Operational characteristics of a bus service and their modification due to a safety-driven acceleration limit

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ABSTRACT
Active transportation can greatly benefit societies by improving people's health and well-being. Buses are a form of active transportation; however, their high level of acceleration can make private vehicles less attractive to users. Even worse, it can be responsible for severe injuries that require hospitalization or for the development of fear of falling, especially to the older ones. A level of bus acceleration that does not exceed 1 m/s^2 has been proven appropriate as evidence has shown that it enables passengers to move in a natural way inside the moving vehicle, hence reducing instability, non-collision injuries and increasing safety. Although operators might be willing to implement such an intervention, they might also be skeptical about its impact to the operational characteristics of a service, such as timetabling, in-vehicle travel times, passenger waiting times etc.

In this work we investigate the effect of a safety-driven acceleration limit to the operational characteristics on a random round trip of a bus service in London. Data regarding speed, acceleration, journey time and stops were recorded at 2Hz and extracted from the engine of a bus. Further computation resulted in passenger waiting times and headways between the examined bus and its preceding and following buses. A vehicle movement model was used to test how these operational characteristics would be affected if the safety-driven acceleration limit of 1 m/s^2 were to be implemented. The derived results suggest that the difference between the current bus service (do-nothing) and the case that the safety-driven acceleration limit is imposed is not considerable, and a discussion of the results is provided.

Keywords: bus acceleration; bus travel times; headway variation; safety; passenger satisfaction.

INTRODUCTION

"An active city is a competitive city" Designed to move (*1*) is a motto that shapes the ideology of many city officials around the world and guides their strategic urban and transport planning for societal, economic and environmental growth. Being physically active has been scientifically associated with the improvement of people's health and well-being when compared to the excessive use of cars Frank et al. (*2*) and forms the basis of global campaigns focused on healthier future societies WHO (*3*).

Choosing active transport modes for the completion of everyday activities greatly contributes towards achieving the activity recommendation for a healthier lifestyle WHO (*4*). The bus system is one form of active transportation that can be chosen when undertaking activities. Besides the fact that it is the most widespread public transport network in the world, it is also the most cost-effective means of mobility for people of all age groups Transport for London (*5*).

Cost-effectiveness and a healthier lifestyle, however, do not seem to be factors that affect people's choices when it comes to commuting. Passenger cars are still the most preferred mode of travelling (83%), whereas people use buses and coaches (9.2%) more than trains (7.6%) for their everyday movements Eurostat (*6*). Nonetheless, bus journeys have been fluctuating since the beginning of the previous decade, with the lowest demand in Europe recorded in 2009 Eurostat (*6*) and in the UK in 2014 Transport for London (*7*).

Looking into the reasons why people still prefer their cars over the bus service and why bus passenger mileage is reducing, an official survey, that was carried out in London and interviewed 11,000 passengers, revealed that 25% of bus passengers are dissatisfied with the speed and acceleration of the bus. According to regular bus users, this is the third most important area that requires improvement and comes after the punctuality (31%) and frequency (29%) of the service (page 20, London Travel Watch (*8*)). Due to the abrupt bus movement, people are involved in non-collision accidents as they lose their balance, which in older passengers might result in fear of falling and avoidance of participating in societal activities.

Non-collision injuries aboard buses are at dramatic levels and affect passenger demand for bus services around the world. In Sweden, more than half of the recorded injuries on buses were caused by non-collision accidents Björnstig et al. (*9*) whereas in Portland Oregon, USA 80% of non-collision incidents involved loss of balance, with some of them occurring during the bus movement Strathman et al. (*10*). Moreover, the 3000 falls recorded every year during non-collision accidents on buses in the UK for those over 65 years old Kendrick et al. (*11*) reinforce the work of Green et al. (*12*) which states that the current bus service is dangerous and not designed to accommodate the needs of the elderly users. Similar statistics can be found for other countries in Europe and in the world in the work carried out by O'Neill (*13*).

Bus accelerations of levels higher than 2.0 m/s^2 are considered extremely dangerous for standing passengers whose balance is jeopardized in the case they do not get hold of a handrail Browning, Dorn (*14, 15*). Investigating the level of acceleration at which the London bus service operates, accelerations of up to 2.5 m/s^2 are recorded by the official operator Sale (*16*) and are confirmed by the users Karekla and Tyler (*17*). Although extensive work is being done by transport operators worldwide to reduce the environmental impact of bus services by introducing hybrid buses that control the way buses accelerate, still the acceleration levels are higher than the levels a healthy bus passenger could tolerate if they were to walk naturally inside a moving bus Karekla and Tyler (*18*).

Therefore, it is evident that a much lower level of bus acceleration of 1.0 m/s^2 should be sustained in order to increase accessibility and comfort during bus journeys, but also to increase patronage for this active mode of transportation Karekla and Tyler (*17*). More importantly, achieving a lower level of acceleration will reduce, and ideally eliminate, bus passenger injuries which will reduce the substantial costs associated to it as a result of medical treatment and loss of earnings. In the UK, £4.6 million were spent every day in 2010 to cover fall-related costs Age UK (*19*). The equivalent cost for 2010 in the USA reached US$82 million.

Bus operators might expect that conforming to the recommended acceleration level will come at a cost, such as increased travel times and uneven headways that result in bus bunching Gkiotsalitis and Maslekar (*20*). This study focuses on these aspects and investigates the impact of imposing a maximum, safety-friendly acceleration level to a bus service in London. This investigation is performed using real-time CAN bus data from the engine of a bus that indicates its acceleration, deceleration and trajectory. In addition, we generate the expected trajectory of the same bus using an extension of the mathematical model of Fu et al. (*21*) when imposing a maximum, safety-friendly acceleration limit. In doing so, we investigate the trade-off between improving safety and reducing the operational efficiency, e.g., increase the trip travel time.

The remainder of this paper is structured as follows. In section 2, we review related studies on the operational characteristics related to bus service efficiency to investigate the trade-off between safety and operational costs. In addition, the contribution of this work to the scientific field is provided. Section 3 details the examined case study and the performance of the current operations that do not impose an acceleration limit to bus trips. Section 4 investigates the effect of enforcing lower accelerations to the operational efficiency of the bus service by using an extension of the mathematical model of Fu et al. (*21*). Finally, section 5 provides the conclusion and the limitations of this work.

BACKGROUND

Operational characteristics related to bus service efficiency

Imposing limits on acceleration levels might increase the travel times of bus trips. This will have an effect on the passenger travel times, the trip dispatches (which might be delayed resulting in "schedule sliding"), the operational headways and the vehicle and crew schedules Gkiotsalitis and Cats, Cats et al., Gkiotsalitis and Van Berkum (*22, 23, 24*). Several works have acknowledged the adverse effects of increased travel times and proposed to proactively embed slack times to the bus schedules to cater for unexpected delays Xuan et al., Daganzo, Adamski and Turnau, Zhao et al. (*25, 26, 27, 28*).

Apart from adding slack times, one can deploy real-time control measures such as stop-skipping Chen et al., Yu et al., Sun and Hickman (*29, 30, 31*) and short-turning Zhang et al., Gkiotsalitis et al. (*32, 33*) to reduce the travel times of specific bus trips. Nevertheless, short-turnings can increase the deadheading times of buses and stop-skippings increase the inconvenience of passengers that are unable to board the buses Liu et al. (*34*).

Increased travel times because of acceleration limits can also impact the synchronization of bus services with other bus services or trains. This is reported in a distinct line of works has been focused on bus schedule synchronization (including the works of Ceder et al., Cevallos and Zhao, Wei and Sun, Gkiotsalitis and Maslekar (*35, 36, 37, 38*)).

Apart from the impact to the trip travel times, lower accelerations can also degrade the regularity of bus services. Especially in high-frequency services, such as bus services with frequencies of more than 5 buses per hour, the main objective is to reduce the variation between the actual and the scheduled waiting times of passengers for increasing the service regularity Trompet et al. (*39*). The actual arrival times of buses at stops are monitored with the use of telematics; thus, enabling the transport authorities to penalize the underperforming bus operators and reward the best-performing ones Jansson and Pyddoke (*40*). Incentivizing bus operators to improve the service regularity helped to reduce the excess waiting times (EWTs) of passengers in London where the EWT has been reduced from 4 minutes in 1979 to 1.2 minutes in 2012 TfL (*41*).

From the above literature, it is evident that there is an increased pressure on bus drivers to adjust their speeds and accelerate beyond the safety-recommended levels in order to meet the operational key performance indicators (this is also noted in Koehler et al., Daganzo and Pilachowski (*42, 43*)). Notwithstanding, to the best of the authors' knowledge, past works on improving the bus operations (i.e., the travel times and EWT of passengers) do not consider the adverse effects to the passenger safety due to abnormal accelerations Eberlein et al., Chen et al., Gkiotsalitis and Kumar (*44, 45, 46*).

Contribution of this study

This study is the first to investigate the way a safety-based maximum acceleration impacts the main key performance indicators of bus services that operate in densely-populated areas. Based on previously published work, those key performance indicators are:

- the regularity of bus services (which indicates the passenger waiting times);
- the trip travel times (which indicate the travel times of passengers aboard a bus).

Given that the impact of enforcing an acceleration limit to a low-frequency bus route might be not critical due to the low frequencies, we focus on a high-frequency bus route in a densely populated area in London. Using CAN bus data from one bus we report the regularity, the trip travel time, and the acceleration/deceleration of the bus every 2 seconds. Then, we apply the well-established model of Fu et al. (*21*) to investigate how a safety-based acceleration limit can impact the trip travel times and the service regularity.

CASE STUDY DESCRIPTION AND PERFORMANCE OF THE ACTUAL OPERATIONS

Imposing an acceleration limit to a bus service, that would increase passenger safety aboard buses, can impact the operations in cities with intense bus services, such as London, Ottawa, Hong Kong, or Singapore. To investigate this effect, we focus on a high-frequency, bi-directional bus line in London that performs the route Stratford City−Elephant & Castle and serves 36 bus stops (Bus route 388). The topology of the bus line is provided in Figure 1 where the line layout and the 15 most important bus stops are presented. The total length of the routes in both directions is 22.56 km.

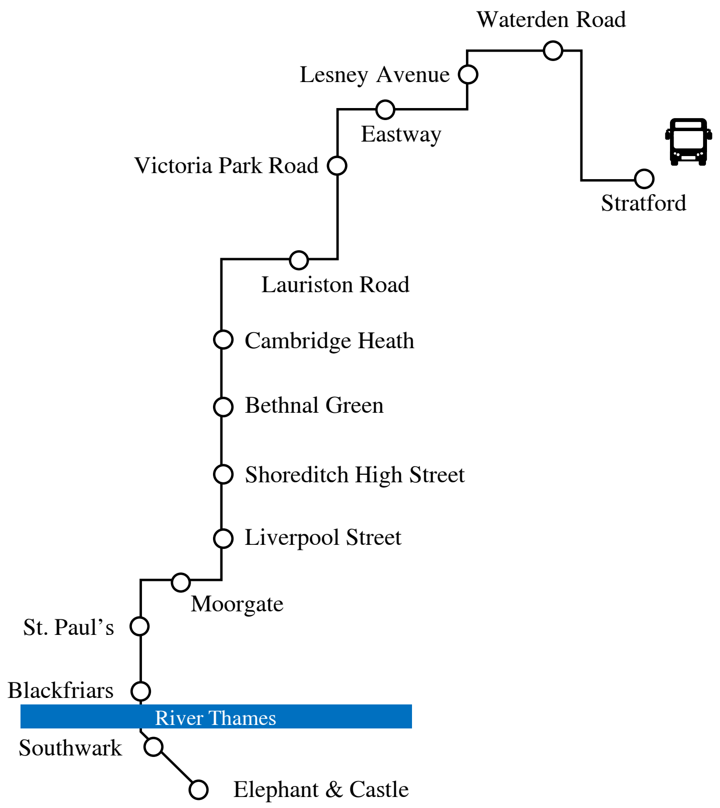

FIGURE 1 : Main stops of bus route 388 between Stratford City and Elephant & Castle

The first buses arrive at the Stratford City bus stop as early as 05:25 and the last ones at 23:50 on both weekdays and weekends. In the other direction, the service from Elephant & Castle starts at 05:45 with the last trip occurring at 00:40. Successive buses in both directions are dispatched with a headway that varies between 9-14 minutes depending on the peak and off-peak time of the day.

To investigate the acceleration / deceleration in actual operations, the real-time acceleration / deceleration from the engine of one bus serving this route has been collected. The bus is owned by the UCL PAMELA Laboratory, it is a hybrid bus and performs the 388 service for Transport for London (TfL), when not needed by the university. Complete data from one round-trip performed by the aforementioned bus on a Saturday from 11:21 until 13:38 were obtained.

In more detail, vehicle speed, acceleration and deceleration data is collected every 2 seconds. The total duration of the data collection is 2h and 17min and includes an entire round-trip. The high-granularity data is exported from the vehicle engine, digitized and organized into a database for further manipulation. To identify which data were associated with the bus being in motion and which with the bus being idle at bus stops or traffic lights, the bus acceleration measurements were analyzed.

Based on the acceleration data, the bus was in motion for 5754s and idle for 2644s (resulting in 8398s of total time of data collection). The bus was completely stopped 109 times (acceleration = 0 m/s^2) in 36 traffic lights and 72 bus stops. At one instance, around 13:13:34, the bus was stationary for 153 s because of a change of driver shifts. The final database, part of which is presented in Table 1, includes variables such as time, the bus speed and acceleration, vehicle status (running or stopped), and stop duration.

TABLE 1 : Example of CAN bus data collected every 2 seconds from the vehicle engine

timestamp		speed	acceleration	status
hh:mm:ss	seconds	m/s	m/s2	
11:22:16	40936	0.77	-1.3085	running
11:22:18	40938	0	-0.3858	running
11:22:20	40940	0	0	idle (bus stop)
11:22:22	40942	0	0	idle (bus stop)

The observed dwell time at each bus stop varied between 4 and 22s. TfL provides 3 sets of open access information of the bus arrival times at 12 key bus stops along the route, known as control point stops. At these control point stops, the regularity of the service is evaluated with the use of a specific key performance indicator. This key performance indicator is the expected passenger waiting time (EWT). In addition, we also measure the total round-trip travel time which indicates the travel times of passengers aboard a bus and the operational costs.

As mentioned earlier, in this work, the enforcement of safety-driven acceleration limits and their impact on those two key performance indicators are studied. It should be noted at this point that the crowding level in the bus can be an additional key performance indicator, however such data were not collected.

The acceleration / deceleration of the examined bus was monitored every 2 seconds and the observed values are presented in Fig.2.

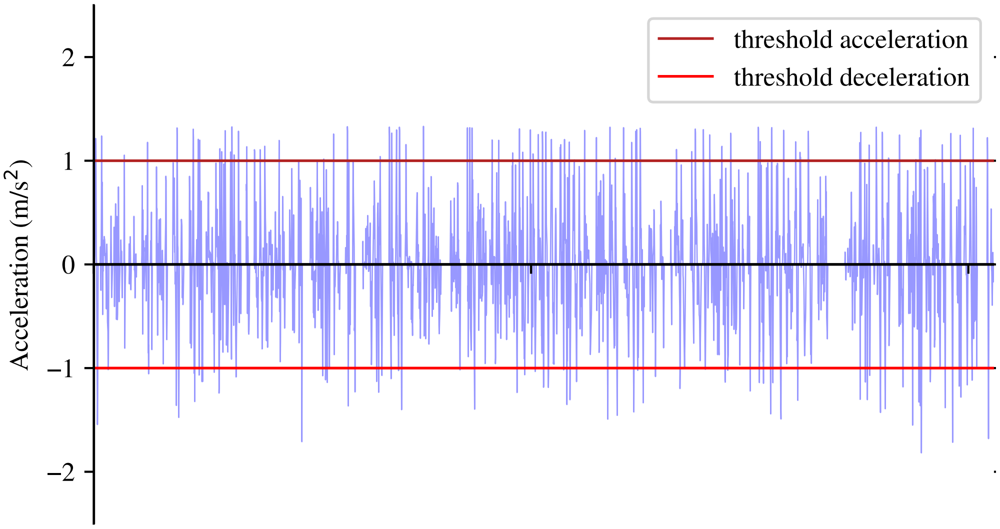

FIGURE 2 : Observed acceleration(s) from the beginning of the bus trip until its end

In Fig.2 there are several instances where the acceleration or the deceleration are more than 1 m/s^2, which is the acceleration limit recommended by Karekla and Tyler (*17*). This indicates that the current service is not smooth and this impacts the safety and comfort of passengers. To investigate further the occurrence of abrupt acceleration / deceleration instances, the frequency of its exceedance above 1 m/s^2 is reported in Table 2.

TABLE 2 : Statistics of data collected every 2 seconds from the vehicle engine

total observations	mean acceleration	minimum observed acceleration	maximum observed acceleration	number of instances where acceleration > 1 m/s^2	number of instances where acceleration < -1 m/s^2
4117	$6 \cdot 10^{-5}$ m/s^2	-1.82 m/s^2	+1.33 m/s^2	132 (3.21%)	97 (2.35%)

Additionally, the total round-trip travel time is 137min and 20s. A final key performance indicator is the service regularity which in high frequency services is calculated in the form of expected (i.e., average) passenger waiting times (EWT) Trompet et al. (*39*). The measure of instability of the expected passenger waiting times is the coefficient of variation of the actual headways. Assuming random passenger arrivals at stops follow the Poisson distribution, the expected passenger waiting times are directly proportional to the coefficient of variation of headways, H, and are expressed by the relation of Newell and Potts (*47*):

$$\mathbb{E}[W] \doteq \frac{\mathbb{E}[H]}{2} + \frac{\mathrm{Var}[H]}{2\mathbb{E}[H]} \tag{1}$$

where $\mathbb{E}[W]$ is the average passenger waiting time and $\mathrm{Var}[H]$ the headway variance. To compute the EWT of passengers, we plot initially the time headways between the examined trip and its preceding and following trip at every control point stop. Those plots are presented in Fig.3 where the left sub-plot refers to the direction from Elephant & Castle to Stratford City and the right sub-plot to the direction from Stratford City to Elephant & Castle.

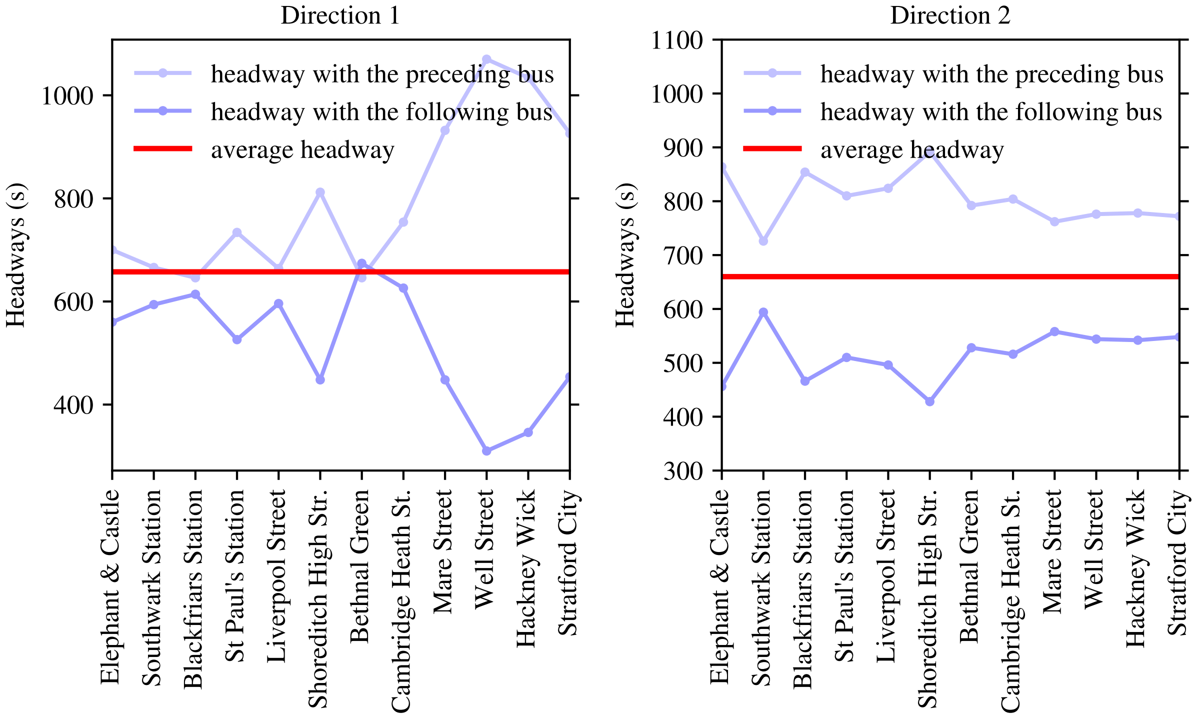

FIGURE 3 : Observed time headways between the examined bus and its preceding and following bus at each control point stop

From Fig.3 it is evident that the examined bus was left behind after the Cambridge Health Street control point stop when it was operating in direction 1. Indeed, after that control point stop its time headway with its preceding bus was in the range of 900-1100s and with its following in the range of 200-500s. This clearly indicates that the examined bus and its following bus were bunching together. In direction 2 (shown in the right sub-figure) no significant bunching problem was observed. However, the examined bus was persistently closer to its following bus maintaining a large headway with its preceding bus that was more than 1 min above the average headway. Using the observed headways, the average passenger waiting time (EWT) was calculated at every stop, as it is presented in Fig.4. As expected, the EWT of passengers in direction 1 is significantly higher than the respective one in direction 2. The problematic control point stops are the ones after Cambridge Health Street where passengers have to wait for more than 6.4min on average, and up to 7.5min in the worst case.

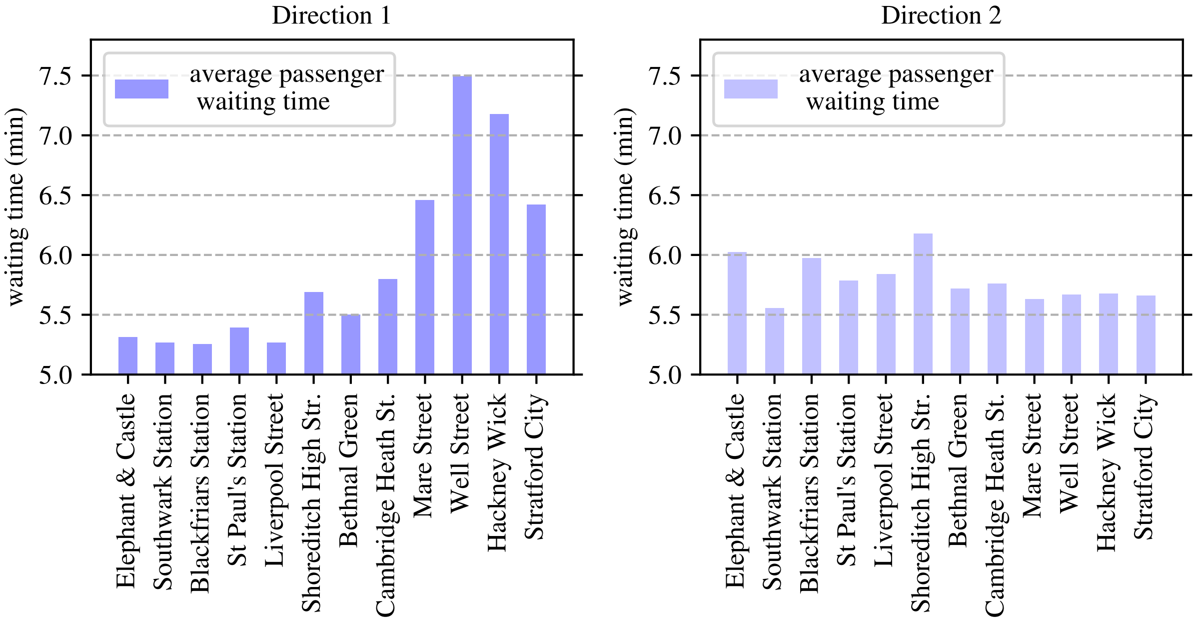

FIGURE 4 : Average passenger waiting time for the experimental bus trip and its preceding/following trip at each control point stop in minutes

OPERATIONAL IMPACT OF THE SAFETY-DRIVEN ACCELERATION LIMIT

To investigate the impact of the safety-driven acceleration limit of 1 m/s^2 to the examined bus trip, a simulation using the well-established model of Fu et al. (*21*) that generates vehicle trajectories with the use of acceleration / deceleration data was performed.

The vehicle movement model of Fu et al. (*21*) relies on the following assumptions:

(1) Buses that serve the same line do not overtake each other. This is a realistic assumption used in several vehicle movement models (refer to Xuan et al., Chen et al. (*25*, *45*));

(2) The passenger arrivals at stops are random because the passengers cannot coordinate their arrivals with the arrival times of buses at high-frequency services (Welding, Randall et al. (*48*, *49*));

(3) Travel time changes when imposing a maximum acceleration depend only on the delay due to the upper-bounded acceleration.

The new trajectory of the examined bus, after imposing the safety-driven acceleration limit, is generated with the extension of the vehicle movement model. For a more comprehensive discussion, its nomenclature is introduced in Table 3 :

TABLE 3 : Nomenclature of vehicle movement model parameters

N	set of bus trips, $N=\{n-1,n,n+1\}$, where n is the examined bus;
S	set of bus stops, $S=\{1,...,s,...,\lvert S\rvert\}$;
$\mathbf{T}\in\mathbb{R}_{+}^{\lvert N\rvert\times(\lvert S\rvert-1)}$	matrix of running times where $t_{n,s}\in\mathbf{T}$ is the running time of the n-th trip between stop $s-1$ and s where $s\in S\setminus\{1\}$;
$\boldsymbol{\tau}\in\mathbb{R}_{+}^{\lvert S\rvert-1}$	vector of free-flow running times $\boldsymbol{\tau}=(\tau_2,...,\tau_{\lvert S\rvert})$ where τ_s is the free-flow running time between stop $s-1$ and s where $s\in S\setminus\{1\}$;
$\mathbf{D}\in\mathbb{R}_{+}^{\lvert N\rvert\times\lvert S\rvert}$	matrix of departure times where $d_{n,s}$ is the departure time of trip n from stop s where $n\in N$ and $s\in S$;
$\mathbf{A}\in\mathbb{R}_{+}^{\lvert N\rvert\times\lvert S\rvert}$	matrix of arrival times where $a_{n,s}$ is the arrival time of trip n at stop s where $n\in N$ and $s\in S$;
$\mathbf{K}\in\mathbb{R}_{+}^{\lvert N\rvert\times\lvert S\rvert}$	matrix of dwell times where $k_{n,s}$ is the dwell time of trip n at stop s where $n\in N$ and $s\in S$;
$\mathbf{H}\in\mathbb{R}_{+}^{(\lvert N\rvert-1)\times\lvert S\rvert}$	matrix of bus headways times where $h_{n,s}$ is the headway between trips $n-1$ and n at stop s where $n\in N\setminus\{1\}$ and $s\in S$;
$\mathbf{W}\in\mathbb{R}_{+}^{\lvert N\rvert\times\lvert S\rvert\times\lvert S\rvert}$	matrix where each $w_{n,sy}\in\mathbf{W}$ denotes the number of passengers waiting for bus n and traveling from stop s to y (note: $w_{n,sy}=0,\ \forall y\leq s$);
$\mathbf{L}\in\mathbb{R}_{+}^{\lvert N\rvert\times\lvert S\rvert\times\lvert S\rvert}$	matrix where each $l_{n,sy}\in\mathbf{L}$ denotes the number of passengers traveling from stop s to stop y skipped by bus n (note: $l_{n,sy}=0,\ \forall y\leq s$);
$\mathbf{M}\in\mathbb{R}_{+}^{\lvert N\rvert\times\lvert S\rvert}$	matrix where each $m_{n,s}\in\mathbf{M}$ denotes the number of passengers at stop s skipped by bus n where $n\in N,s\in S$ (note: $m_{n,s}=\sum\limits_{i=s+1}^{\lvert S\rvert}l_{n,si}$);
$\mathbf{U}\in\mathbb{R}_{+}^{\lvert N\rvert\times\lvert S\rvert}$	matrix where each $u_{n,s}\in\mathbf{U}$ denotes the number of passengers boarding bus n at stop s where $n\in N,s\in S$ (note: $u_{n,\lvert S\rvert}=0,\ \forall n\in N$);
$\mathbf{B}\in\mathbb{R}_{+}^{\lvert N\rvert\times\lvert S\rvert\times\lvert S\rvert}$	matrix where each $b_{n,sy}\in\mathbf{B}$ denotes the number of passengers boarding bus n at stop s whose destination is stop y (note: $b_{n,sy}=0,\ \forall y\leq s$);
$\mathbf{V}\in\mathbb{R}_{+}^{\lvert N\rvert\times\lvert S\rvert}$	matrix where each $v_{n,s}\in\mathbf{V}$ denotes the number of passengers alighting bus n at stop s where $n\in N,s\in S$ (note: $v_{n,1}=0,\ \forall n\in N$);
r_1	average boarding time per passenger, a constant;
r_2	average alighting time per passenger, a constant;
$\boldsymbol{\Lambda}\in\mathbb{R}_{+}^{\lvert S\rvert\times\lvert S\rvert}$	matrix where each $\lambda_{sy}\in\boldsymbol{\Lambda}$ denotes the average passenger arrival rate at stop s whose destination is stop y (note: $\lambda_{sy}=0,\ \forall 1\leq y\leq s\leq N$);
$\boldsymbol{\mu}\in\mathbb{R}_{+}^{\lvert S\rvert}$	vector where each $\mu_s\in\boldsymbol{\mu}$ denotes the average passenger arrival rate at stop s (note: $\mu_s=\sum\limits_{i=s+1}^{\lvert S\rvert}\lambda_{si}$)
c_1	unit time value associated with the passenger waiting times (\$/h);
c_2	unit time value associated with the passenger in-vehicle travel time (\$/h);
c_3	unit time value associated with vehicle operation time (\$/h);
$I_n^{s-1,s}=\{1,2,...\}$	is a set denoting the frequency of occurrence of a measurement/observation of the instantaneous acceleration of trip n when a bus travels from stop $s-1$ to stop s;
$e_{n,i}^{s-1,s}\in\mathbb{R}$	the instantaneous acceleration of trip $n\in N$ according to the i-th measurement, where $i\in I_n^{s-1,s}$ and the bus trip n travels from stop $s-1$ to stop s;
$g_{n,i}^{s-1,s}\in\mathbb{R}_{+}$	the instantaneous speed of trip $n\in N$, where $i\in I_n^{s-1,s}$ and the bus trip n travels from stop $s-1$ to stop s;
$\mathbf{z}\in\mathbb{R}_{+}^{\lvert S\rvert-1}$	vector where each $z_s\in\mathbf{z}$ denotes the travel distance between bus stop $s-1$ and s in meters.

Vehicle movement model

The new trajectory of the examined bus, after imposing the safety-driven acceleration limit, is generated with the extension of the vehicle movement model of Fu et al. (*21*). In the vehicle movement model, the arrival time of the examined bus trip n at stop s is equal to its departure time at stop $s-1$ ($d_{n,s-1}$) plus the travel time between the two stops:

$$a_{n,s} = d_{n,s-1} + t_{n,s},\ \forall s \in S \setminus \{1\} \tag{2}$$

In addition, the departure time of the examined trip n from stop s is equal to its arrival time plus the dwell time $k_{n,s}$:

$$d_{n,s} = a_{n,s} + k_{n,s},\ \forall s \in S \setminus \{1\} \tag{3}$$

Assuming that overtaking between buses of the same line is not allowed, the departure headway between bus trip n and its preceding one reads:

$$h_{n,s} = d_{n,s} - d_{n-1,s},\ \forall n \in N \setminus \{n-1\}, s \in S \tag{4}$$

The dwell time of each bus trip n at each stop s depends on the number of passengers who will board and alight at the stop, denoted by $u_{n,s}$ and $v_{n,s}$, respectively:

$$k_{n,s}{}^{1} = r_1 u_{n,s} + r_2 v_{n,s},\ \forall n \in N \setminus \{n-1\}, s \in S \setminus \{1\} \tag{5}$$

The expected number of passengers who will board bus trip n at stop s (assuming bus n stops at stop s) depends on the number of passengers traveling between stops s and y ($y > s$):

$$u_{n,s} = \sum_{y=s+1}^{|S|} w_{n,sy},\ \forall n \in N \setminus \{n-1\}, s \in S \setminus \{|S|\} \tag{6}$$

The expected number of alighting passengers for bus trip n at stop s depends on the number of passengers traveling between stops y and s ($y < s$):

$$v_{n,s} = \sum_{y=1}^{s-1} w_{n,sy},\ \forall n \in N \setminus \{n-1\}, s \in S \setminus \{1\} \tag{7}$$

In addition, $e_{n,i}^{s-1,s}$ is the i-th observation of the instantaneous acceleration of the examined bus n that travels from stop $s-1$ to stop s (thus, $i \in I_n^{s-1,s}$). A new measurement of the instantaneous acceleration was collected every 2 sec for the examined bus. Therefore, each observed instantaneous acceleration $e_{n,i}^{s-1,s}$ where $i \in I_n^{s-1,s}$ refers to the (very short) time period $[i,\ i+2 \text{ sec})$. Assuming that the observed instantaneous acceleration $e_{n,i}^{s-1,s}$ does not deviate significantly within each time period $[i,\ i+2 \text{ sec})$, the instantaneous speed at each instance $i \in I_n^{s-1,s}$ can be derived as:

$$g_{n,i}^{s-1,s} = \begin{cases} g_{n,1}^{s-1,s} \text{ if } i = 1 \\ g_{n,i-1}^{s-1,s} + \int_{i}^{i+2} e_{n,i}^{s-1,s} \mathrm{d}t,\ \forall i \in I_n^{s-1,s} \setminus \{1\} \end{cases} \tag{8}$$

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[1] if passengers use different door channels for boarding/alighting; then, the dwell time can be expressed as $k_{n,s} = \max\{r_1 u_{n,s}; r_2 v_{n,s}\}$

where $\int_{i}^{i+2} e_{n,i}^{s-1,s}\mathrm{d}t = 2e_{n,i}^{s-1,s}$ (m/s). Eq.8 denotes that the instantaneous speed $g_{n,i}^{s-1,s}$ of our trip n when it departs from any stop $s-1 \in S\setminus\{1\}$ is initially $g_{n,1}^{s-1,s}$, where $g_{n,1}^{s-1,s} = 0$ (m/s) if bus trip n stopped at bus stop s, and is updated by adding the integral of the observed instantaneous acceleration to the previously calculated value of the instantaneous speed, $g_{n,i-1}^{s-1,s}$.

Based on the above, the running time of the examined bus $n \in N$ from any bus stop $s-1$ to bus stop s where $s \in S\setminus\{1\}$ can be calculated as:

$$t_{n,s} = z_s \left[\frac{g_{n,1}^{s-1,s} + \sum_{i=2}^{|I_n^{s-1,s}|} \left(g_{n,i-1}^{s-1,s} + \int_{i}^{i+2sec} e_{n,i}^{s-1,s}\mathrm{d}t\right)}{|I_n^{s-1,s}|} \right]^{-1} \tag{9}$$

where $\frac{g_{n,1}^{s-1,s} + \sum_{i=2}^{|I_n^{s-1,s}|} \left(g_{n,i-1}^{s-1,s} + \int_{i}^{i+2sec} e_{n,i}^{s-1,s}\mathrm{d}t\right)}{|I_n^{s-1,s}|}$ is the average speed of trip n between stops $s-1$ and s according to the actual measurements of the instantaneous acceleration.

Results

Replacing the instantaneous accelerations in Eq.9 with the acceleration limit of 1 m/s^2 for those accelerations that exceeded the safety-driven limit, results in an updated trajectory for the examined bus.

Fig.5 shows the trajectory of the examined bus before imposing the safety-driven acceleration limit (actual bus trajectory) and the expected trajectory in the case this limit is imposed, when performing the round-trip from Elephant & Castle Station to Stratford City and back to Elephant & Castle.

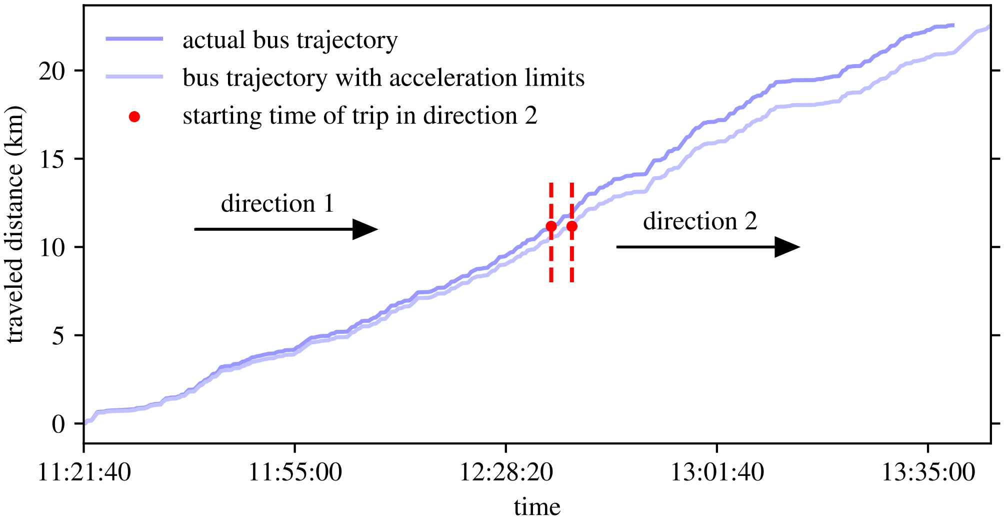

FIGURE 5 : Actual trajectory of the examined bus and estimated trajectory when the acceleration limit of 1 m/s^2 is implemented
]

From Fig.5 one can note that in the actual operations the examined bus started its journey at 11:21:40, arrived at Stratford City around 12:34:00, and completed its round-trip at 11:38:52. Additionally, as previously discussed, around 13:13:34 the bus remained idle for 153s because of a change of driver shifts. When the acceleration limit is imposed, the examined bus is expected to take 6 minutes longer to complete the same round trip, arriving at the final stop at 13:44:54.

Besides the extension of the total travel time, that affects passenger travel times and suspends the dispatch of the next bus, imposing the safety-driven acceleration limit could impact the regularity of bus services. This work considers the worst-case where the examined trip follows the safety-driven acceleration limit whilst its preceding and following buses operate as usual. This extreme situation is not expected in practice as in the case a bus operator implements an acceleration limit, this will apply to all buses serving the route. Nonetheless, this work measures the worst-possible impact to the service regularity when only one trip complies with the recommended acceleration limit. The results are presented in Fig.6 and are expressed in terms of average passenger waiting times at every control point stop of direction 1.

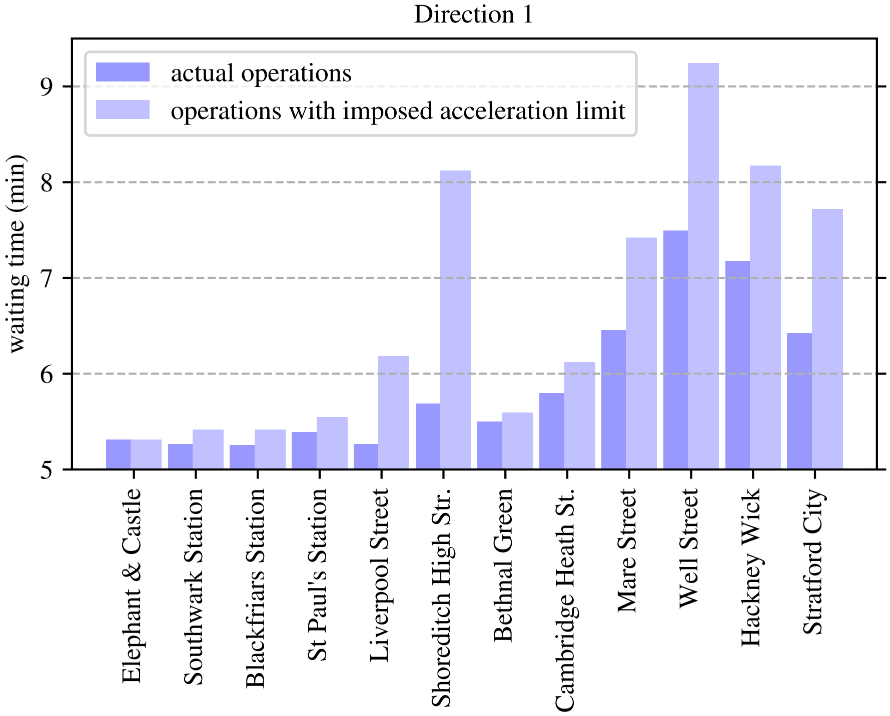

FIGURE 6 : Average passenger waiting time at each control point stop, in minutes, with and without the recommended acceleration limit. Note that in this experiment an acceleration limit was imposed to the examined bus only, not to its preceding and following buses.

The results of this experiment, are summarized in Table 4 and focus on the following three factors:

- travel time of the examined bus in the actual situation (do-nothing) and the situation where a safety-driven acceleration limit is imposed;
- coefficient of variation (CV= $\frac{\text{standard deviation}}{\text{mean}}$) of the passenger waiting times in directions

1 and 2 before and after imposing the recommended acceleration limit. The CV shows the extent of variability in relation to the mean, and in a perfectly regular service CV=0.

- violations of the recommended acceleration limit that might lead to collision and non-collision passenger injuries.

TABLE 4 : Performance summary in the actual case (do-nothing) and in the case the recommended acceleration limit of 1 m/s^2 is imposed

	Do-nothing	With Accel. limit
Bus travel time	137.2 min	143.2 min
CV of passenger waiting time - direction 1	0.29	0.47
CV of passenger waiting time - direction 2	0.23	0.39
Violations of recommended acceleration	132	0

DISCUSSION AND CONCLUDING REMARKS

Ensuring that bus services provide an increased level of accessibility and enable people's mobility to reach and pursue everyday activities is crucial for the health and well-being of future generations. As abrupt bus accelerations have been reported as one of the most disappointing element of current bus services, that can refrain users from using the provided services, lower bus accelerations can be a way to attract people to active means of public transportation.

The 388 bus service in London, operating along a 23km corridor, provided the platform to investigate the effect of a safety-driven acceleration limit of 1 m/s^2 on the operational characteristics of the service. Long bus journey times involve the risk of turning people away from using buses and as a result operators would avoid adopting lower acceleration levels in order to maintain their service demand. A reduced service demand would lead to less passengers, increased fees for the remaining patronage and therefore increase of car ownership and decay of people's health.

Bus speed, acceleration and deceleration, as well as travel time for a round trip of the 388 service were recorded at 2Hz and extracted from the bus engine. The data were organized in a database and revealed that around 5% of the acceleration data exceeded the safety-driven acceleration limit in both the acceleration and deceleration phases. Although these instances do not occur frequently, and are not sustained for prolonged periods throughout the bus journey, they are capable of causing severe imbalances and non-collision injuries to passengers aboard the bus. Hence, it is beyond essential for bus services to operate at lower acceleration levels and to provide a more accessible bus service.

With regards to the time headways between the examined bus and its preceding and following buses, it was shown that the provided service deviated from the published timetable and as a result the examined bus was operating at large headways from its preceding bus and short headways from the bus behind it. This was especially apparent in direction 1. It did not come as a surprise that passengers of the examined bus were waiting at bus stops for unusually long times that reached up to 7.5min.

Applying the safety-driven acceleration limit of 1 m/s^2 only to accelerations that exceeded this threshold, it was concluded that a bus of this service would require 6min longer to complete the round trip. At the same time waiting times at some stations could reach up to 9.5min which would be extremely long for such a high-frequency service and would result in great passenger dissatisfaction. It is important to mention though that the calculations regarding passenger waiting times for the proposed service considered the published timetables of the preceding and following buses. Given that an acceleration threshold would be applied to all buses operating a route, the arrival and departure time of those two buses at stops along the route would also be altered.

We finally note that this work is not trying to solve the universal operation problem of a bus route that could arise from the application of an acceleration limit. Instead, it investigates the operational effects of the implementation of measures that increase bus safety and reduce non-collision injuries aboard buses. Looking at the journey time parameter in isolation, a journey that could last up to 6min longer when the safety-driven acceleration limit is imposed would not cause great dissatisfaction to passengers as currently some of them are waiting longer than expected (7.5min). However, it is with no doubt that the combination of a longer journey time (+6min) and waiting times of up to 9.5min would leave passengers unsatisfied and the importance of the accessibility of the service would be diminished.

Hence, as part of a future work, the acceleration data of the preceding and following buses should be analyzed in conjunction with the examined bus. This would draw a more complete picture of the impact that such an intervention would have on a bus service. Moreover, combining the proposed acceleration limit with bus priority measures would be more effective and would eliminate some of the limitations included in this work.

Author Contribution Statement

The authors confirm contribution to the paper as follows: study conception and design: X. Karekla, K. Gkiotsalitis; data collection: X. Karekla; analysis and interpretation of results: X. Karekla, K. Gkiotsalitis; draft manuscript preparation: K. Gkiotsalitis, X. Karekla. All authors reviewed the results and approved the final version of the manuscript.

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