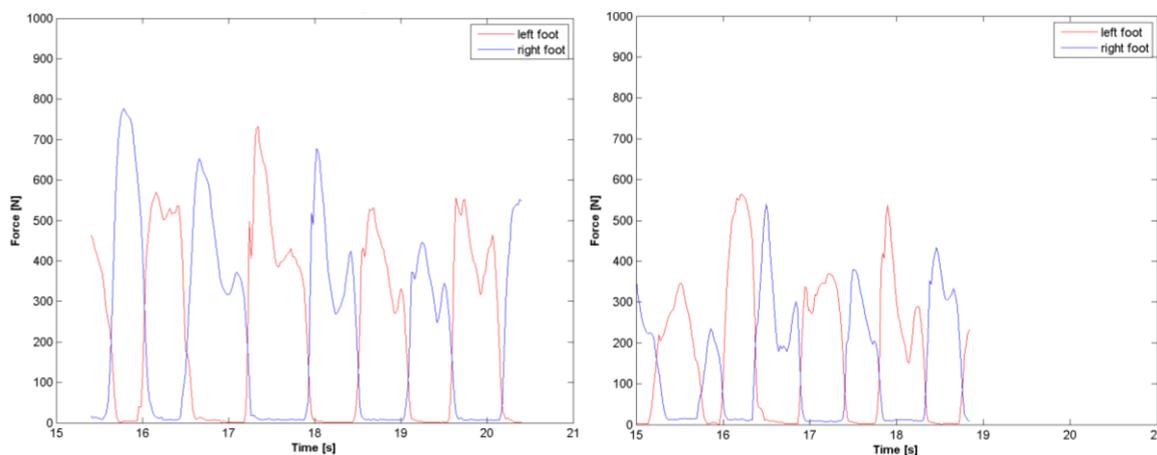
**Figure 4: Gait pattern of participant whilst walking to a seat when the bus is stationary (left) and moving (right)**

Specifically for Condition 1 (Figure 4), it was shown that the gait pattern during Task A consisted of mostly two-peak strides whereas gait during Task B consisted of more three-peak strides. One stride in particular revealed higher TO than HS force which shows the subject's attempt to decelerate so as to maintain balance. Furthermore, two additional steps were taken by the subject during Task B and hence the duration of the task was longer.



**Figure 5: Gait pattern of participant whilst ascending the stairs when the bus is stationary (left) and moving (right)**

Ascending and descending the staircase (Figure 5 and Figure 6) consisted of eight steps each but it was noticed that the participant took more steps at the top of the staircase as deceleration commenced with a foot alteration. The participant required more time to ascend the stairs however both ascending and descending were completed in a shorter time when the bus was moving. This indicates that in the case when the participant lost balance, he tried to regain in the following step. Regarding the subject's gait, it can be seen that the force profiles during Task B do not follow a particular pattern. It is important to note that the force profile of Condition 2-descending is similar to that of Condition 1 where the higher force of each step corresponds to the heel and the lower one to the front part of the plantar. On the other hand, in Condition 2-ascending, the higher force relates to the front part and the lower one to the heel of the foot [Low and Dixon, 2010].



**Figure 6: Gait pattern of participant whilst descending the stairs when the bus is stationary (left) and moving (right)**

The above interpretation of the results points out that the movement of the bus affects the way the particular subject walks inside a moving bus. In order for this to

be more apparent, it was decided to describe the movement before and after the change in acceleration, according to some specific characteristics of a footstep. Hence, heel strike (HS), toe-off (TO), stance time (ST), double support time (DST) and swing (S) of four adjacent steps were chosen. In Condition 1, the change of acceleration happens at 9.3 sec and therefore the 5<sup>th</sup>, 6<sup>th</sup>, 7<sup>th</sup> and 8<sup>th</sup> step for both Task A and B were analysed. In Condition 2, the first change of acceleration occurs 10 sec after the beginning of the task which coincides with the ascending of the staircase whereas the second concurred with the turning point at the top of the steps. Steps 3, 4, 5 and 6 were analysed for both ascending and descending.

The results for Condition 1 (Table 1) show that the HS and TO force reduce because of the movement of the bus while S reduces before and increases after the change. In addition, the subject appears to increase the time he spends on both feet right before the change but spends less time on both feet after the change. The alteration of DST and S affect ST accordingly.

Condition 1	Step	HS	TO	DST	S	ST
Before change	5 <sup>th</sup>	+1%	-19%	-40%	-9%	-18%
	6 <sup>th</sup>	-38%	-28%	+44%	-9%	+6%
After change	7 <sup>th</sup>	-9%	-46%	-11%	+24%	+13%
	8 <sup>th</sup>	-16%	-34%	-60%	+13%	-9%

**Table 1: Alteration of the characteristics of adjacent steps occurring before and after the change of acceleration - Condition 1**

Whilst ascending (Table 2), the movement results in a general increase of the HS force and a decrease of the TO force. S and ST appear to be reduced in all four steps with the highest reduction occurring after the change of the bus acceleration. DST on the other hand, increases before the change which shows that due to the movement of the bus the subject spends more time on both feet but as soon as the change happens, he changes his gait by moving his feet more quickly from one step to the next.

Condition 2 ascending	Step	HS	TO	DST	S	ST
Before change	3 <sup>rd</sup>	+13%	-49%	+20%	-10%	-6%
	4 <sup>th</sup>	+2%	-39%	+17%	-27%	-19%
After change	5 <sup>th</sup>	+5%	-26%	-29%	-38%	-35%
	6 <sup>th</sup>	-29%	-52%	-43%	-32%	-34%

**Table 2: Alteration of the characteristics of adjacent steps occurring before and after the change of acceleration - Condition 2 ascending**

Whilst descending the staircase (Table 3), all the characteristics of the four footsteps present a reduction due to the movement of the bus. Only the DST of the 4<sup>th</sup> step shows an increase which is considered to be an anomaly and it cannot be explained due to the small sample size. This variability is still under study.

Condition 2 descending	Step	HS	TO	DST	S	ST
Before change	3 <sup>rd</sup>	-15%	-100%	-30%	-43%	-40%
	4 <sup>th</sup>	-26%	-30%	+40%	-36%	-26%
After change	5 <sup>th</sup>	-50%	-13%	-20%	-8%	-10%
	6 <sup>th</sup>	-29%	-38%	-33%	-35%	-34%

**Table 3: Alteration of the characteristics of adjacent steps occurring during deceleration - Condition 2 descending**

The same analysis was carried out for the 'Ten steps' test and the average was compared to the above results (Table 4). An increase of HS and TO force was observed for both tasks of Condition 1 whereas DST, S and ST were reduced. For Condition 2 during ascending, HS force was decreased while TO force presented the highest increase of the three cases. DST and ST were decreased while S was increased for Task A and decreased for Task B. DST, S and ST showed the same trend during descending whereas HS and TO were increased during Task A and decreased during Task B.

	HS	TO	DST	S	ST
Condition 1-Task A	61%	71%	-14%	-18%	-17%
Condition 1-Task B	34%	15%	-30%	-14%	-19%
Condition 2 -Task A ascending	-12%	166%	-43%	4%	-10%
Condition 2 -Task B ascending	-16%	52%	-50%	-23%	-31%
Condition 2 -Task A descending	29%	34%	-41%	5%	-8%
Condition 2 -Task B descending	-10%	-24%	-50%	-28%	-34%

**Table 4: Comparison of the 'Ten steps' baseline test to the tasks of the two conditions**

#### 4. CONCLUSIONS

The review of the literature showed that the way people walk on a flat surface differs from the way they walk on a staircase. A further alteration of the walking pattern occurs while moving inside a moving vehicle. However, none of the reviewed studies considered examining the gait of moving passengers in a moving vehicle and hence there is currently no quantified result proving the above.

The purpose of this study was to investigate whether the movement of the bus affects the ability of the passengers to maintain their balance as well as to establish whether these changes could be measured and detected. A young, healthy male of high balance undertook a series of tests in a static environment and on a stationary and moving bus where plantar forces were collected. Five characteristics of a step such as HS, TO, DST, S, ST, were then used in order to define potential changes.

The results showed that in general the movement of the bus affects the characteristics of the gait cycle and therefore the stability of the passenger. In general, when no acceleration is introduced, HS forces were found to be higher

when the subject was walking on a flat surface towards a seat (Condition 1) and during descending. TO forces during ascending were higher than those during descending and movement on the lower deck. When the movement of the bus was introduced the gait pattern of the subject was altered leading to a decrease of HS and TO for Condition 1 and stair descending and an increase of HS during stair ascending. This shows that the subject's step becomes softer when the bus is moving but requires stronger footsteps when ascending. As for the rest of the characteristics, DST, S and ST reduce when the subject moves on a stationary bus revealing that the subject had higher balance while walking on a static surface. When the bus is moving, DST, S and ST reduce for both ascending and descending whereas S increases and DST decreases during Task B of Condition 1. This shows that while using the stairs, the subject steps more frequently without spending a lot of time with both feet on the ground and during feet changes. On the other hand, while walking on the lower deck he chooses to spend less time with both feet on the ground and more time balancing on one foot.

The general outcome of this study is that we have shown that it is possible to measure the forces and outcomes associated with moving around a moving vehicle so that further research can be conducted to establish in more detail what the mechanisms involved in these manoeuvres so that we can establish different control regimes for the bus and mitigation approaches for older people. The data confirm that bus acceleration and deceleration is an influential factor of passengers' balance. However, no significant conclusions about the detail of these influences can yet be drawn as the tested sample was very small. We will be conducting a larger study with a larger sample as well as people of different age groups. Moreover, repeating the same experiment on a hybrid bus is crucial as it might be revealed that passengers' stability is affected less and balance loss events are less frequent on hybrid buses than on conventional buses.

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