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Standing Passenger Comfort: A New Scale for Evaluating the Real-Time Driving Style of Bus Transit Services

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***Abstract*— On-board bus comfort is a key factor affecting the quality of transit service. Thus, its assessment is crucial for public transport companies, as it can support the monitoring, evaluation and implementation of specific actions to improve their services. Previous research mainly focused on separate subjective and objective measurements of on-board comfort. Furthermore, even if concurrent measurements of objective and subjective on-board comfort have been collected, no study has built a gradual scale for the real-time measurement of comfort. This paper covers this gap by integrating subjective measurements of driving style with objective measurements of longitudinal and transversal accelerations collected by intelligent transportation system tools. These findings are very useful because they represent the first contribution for establishing a comfort scale in a real operational environment as a tool to regulate driver behavior, i.e., each driver will be able to recognize when passengers experience conditions of discomfort and acts to improve comfort.**

***Index Terms*— On-board bus comfort, real-time comfort monitoring, comfort scale, driving style, kinematic parameters, passengers' perceptions.**

Nomenclature

OBCL	On-Board Comfort Level.
PTC	Public Transport Company.
RMSWA	Root Mean Square Weighted Accelerations.

I. Introduction

A. Motivation

CURRENTLY, many people spend much of their time traveling on public transport. Thus, providing public transport services with high levels of quality is expected to increase the number of passengers and reduce the use of cars (and their negative effects). In public transport, there are several factors that contribute to improving the service quality, such as the reliability, waiting time, frequency, *etc.* (*e.g.*, [1]–[3]). Nevertheless, on-board bus comfort is a relevant factor influencing the overall satisfaction perceived by passengers, since the improvement of comfort may be a convenient strategy for public transport companies (PTCs) to attract more customers (*e.g.*, [1], [4], [5]). Moreover, there are various reasons for continuing to improve the on-board comfort conditions. For instance, a good internal environment may result in better performance by the driver, thus improving safety and reducing the annoyance of all passengers.

Over the past decade, the interest in the On-Board Comfort Level (OBCL) on buses has received increasing attention regarding the attributes and measurement methods. Most of the research on passenger comfort is focused on the technical side, and this research includes the measurement of vibrations,[1] noise, temperature, *etc.*(*e.g.*, [6]–[10]). Conversely, the driver's behavior is considered in relatively few studies ([11]–[13]). Hence, it may be of interest to increase the research concerning the relationship between the driving style and passenger comfort. Previous research has evaluated the comfort level using subjective or objective methods. For instance, the dated review of [14] separately analyzed subjective and objective comfort studies on the effects of longitudinal movement variations, such as accelerations and jerk on comfort. Some longitudinal acceleration values may be considered as comfort thresholds for various types of vehicles and conditions. However, subjectively measuring the OBCL may be an expensive task in terms of effort, relying on surveys and personal interviews, and it may provide judgments that are too varied. Hence, systems collecting objective data on OBCL are being proposed (*e.g.*, [8]). However, these systems might provide a measure that is too focused on the PTC side, as has happened for other transit quality parameters, such as the regularity (*e.g.*, [15], [16]). Thus, an emerging approach relying on the simultaneous measurement of subjective and objective attributes of comfort is being proposed (*e.g.*, [12], [13], [17]). Nevertheless, there is the need to establish a gradual and real-time comfort scale that integrates these different measures.

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[1]According to [6], vibrations may be defined as the recurring accelerations with small amplitude and high frequency, changing direction rhythmically.

B. Objective

The objective of this paper is to develop an innovative framework for the establishment of a gradual comfort scale in bus transit services to allow bus drivers the ability to monitor the quality of a bus ride in real-time and to sensitize them towards gentler driving behavior. To this aim, the authors adopted a subjective and an objective measure of comfort. The subjective measure considers the perception of passengers on comfort and is linked mainly to the driving style. This was assessed through a detailed designed questionnaire. Conversely, the objective measure has been obtained through the instantaneous acceleration values recorded continuously along the trajectories followed by the buses. Matching the subjective judgments with the objective ones, the authors found different thresholds of kinematic parameters that are representative of different levels of comfort. Each acceleration threshold corresponds to a different average subjective judgment. Finally, the authors developed a comfort function, which shows how the acceleration thresholds vary according to the comfort level. It is a gradual scale that measures the OBCL in real-time.

C. The Implications for Theory and Practice

This paper sheds new light on a research area that, to our knowledge, has not completely been addressed. This research is of interest for practitioners of the transit industry needing to improve the service quality on routes for benchmarking and/or quality certification purposes according to European norms ([18]). Moreover, bus operators can monitor the real-time OBCL of the overall fleets, thus reducing the costs for comfort surveys performed with on-board interviewers.

This study may be of interest for bus manufacturing, which may add a new instrument to the traditional on-board instruments (*e.g.,*the dashboard to measure the status of fuel consumption); this would show in real-time when the bus driver is driving in comfortable/uncomfortable conditions.

Finally, further related research areas, such as health, social studies, psychology, and safety may be involved. For instance, providing a comfortable bus floor may help standing passengers improving their health, *i.e.*, vertical accelerations may be further softened.

D. Paper Outline

Following this introduction, Section II describes in-depth the state-of-the-art models and methods to measure the OBCL in bus transit services. Section III presents the framework to build a gradual comfort scale. Section IV describes the experimentation of this framework in a real case study. Finally, Section V provides the conclusions and research perspectives.

II. Prior Work

A. What Is On-Board Comfort

The service quality can be influenced by several factors, such as speed, travel time, reliability, convenience, maneuverability, cost, accessibility, safety, and comfort (*e.g.*, [18]–[20]). Comfort is a crucial factor and may be considered as a multidimensional construct. For instance, Faris *et al.* [21] defined ride comfort as how a vehicle responds to road conditions. Hoberock [14] points out that passenger comfort in transit systems depends on the changes in motion felt in all directions, as well as by other environmental effects. The literature has shown that different attributes may be adopted to evaluate the OBCL (see Table I). For instance, a comprehensive list of attributes is provided by [18], in which their definition of comfort includes elements for making the trip relaxing and pleasurable.

TABLE I

A List of Comfort Attributes

Authors, year, source	**Comfort attributes**
Oborne and Clarke, 1973, [7]	Noise, vibrations, temperature, and posture
Hoberock, 1977, [14]	Longitudinal accelerations and jerk
ISO 2631, 1997, [22]	Vibrations
EN 13816, 2002, [18]	Passenger facilities, Seating and personal space, Ride comfort, Ambient conditions
Kittelson & Associates Inc. *et al.*, 2003, 2013 ([19-20])	Passenger loads
Kumar *et al.*, 2004, [23]	Passenger loads
AFNOR, 2005 ([24-25])	Space on-board and cleanliness
Af Wahlberg, 2006, [11]	Driving Style (Overall comfort, jerk, noise and safety, longitudinal acceleration)
EN 12299, 2009, [26]	Accelerations experienced by standing or sitting passengers (Railway)
Lin *et al.*, 2010, [27]	Vibrations
Lin and Chen, 2011, [28]	Vibrations
Barabino *et al.*, 2012, [29]	Space on-board, cleanliness, driving style
Prashanth *et al.*, 2013, [30]	Vibrations and noise effects on discomfort during travel while performing sedentary activities (reading a newspaper)
Sekulic *et al.*, 2013, 2016, 2018 ([8], [31-32])	Vibrations
Castellanos and Fruett, 2014, [17]	Jerk, accelerations, and vibrations
Maternini and Cadei, 2014, [33]	Accelerations on the standing passengers
Vovsha *et al.*, 2014, [34]	Load factor
Zhang *et al.*, 2014, [9]	Noise, vibrations, thermal comfort, longitudinal acceleration
Sekulic and Mladenović, 2016, [35]	Vibrations
Eboli *et al.*, 2016, [12]	Driving style and longitudinal and lateral accelerations
Shen *et al.*, 2016, [4]	Load factor and in-vehicle time
Zhao *et al.*, 2016, [10]	Vibrations
Meiping and Wen, 2017, [36]	Riding comfort and vibrations
Barabino *et al.*, 2018, [13]	Driving style and longitudinal and lateral accelerations

Representative, but not a comprehensive list of references.

Table I shows that the attributes may be clustered into four different groups.

The first group includes attributes concerning the space available for passengers, such as seating and personal space, the usability of passenger facilities, passenger loads, and load factor. The second group includes attributes related to the ambient conditions on the bus, such as cleanliness, noise, and temperature. The third group relies upon the physical and cinematic elements concerning the type and conditions of the road, traffic and, particularly, the in-vehicle time and vibrations. Finally, the last group consists of attributes concerning the driver's driving style and includes longitudinal acceleration due to the acceleration and braking actions, transversal accelerations due to the route characteristics and vertical accelerations due to the pavement roughness (e-mail: giuseppe.pungillo@libero.it).

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Three main approaches are commonly adopted to measure the OBCL, namely, subjective, objective and mixed approaches. These approaches will be discussed in the following subsections.

B. Subjective Evaluation of the OBCL

The first approach is based on subjective measures of comfort, as a function of road conditions, the type of vehicle, internal vehicle conditions, *etc.* These measurements reflect the passengers' viewpoints on desires and perceptions, as reported in the customer satisfaction surveys [37]. For instance, the perception for a given comfort attribute (*e.g.*, ride comfort, space on-board) is rated by passengers on a qualitative or quantitative scale, which may also be suitable for capturing opinions on a wide range of attributes. In the past, [7] measured the comfort through a questionnaire administered to on-board passengers. The following two different rating scales were considered: 1) the graphic scale and 2) the numerical scale. They concluded that the numerical scale is preferable due to several difficulties encountered in the interpretation of the graphic scale (*e.g.*, misunderstanding of rating).

Among recent studies, [23] concluded that comfort perception on rural buses significantly impacted the generalized cost of passengers (*i.e.*, the weighted sum of attributes related to the journey, such as the discomfort level experienced). In [29], the cleanliness on-board was shown to be perceived as the worst comfort attribute. Vovsha *et al.* [34] showed that when a passenger has less than 40% probability of obtaining a seat, s/he feels her/his travel is uncomfortable.

C. Objective Evaluation of the Obcl

The second approach in the measurement of the OBCL is based on an objective measure of comfort, which allows for a more reliable evaluation. Different comfort attributes are measured through technical devices, such as accelerometers, which return data that are free from any conditioning. However, the great majority of these studies analyzed the comfort regarding vibrations. Indeed, during the ride, drivers and passengers are exposed to vibrations from the road surface, which may reduce the working ability and generate a feeling of discomfort. Moreover, to connect the objective measurement to the subjective feeling of comfort, most of these studies relied on the international standard ISO 2631 [22]. It quantifies the whole-body vibrations and evaluation of their effects on health, comfort, perception and the occurrence of "seasickness", using the total value of the Root Mean Square Weighted Accelerations (RMSWA) on axes x, y and z from the passengers' seats.

Research on the objective evaluations of bus comfort can be roughly divided into three categories with the objective of finding thresholds that explain the comfort/discomfort on-board. The main characteristics are summarized in Table II.

The first category included studies that evaluated the OBCL without involving passengers. For example, the studies of [8], [31], [35] analyzed the effects of vibrations on the OBCL on an intercity bus. Sekulić *et al.* [8] measured the vertical oscillation of the driver and sitting passengers in the middle of the bus and the rear overhang. They concluded that for a bus speed of 100 km/h, passengers in the rear overhang have the lowest comfort level. Other simulations in [35] and real applications in [31] confirmed these results. Evaluating the effects of vibrations on the exposure time by simulation, Sekulić *et al.* [32] concluded that passengers at the bus front and rear overhang might be exposed to vibrations for a very short time.

TABLE II

CHARACTERISTICS OF THE STUDIES ON THE OBJECTIVE EVALUATION OF THE OBCL

Category	Source	Involved Passenger	ISO 2631	Acceleration data from	Setting	Type of service
1st Category	[8], [31]	N	Y	WBV tri-axial seat pad accelerometer B&K type 4321	Real test	Intercity Bus
	[32], [35]	N	Y	n/a	Simulation	Intercity Bus
2nd Category	[10]	Y	Y	Smartphone	Real test	Urban bus
	[36]	Y	Y	Smartphone	Real test	Shuttle bus
	[27-28]	Y	Y	Smartphone	Real test	Urban bus
3rd Category	[14]	N	N	n/a	Real test	Transit systems
	[33]	N	N	Proprietary system	Real test	Urban bus

The second category included studies that evaluated the OBCL involving passengers in a passive approach. More precisely, voluntary passengers were employed to collect comfort data regarding only accelerations. For instance, [27], [28] developed systems using participatory smartphones to collect data on passenger trajectories and vibration measurements regarding longitudinal, transversal and vertical accelerations. These data were forwarded to the systems via GPRS networks and processed according to [22]. They concluded that the comfort level varies a great deal along a trajectory, and smaller buses are the least comfortable vehicles. Similar systems were proposed by [10] and [36] using other communication networks. For instance, [10] used the Wi-Fi network to send acceleration data to the web server.

The third category included studies which neither adopted the international standard [22] nor involved passengers. For instance, the dated survey of [14] reported that, for transit systems, steady nonemergency accelerations ranging from 0.11 g to 0.15 g (*i.e.*, 1.078 m/s^2 to 1.470 m/s^2) fall in the comfortable range and could be larger. Finally, [33] proposed an objective scale to evaluate the OBCL. This scale is built by integrating a specific comfort index with the dynamic effects suffered by the standing bus passengers and some road characteristics (*e.g.*, the presence of roundabouts along the route).

D. Integrating Subjective and Objective Evaluations of the OBCL (Mixed Approach)

The third approach in the measurement of the OBCL is emerging and incorporates subjective and objective data on several comfort attributes. It can be roughly divided into two categories.

The first category includes studies that evaluate the OBCL using regression models. The objective of these models is to look for variables explaining the OBCL. Interestingly, all these models were calibrated inferring the subjective perception of the OBCL as the dependent variable and a pool of objective (observed) independent variables evaluated during the same ride. For instance, [9] built a model estimating the perception of comfort as a linear combination of a set of physical (observed) parameters, such as noise, vibration, thermal comfort and acceleration, and personal traits, such as age, gender and health. They concluded that the model helps calculate the value of the passengers' perceived bus comfort.

Shen *et al.* [4] developed a model estimating the subjective OBCL using the load factor and in-vehicle time. Adopting several statistic tools, they concluded that both attributes considerably affect the perception of comfort. Moreover, the in-vehicle time has a more significant impact on standing passengers than sitting ones.

The second category includes studies that use descriptive models to quantitatively evaluate the OBCL. The objective of these models is to establish a relationship between the subjective perception of comfort and different objective parameters using simple statistics, such as correlation analysis and percentage values. Interestingly, one of the main outputs of this approach is to establish some comfort thresholds to recognize whether the OBCL is good from the passengers' viewpoint. For instance, by a correlation analysis between comfort ratings and longitudinal acceleration data, [11] concluded that passengers experienced their bus ride as slightly more uncomfortable, noisy, jerky and dangerous after a full-blown, fuel efficient, driving training. Correlating the comfort perception and vibrations recorded on the floor and the seat, [30] concluded that the activity of reading is noticeably disturbed by the vibrations. Moreover, the amplification of vibrations was found to be slightly more annoying for sitting than standing passengers; 2.85 m/s^2 *vs* 2.64 m/s^2 are the maximum accelerations recorded.

Eboli *et al.* [12] compared the perceived OBCL judgments regarding the driving behavior and route surface with two axis and three-axis acceleration values, recorded by smartphone. By calculating the average and the standard deviation of the instantaneous measures, they determined the acceleration thresholds and developed two comfort indices for providing an aggregate comfort judgment.

In [13], passengers rated the driving style associated with measurements of horizontal accelerations only. Next, this judgment was compared with two axes acceleration values. By considering an aggregate measurement of the satisfaction rate, the thresholds of the horizontal accelerations defining a comfort domain were detected. They concluded that a comfortable domain for passengers ranges from -2 m/s^2 to $+$ 2 m/s^2 for both components of the horizontal accelerations.

Finally, [17] developed a system for detecting poor driving styles and possible defects on the pavement, according to the values of acceleration and jerk magnitudes that are out of the comfort range. By comparing the passengers' feedback recorded by push-button actions with acceleration events, they observed that 70% of users perceived a disturbance with a maximum acceleration of 0.7 g (*i.e.,* 6.86 m/s^2), 0.8 g (*i.e.,* 7.84 m/s^2) and 1.4 g (*i.e.,* 13.72 m/s^2) for lateral, longitudinal and vertical events, respectively.

E. Gaps in the Literature

All previous studies presented interesting attributes, systems, models and methodologies to evaluate the OBCL. Moreover, since the comfort is a multidimensional construct, these studies have shown how several approaches may obtain its measurement. However, even if measuring the OBCL is not a new topic in the scientific community, no attention has been given to concurrently evaluating the subjective and objective OBCL measurements to establish a gradual and real-time comfort scale. The following considerations could explain the missing attention.

First, passengers' judgments represent a measure of comfort that is too subjective. Indeed, even if subjective evaluations are useful, these measures may depend on: (i) the mood of the passengers; (ii) the historical memory of the passengers; (iii) the conditioning of passenger evaluations from other opinions; and (iv) the fact that the responses given by a passenger on a questionnaire might be likely to depend upon what s/he thinks is expected of her/him. Nevertheless, this type of measure does not consider the perceptions of non-passengers [37]. Moreover, the passengers' perceptions alone can lead to many biases, especially when passengers are not correctly sampled, and their judgments are too heterogeneous. Furthermore, external issues can influence the comfort perception (*e.g.*, the increasing of fares and the political interferences).

Second, the objective comfort measurements are crucial in the transit service, as they allow repeatability, the comparison between competitors and the creation of measuring scales [38]. However, in many studies, these measurements are not linked to the passengers' perspectives, which are fundamental in understanding why the comfort meets or does not meet their desires. Although the objective measurements of comfort may be linked to the passenger perspective according to [22], this approach is a drawback in the most recent studies. Indeed, this scale expressed vibration comfort under fixed and controlled conditions for one passenger. Moreover, it was derived by in ideal (static) condition (*i.e.,* in the lab) that measures the effects of exposures to different frequencies of vibrations on a human body that is sitting. However, especially in urban bus networks, passengers are subjected to real (dynamic) conditions and often travel standing for a few bus stops. Furthermore, this scale was derived without distinguishing between vehicles (*e.g.*, tram, bus, *etc.*). In the case of smartphone-based systems, the comfort measurement depends on the availability of voluntary passengers and their care when providing the measurement. Moreover, the battery discharge and possible costs associated with data transmission might discourage the voluntary passenger and limit the distance for the measurement. Although [33] proposed a comfort scale, it is compared with the passengers' transversal movements, but it did not integrate the passenger's judgments. In addition, this scale is derived from railway systems [26], which are different from bus systems. In bus systems, passengers may often experience higher accelerations, owing to the plan-altimetric road characteristics, frequent traffic flow interruptions, *etc*.

Third, the last emerging approach appears to be the most suitable to measure the comfort level. Indeed, the PTCs can measure the OBCL as experienced by passengers who use the service. However, [12] identified thresholds recognizing whether comfort/discomfort conditions occur, whereas [13] developed an aggregate comfort domain. Although in [17] passengers directly interact with the system, they only signal a feeling of discomfort by a binary scale with a push button action. Therefore, they do not judge the problem that causes the discomfort nor the quality of the ride if no problems occur.

To summarize, the related literature has so far not developed methods to derive a gradual and real-time comfort scale by combining the passengers' perceptions and acceleration data. These are impediments to providing a real-time comfort index that is more oriented towards the passengers' perceptions.

III. The Framework

In this section, a practical, simple and holistic framework for establishing a comfort scale for urban buses is presented. This framework is organized into the following three main levels: (A) data type, (B) data collection tools, and (C) data analysis, as shown in Fig. 1.

Each level will be separately discussed in the following subsections.

In this paper, a route r is the spatial itinerary between two terminuses, followed by the buses assigned to it. A ride k is the spatial-temporal itinerary followed by a bus along route r.

A. Data Type

The first level is the definition of the data types, which will be used in the framework. On the one hand, subjective data concerning passengers' perceptions are considered. On the other hand, objective data concerning kinematic parameters, on ride k along route r, are considered. It is worth noting that the basic assumption of this framework mainly considers the OBCL as a function of passenger shaking due to the bus motion affected by the driving behavior. Thus, some kinematic parameters need to be considered as affecting the passengers' feeling of comfort/discomfort on-board.

B. Data Collection Tools

The second level is the description of the data collection tools. Indeed, since two types of data will be collected, two types of instruments will be used.

In this framework, subjective data will be collected by surveying users about their perception of the comfort level; objective data will concern the analysis of the kinematic parameters on ride k, which is recorded through technical devices.

More precisely, an on-board questionnaire administered to passengers will be adopted.

Since the comfort can be described in different ways, as shown in Section II, in this step, some questions which

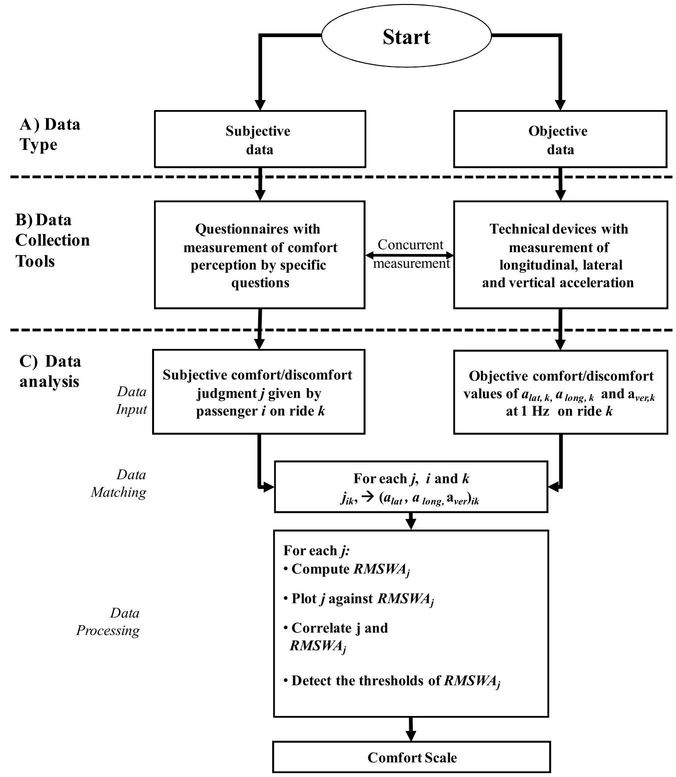

Fig. 1. The proposed framework to build the bus comfort scale.

mainly reflect the passenger's viewpoint on comfort will be used. It is worth noting that the characteristics of the vehicle type (*e.g.*, age, dimension, materials, and seats), route (*e.g.,*geometry, tortuosity, turn radius, stops, and pavement roughness), traffic (*e.g.,*density, speed, congestion, and stop and go), passengers (*e.g.,*age, health, gender, travel time, posture, and location on bus) and driving behavior are the main factors that affect the shaking comfort level of the bus. However, in this framework, the subjective measure of the OBCL is evaluated regarding the bus driver's driving style, since it mainly affects the shaking of the passengers.

With respect to the objective data, the kinematic parameters taken into consideration are the longitudinal, lateral and vertical accelerations. Moreover, the measure of the driving style concerns oscillations at low frequencies. This is because frequencies larger than or equal to 3 Hz are affected more by the vehicle age, materials and seats, pavement roughness and bus propulsion and transmission, whereas frequencies lower or equal to 2 Hz basically depend on the bus gross weight, length and suspension type, traffic density, speed distribution, geometric bus-route characteristics and driving behavior ([39], [40]). In this study, the location-at-time data (*i.e.*, the bus location at the arbitrary time when it is polled) on accelerations are recorded continuously on ride k along route r. As a result, much more data can be gathered, and the OBCL can be assessed according to the spatial characteristics of the route.

Finally, subjective and objective data need to be collected concurrently to avoid temporal mismatches and biases in the measurement. This may be done by interviewers and technicians simultaneously. Indeed, for each ride, interviewers

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administer the questionnaire (or may use a self-administered survey) to a group of users and technicians simultaneously detect the kinematic measures with the devices.

C. Data Analysis

The third level concerns using data analysis to establish a comfort scale. Data analysis is performed combining both measures, *i.e.*, subjective and objective, to determine the passengers' tolerance to longitudinal, lateral and vertical accelerations. This combination is based on threshold values, which help determine the comfort/discomfort conditions. The data analysis is organized into three sublevels, which are as follows: i) raw data input; ii) data matching and iii) data processing.

First, the subjective and objective raw data are collected concurrently and thus, they refer to the same time. Each passenger i rates with average judgment j the on-board driving style of ride k. Judgments can be provided on qualitative (very uncomfortable, uncomfortable, *etc.*) or quantitative scales (*e.g.*, $1, 2 \ldots, 10$), which may be suitable for capturing opinions on the OBCL. To provide a variety of judgments, passengers rate ride k according to their in-vehicle time and at the end of their journey. Therefore, if passengers travel between terminuses, their judgments refer to the entire k; if passengers travel between two bus stops, their judgments refer to only part of k. Simultaneously, the technical device collects raw data on the lateral a_{lat}, longitudinal a_{long} and vertical a_{vert} accelerations.

Second, data matching between the judgments and accelerations is performed. More precisely, for each judgment j,a list of rides is built. This list contains all rides k where the judgment j was recorded, independently from the route investigated. As a result, one builds as many lists, as many items have the judgments scale. For example, if passenger i rates j ride k on route r, and passenger $i+1$ rates j ride $k+1$ on route r_1, the list of judgment j contains both ride k and $k+1$. Nevertheless, since this framework helps build a comfort scale in an average sense, the time information is disregarded when the list of rides for each judgment is built.

Third, data processing follows. Since the comfort experience on the bus can be complex and difficult to evaluate, in this framework, the authors assume that the RMSWA is a technical indicator of the shake comfort mainly due to driving style that is measured by accelerations, braking maneuvers and turns. Moreover, for each judgment j, an estimation of RMSWA is performed and a linear combination is sought. Let:

- q be the index of the observation;
- N_j be the total number of samples of a_{lat}, a_{long} and a_{vert} associated with judgment j.
- $RMSWA_j$ be the total value of the root mean square of the weighted accelerations in m/s^2 for each judgment j;
- $RMSWAa_{lat}$j, $RMSWAa_{long}$, j, and $RMSWAa_{vert}$j are the root mean square value of the weighted accelerations along the transversal *x*, longitudinal *y* and vertical *z* axes, respectively, in m/s^2 for each judgment j;
- $a_{lat,j}$, $a_{long,j}$, and $a_{vert,j}$ are the transversal, longitudinal and vertical components, respectively, of the accelerations for each judgment j;
- k_{lat}, k_{long}, and k_{vert} are the weight factors that reflect the importance of the acceleration along the *x, y,* and *z* axes, respectively.

The total value of the root mean square of the weighted accelerations for each judgment j ($RMSWA_j$) is calculated as follows:

$$RMSWAa_{lat,j} = \sqrt{\frac{\sum_{q=1}^{N_j} \left(a_{lat,j,q}\right)^2}{N^j}} \; \forall j = 1, \ldots J \quad (1)$$

$$RMSWAa_{long,j} = \sqrt{\frac{\sum_{q=1}^{N_j} \left(a_{long,j,q}\right)^2}{N^j}} \; \forall j = 1, \ldots J \quad (2)$$

$$RMSWAa_{vert,j} = \sqrt{\frac{\sum_{q=1}^{N_j} \left(a_{vert,j,q}\right)^2}{N^j}} \; \forall j = 1, \ldots J \quad (3)$$

Equations (1), (2), (3) and (4), are taken from [22] with some simplifications, including the frequency range and the method of measurement. Unlike [22], which adopts a frequency range from 1.0 Hz - 80.0 Hz, we consider the RMSWA at 1.0 Hz because the major annoyance to the passengers in the transportation vehicles is in the range of $0.5 \div 5$ Hz, according to *e.g.*, [39], [40]. Moreover, the human body exhibits the maximum sensitivity for horizontal acceleration at 1.0 Hz, and the lower or higher frequencies are less relevant. Unlike [22], the RMSWA is evaluated in real conditions.

Next, each judgment j is plotted against the values returned by eqn. (4), shown at the bottom of the next page, to find a relationship between the subjective judgments and the objective values of acceleration. Several regression methods may be adopted to fit the best trend for the data distributions.

Finally, this *modus operandi* helps provide a gradual and real-time comfort scale associated with each judgment j. The range between two consecutive judgments marks the thresholds between two values of accelerations or the *RMSWA*.

IV. Experimentations in a Real-World Case

A. Case Study

The authors have experimented with this framework in the urban bus transport system in the area of Cagliari, located on the island of Sardinia (Italy).

The local PTC, called CTM, manages the public transportation with 271 vehicles (*i.e.*, buses and trolleys) and serves approximately 38.9 million trips a year. Moreover, these vehicles travel over 12,3 million kilometers per year along 32 urban routes [41]. CTM collected data for this experimentation on a pool of 8 routes, which are representative of the general bus network regarding passengers, lengths ($6 \div 13$ km), vehicle types ($7 \div 12$ m) and capacities ($29 \div 105$ passengers) - see Table III.

According to CTM's quality policy, before the survey, aims, scope and the data collection methods were presented to trade unions and drivers.

B. Types of Data and Collection Tools

As mentioned in Section III B, both types of data were collected simultaneously on different days. Each route was

TABLE III
CHARACTERISTICS OF ROUTES AND BUSES

Route name	Route type	Inbound length [km]	Outbound length [km]	Inbound bus stops [#]	Outbound bus stops [#]	Bus length [m]	Bus capacity [passenger (seats)]
L1	2 way	13.200	11.190	46	35	12.00	105 (27)
L2	2 way	9.648	9.384	35	35	12.00	105 (27)
L3	2 way	6.140	6.720	23	25	7.90	58 (10)
L4	1 way	9.941	-	31	-	9.23	85 (15)
L5	1 way	18.490	-	49	-	12.00	83(25)
L6	1 way	9.212	-	28	-	7.00	29 (10)
L7	2 way	8.850	10.450	30	38	12.00	105 (27)
L8	2 way	10.383	10.637	30	28	12.00	105 (27)

examined during the time period from 7:00 AM to 7:00 PM, from 3 to 6 consecutive hours. Since CTM adopts split-shifts, different bus drivers have been used in the analysis. This results in the possibility of analyzing several driving styles.

It is worth noting that no distinction was made between standing and seated passengers. However, this is not a strong drawback of this framework, since, as shown in the last column of Table III, the availability of standing places is greater than those of seated. Therefore, we can reasonably assume that standing passengers constitute the dominant share of the interviewed sample. Moreover, they are supposed to travel less comfortably than sitting passengers.

*Subjective data*were collected by interviewing passengers with a questionnaire. Before deciding on the type of survey, we carefully evaluated the situation in which the passenger can write, since it might provide a comfort perception better than the opposite. Therefore, our dilemma was between the use of a self-administered survey or a paper-and-pencil interview administered by interviewers. After a careful evaluation, we opted for a paper-and-pencil interview administered to passengers approached onboard the bus. Indeed, the passengers do not need to write and, therefore, can experience the real comfort/discomfort situation. Although the interviewers write, they are not the subjects of this study, since they were adopted only as a "means" to collect the passengers' perceptions of the driving style. In addition, all the routes run in the urban area, have many and close bus stops and the passengers stay on board for ten bus stops on average ([42]–[46]). The characteristics of the journeys make engaging in the activity of writing seldom possible. As a result, a paper-and-pencil interview may not generate a biased measurement in the assessment of the comfort, which conversely could have been generated using a self-administered questionnaire. Furthermore, unlike self-administered surveys, the paper-and-pencil interview has been chosen to improve the accuracy and quality of the answers provided. This is to avoid a low response rate, minimize the no response bias and the misinterpretation of some questions, especially by uneducated passengers and the elderly passengers in Cagliari [29]. These represent further reasons for using this type of survey.

The questionnaire was organized into four sections. The first section is general and reports on contextual information, including the date, time, route investigated and a question regarding the passengers' agreement to participate in the survey. The remaining sections are organized as follows:

- Sociodemographic attributes, including gender, age, educational qualifications, employment, car availability and reason for using the bus;
- Trip-related attributes, including trip purpose, in-vehicle time, other transit systems used, and bus use frequency;
- Quality rating on the OBCL.

More precisely, the perceptions of comfort on-board from the passenger's viewpoint were evaluated by a specific question about the driving style of the bus driver. The question was formulated as follows: "On a scale from 1 to 10, how satisfied are you with the bus operator's driving style concerning this route?" The motivating reason to adopt a 1 to 10 scale is its adoption in the Italian scholastic evaluation method. Thus, we assume that, for the interviewed passengers, it is easier to provide ratings from 1 to 10, rather than the 1 to 5 or 1 to 7. Nevertheless, [47] pointed out the similar reliability of different scales from a statistical viewpoint, even if more options tend to lead to somewhat lower scores. However, the choice of a 1-10 scale does not influence the generality of the method, which is effective using any scale range. A pre-test and piloting were also conducted. As a result, the order of some questions was slightly adjusted; moreover, formatting and data entry errors were pointed out and addressed before starting the full survey.

In this paper, the OBCL is directly related to the driver's style on the horizontal plane, as it is mainly influenced by slowing down, braking, accelerations and steering due to traffic conditions and route characteristics. Nevertheless, there are cases, such as speed bumps, where the OBCL might be directly related to the driver's style and vertical acceleration. However, the routes in Table III travel along itineraries without speed bumps and the passengers were not asked to rate this characteristic. Therefore, the vertical acceleration is omitted and, thus, eqn. (4) is adjusted by disregarding $RMSWAa_{vert,j}$.

In addition, we suppose that the vertical acceleration is more related to pavement roughness rather than the horizontal driving style. Nevertheless, these routes travel on pavements characterized by uniform roughness, which should limit the vertical acceleration.

To collect accurate data, the interviewers were adequately instructed on how to conduct the interview during classroom lessons on the following facets: 1) the introduction of the interviewer to the passengers; 2) the presentation of the study about the evaluation of the OBCL; 3) the way to administer the questionnaire, *i.e.*, how to read the questions to achieve uniformity; and 4) the way to compile the questionnaire. Nevertheless, the on-board survey may result in passengers' mobility problems, especially on congested routes. However, the passengers' mobility was not an issue in our survey, since

$$RMSWA_j = \sqrt{[(k_{lat} RMSWAa_{lat,j})^2 + (k_{long} RMSWAa_{long,j})^2 + (k_{vert} RMSWAa_{vertj})^2]} \forall j = 1, \dots J \quad (4)$$

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

all routes of CTM are certified according to EN 13816:2002 ([18], [48], [49]). Regardless, in the rare event that passenger mobility problems may be detected, the interviewers were adequately instructed on how to select passengers. Those travelling in the proximity of the interviewer were recommended for selection. Moreover, the interviewers were trained to persuade passengers to agree to answer the survey through appeals to intentions, attitudes and values. Despite the inability to eliminate the bias associated with this type of survey and possible passenger mobility problems, we assumed that the interviewers are homogeneous in the administration of the questionnaire. The questionnaire was administered by two interviewers: one for each investigated ride.

Before starting the survey, we carefully reflected on the type of sample and on its size. We opted for a statistical sample, large enough and well representative of the population of CTM's passengers. More precisely, let:

- ε be the margin of error or the maximum distance desired for the sample estimate to deviate from the true value;
- z be the z score at the 95% confidence interval (CI);
- p be the proportion of female (or male) passengers;

the simple size n was planned as follows:

$$n = \frac{z^2 * p * (1 - p)}{\varepsilon^2} \tag{5}$$

Next, owing to budget constraints, we set the error ε in the range of [5%÷ 6%] and the z score at the 95% confidence interval. Moreover, we set the proportion of female passengers, *i.e.*, *p,* at 63% ([42]–[46]). Therefore, according to eqn. (5), our survey will be acceptable when the total number of observations ranges from 249 to 358 interviews.

Objective data were collected by Smartphone "Samsung j5" which is based on Android system. Moreover, it is equipped with a GPS device and 3-axis accelerometer MEMS (Micro Electro Mechanical Systems). With a frequency of 1 HZ, a specific app (Torque) recorded the location-at-time data of several parameters along the bus route during ride k. Some professional equipment, such as Vbox, may be used to record the measurements. However, in this paper, smartphones have been used for ease of measurement. The smartphone is less bulky than the Vbox and it is easier to install on-board. Further, the smartphone helps to acquire a huge amount of data at a low cost. Moreover, smartphones still guarantee reliably collected data from different technical specifications and fixation strategies (*e.g.*, [50]–[52]). The most relevant data attributes for this study are as follows: the GPS Time (in hh, mm, ss), the instantaneous bus position (in latitude and longitude), the speed (in m/s) and the two components of the acceleration (in m/s^2), *i.e.*, a_{lat} and a_{long}. For instance, the first record of Table IV represents the location-at-time raw data for a bus position on route L1.

A crucial choice was the location of the smartphone to record representative data. It was located inside the bus, close to the driver and on a horizontal plane, but in an unobtrusive location to not influence the driving style of bus driver. This choice can result in an approximation on the perceptions of comfort levels from passengers. Indeed, several passengers can be located quite far from the smartphone location (*e.g.*, in the middle or the rear of the bus). However, in this case study, the interviews were performed close to the smartphone. Nevertheless, in future experiments will use a changed location of the smartphone or more smartphones to further validate the results.

TABLE IV

LOCATION-AT-TIME RAW DATA SAMPLE GATHERED BY THE APP TORQUE ON TUE JUL 18

GPS Time	Longitude [°]	Latitude [°]	GPS Speed [m/s]	a_{lat} [m/s^2]	a_{long} [m/s^2]
10:33:55	9.10102	39.241895	4.01	-0.7346	-0.4840
10:33:56	9.101006667	39.24183833	4.50	-1.0937	0.5383
10:33:57	9.100983333	39.24177833	5.06	0.9893	-0.2925
10:33:58	9.100963333	39.241715	5.61	0.7977	-0.1417
10:33:59	9.100926667	39.24165	6.08	-0.1169	0.1289
10:34:00	9.10092	39.24158667	6.43	-0.7346	0.1193
10:34:01	9.100905	39.241525	6.68	0.1896	-0.4098

To gather accurate data, the technicians were trained in the classroom and on the field on how to calibrate the app, how to start and end a specific measurement session and how to download the collected data. More precisely, the technicians need to calibrate the reference system with respect of the horizontal plane ([12], [13]), so that the smartphone's reference system is integrated with that of the vehicle and the acceleration values are not influenced by the orientation of the mobile device in the vehicle. For instance, this means that the lateral and longitudinal accelerations must be equal to 0 when the bus is stopped at key points on a horizontal plane (*e.g.*, at bus stops). The kinematic quantities are acquired by referring to the smartphone's reference system (which depends on how it is oriented), but, in the modeling of dynamic systems, they must be reported in the vehicle's reference system. To do this, the smartphone's reference system must be rotated using the axis rotation matrix. This is a procedure that goes beyond the scope of the paper, and which is now automated in almost all smartphone applications. Through Torque, the technicians only need to press a button to start an automatic procedure that uses Euler's formulas. This smartphone procedure is used for different analyses of the kinematic parameters in the transport sector, *e.g.*, to analyze the driving behavior [53]–[56], to check the consistency of the road design or to predict the operating travel speed [57] and to analyze the comfort level on-board the bus [12], [13]. Thus, the data integrity and accuracy were guaranteed by Torque. Two technicians recorded the measurements with Torque: one for each investigated ride.

C. Analysis of the Data and Results

A total of 26 hours distributed among 42 complete rides were investigated. The data collection resulted in 294 completed questionnaires and approximately 150,000 raw records of kinematic parameters[2].

1) Relationship Between Rmswa and Judgment: After completing the survey, $\varepsilon = 5.36\%$, which was in the planned range. Moreover, as shown in Table V, female passengers are not overrepresented since p 67.31% is in the range of $CI_{95\%}$ [61.95% ÷ 72.67%]. In addition, Table IV shows that 89.44%

[2]Owing to the confidentiality policy of CTM, we are not allowed to add a link to the survey or to add it in an appendix.

TABLE V
SURVEY ITEMS AND SUMMARY RESULTS OF THE PANEL SURVEYED

Socio-demographic characteristics	Description	Percentage
Gender	Female	67.31%
	Male	32.39%
Age	Under 18 years old	26.76%
	Between 18 and 25 years old	30.99%
	Between 26 and 35 years old	11.97%
	Between 36 and 50 years old	15.49%
	Between 51 and 65 years old	9.86%
	Above 65 years old	4.93%
Educational qualification	Upper school (graduated)	54.23%
	Middle school (graduated)	42.96%
	Middle school (did not graduated)	*2.82%*
Employment	Worker	25.35%
	Student	57.04%
	Unemployed	6.34%
	Housewives	6.34%
	Retirees	4.93%
Car availability	Has a car	30.28%
	Does not have a car	69.72%
Reason for using the bus	It is cheap	3.52%
	Difficulty to park	14.79%
	It is more ecological	2.82%
	It is faster	1.41%
	Less stress	10.56%
	I have no alternatives	66.90%
Travel behaviour characteristics		
Trip purpose	Shopping	0.70%
	Work	20.42%
	School / University	21.13%
	Personal services	23.24%
	Leisure, Sport, Tourism	34.51%
In-vehicle time	Travel time more than 15 minutes	70.42%
	Travel time less than 15 minutes	29.58%
Other transit systems use	Use of other transit systems	45.77%
	No use of other transit systems	54.23%
Bus use frequency	1-2 days a week	11.27%
	1-3 days a month	3.52%
	3-4 days a week	18.31%
	5-6 days a week	53.52%
	Is the first time	3.52%
	Occasionally	9.86%
Driving Style rating	1 (The Worst)	0.70%
	2	0.70%
	3	-
	4	2.82%
	5	6.34%
	6	14.79%
	7	18.31%
	8	33.10%
	9	11.27%
	10 (the Best)	11.97%

of passengers are satisfied with the driving style, since they give a judgment larger than or equal to six, which represents the satisfaction threshold adopted in this study. Hence, they perceive the OBCL as good, and we can expect that passengers are not exposed to very high acceleration values.

Although female passengers rated the driving style lower than males among the routes (7.29 *vs* 7.72, on average), no significant differences at the 95% significance level were observed. Indeed, the result of a two-sample z-test between the means shows that the calculated value (*i.e.,* -1.507) falls in the acceptance region of Z (*i.e.*, $-1.960 < -1.507 < 1.960$). Therefore, the evaluation derived from the subjective data is linked to the objective data on lateral and longitudinal accelerations, without differentiating between routes and gender.

Next, for each judgment, the list of rides and, thus, the lists of the instantaneous values of a_{lat} and a_{long} are built. The results are shown in Fig. 2.

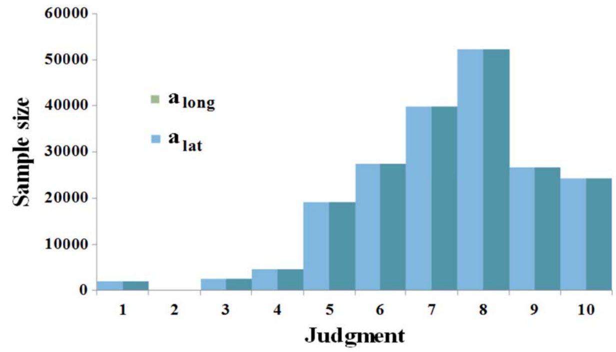

Fig. 2. Sample size of a_{lat} and a_{long} for each judgment.

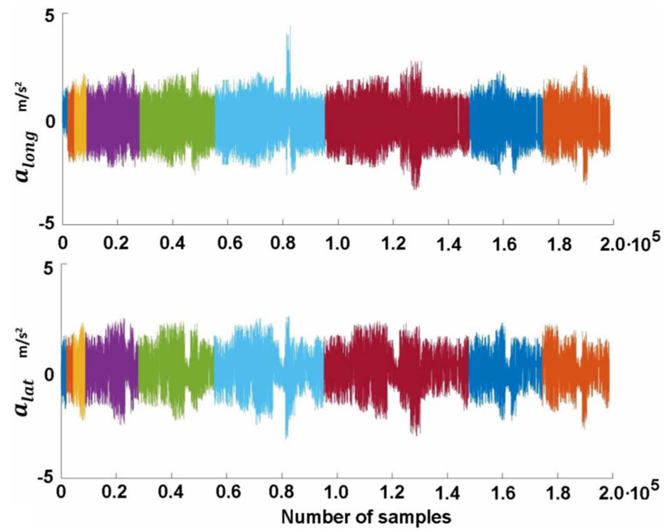

Fig. 3. Values of a_{lat} and a_{long} data for each judgment.

This figure shows that a total of 198,710 instantaneous data points is considered as a result of matching. This fact is not a surprise, as ride k may be associated with different subjective judgments, as passengers may differently rate the same ride k. Moreover, Fig. 2 shows that the judgments of 7 and 8 contain the largest majority of a_{lat} and a_{long}, whereas 1 and 3 contain little data. Moreover, for judgment 2, no data were gathered.

Fig. 3 shows all the lateral (down) and longitudinal (top) acceleration data for each judgment. Each color shows the total data of a_{lat} and a_{long} associated with judgment j. For instance, the total data of a_{lat} and a_{long} associated with judgment 8 are shown in red.

Although Fig. 3 shows differences between the maximum and the minimum values of a_{lat} and a_{long}, no significant differences at the 95% significance level were observed between these ranges, *i.e.*, the thresholds in the ranges of a_{lat} and a_{long} may be considered quite similar. Indeed, the result of the two-sample t-test between means shows that the calculated value (*i.e.*, 0.522) falls in the acceptance region of T (*i.e.*, $-2.12 < 0.522 < 2.12$). Therefore, the comfort perception seems to depend both on the acceleration and braking actions due to traffic conditions and/or transversal movements due to the route characteristics.

Before data processing, a preliminary data cleaning of the original databank is performed to synchronize the judgments

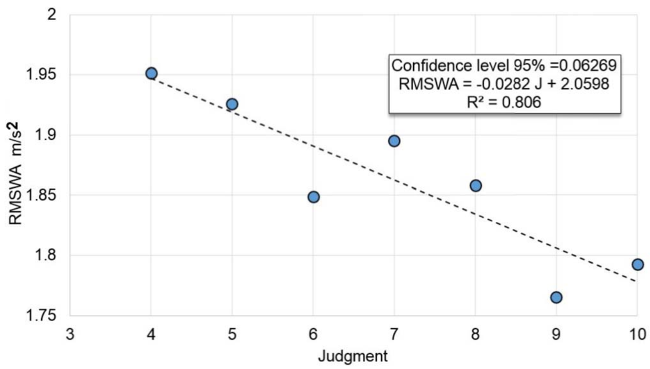

Fig. 4. Estimation of the RMSWA and judgments.

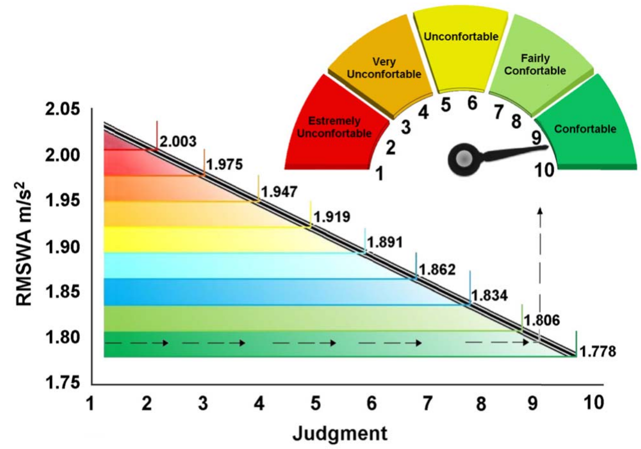

Fig. 5. The comfort scale for the horizontal acceleration RMSWA.

and accelerations. More precisely, the precisions of the ten subjective judgments are different due to their different sample sizes. Thus, to preserve the homogeneity and uniformity of the sample size data with respect to the judgments, the values of a_{lat} and a_{long} that were associated with judgments 1 and 3 were neglected. Only 7 out of 294 questionnaires have been rejected because the standard error is higher than 30% with a significance level of 80%.

Thus, the following analysis was developed using 194,366 instead of 198,710 observations, deliberately disregarding a 2.2% of the objective data. However, this fact is not a strong weakness of the method, as very little data was lost.

Next, the lateral and longitudinal accelerations from adjusted eqn. (4) to derive the *RMSWA* associated with each judgment are considered. According to [22], the coefficients k_{lat}, k_{long} have been set to 1, since the lateral and longitudinal accelerations are evaluated with the same weighed curve.

Moreover, we plot the $RMSWA_j$ against each judgment. Different models have been considered: linear, logarithmic, exponential, power, polynomial. However, the best correlation model between RMSWA and judgment was found considering a linear and a polynomial regression ($R^2 = 0.806$). Despite the similarity of the R^2, the linear model is chosen due to its simplicity. This result is reported in Fig. 4.

Moreover, extending this model towards the low judgments 1, 2 and 3, a comfort scale, as shown in Fig. 5, is obtained.

Eqn. (6) returns the value of human judgment, according to the value of the RMSWA. Nevertheless, to obtain judgments from 1 to 10, eqn. (6) must be considered in the following ranges of the RMSWA, expressed in m/s^2:

$$J = \begin{cases} 1 & if \;\; RMSWA > 2.03 \\ -35.46 * RMSWA + 73.04, & if \;\; 1.78 \leq RMSWA \leq 2.03 \\ 10 & if \;\; RMSWA < 1.78 \end{cases} \tag{6}$$

More precisely, entering the objective values of the *RMSWA* returned by eqn. (4) into eqn. (6), the corresponding value of the subjective comfort is derived. This operation may be performed graphically as follows: i) Move vertically along the segment representing the *RMSWA* of interest; ii) Move horizontally to intercept the value returned by eqn. (6); (iii) Move vertically to intercept the segment representing the subjective judgment. According to Fig. 5, the value of the estimated subjective judgment is the x coordinate at the interception. For instance, in Fig. 5, when RMSWA = 1.78 m/s^2, the corresponding subjective judgment is approximately 9.3, which denotes a good comfort level. The range of acceleration values concerning the judgments is very narrow. The homogeneity of the bus routes selected for the survey and the short average passenger travel distance reduce the variability of all the possible accelerations.

Interestingly, Fig. 5 shows that this scale can be used to identify comfort/discomfort conditions in real-time. Indeed, this scale may be part of a real-time dashboard, which shows the bus driver when s/he is driving in comfortable/uncomfortable conditions. A clear example is shown in the top-right portion of Fig. 5, which represents a pioneering output of this framework. Although this scale has been developed and calibrated by combining the subjective judgments with the objective ones, it helps to evaluate the comfort only through the kinematic data recorded during the bus ride. Therefore, it results in two impressive advantages, as follows: 1) a bus driver can regulate the driving style and 2) the bus company may save many economic resources in the evaluation of the OBCL, as there is no need to perform surveys. Indeed, once the scale has been obtained by the integration of subjective and objective data, only the acceleration measurements will be processed to monitor comfort. For instance, Fig. 6 shows a recorded survey. Since each recorded point is geo-referred, it is possible to measure in real-time the OBCL along the route and match it to the comfort scale. This is useful for the driver, who can adapt his/her driving where the conditions of discomfort are recursive.

2) Further Analysis: It may be of interest to perform a further experiment evaluating the mean values of the positive and negative components of a_{lat} and a_{long} for each judgment j. This is because, for each judgment j, the passenger perceptions on the driving style may be different for right turns, left turns, acceleration or breaking. These components are denoted by $\widehat{a_{lat}^{+\,j}}$, $\widehat{a_{lat}^{-\,j}}$, $\widehat{a_{long}^{+\,j}}$ and $\widehat{a_{long}^{-\,j}}$ and were computed for each judgment. Next, each value was plotted against each judgment, as shown in Fig. 4. More precisely,

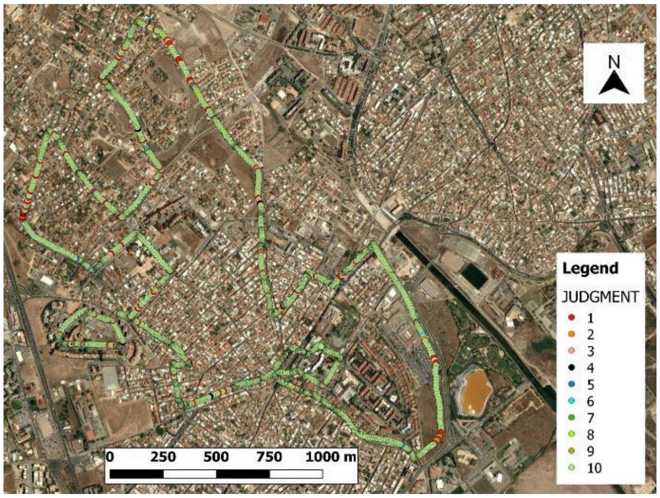

Fig. 6. An example of the real-time evaluation of the OBCL. The maximum comfort conditions are shown in green, while the maximum discomfort conditions are shown in red. Different colors represent the intermediate conditions.

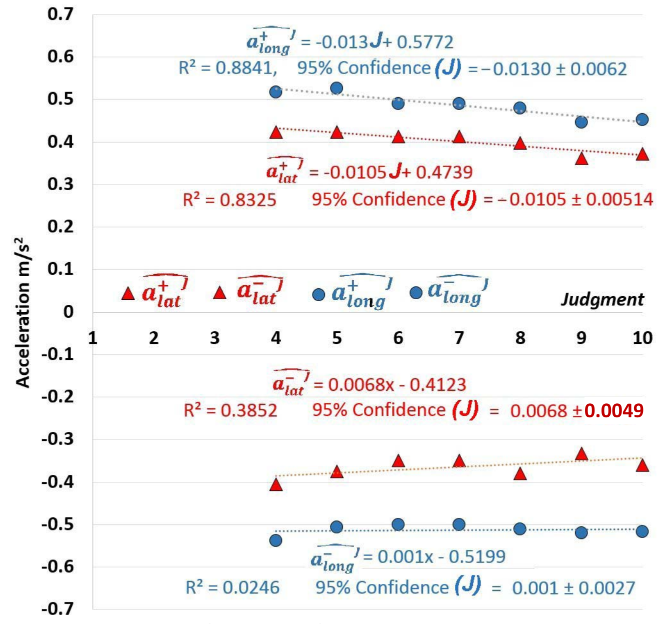

Fig. 7. Estimation of $\widehat{a_{lat}^{+}}^{j}$, $\widehat{a_{lat}^{-}}^{j}$, $\widehat{a_{long}^{+}}^{j}$ and $\widehat{a_{long}^{-}}^{j}$ vs the judgments.

the x-axis reports judgment J using a 1 to 10 scale, whereas the y-axis includes the values of $\widehat{a_{lat}^{+}}^{j}$, $\widehat{a_{lat}^{-}}^{j}$, $\widehat{a_{long}^{+}}^{j}$ and $\widehat{a_{long}^{-}}^{j}$. Next, the functions representing the positive and negative components of acceleration were estimated using the least square linear regression method and the associated R^2 was computed to evaluate the power of the estimation. Although few points are available to estimate the components of the accelerations, they are indicative of its trend, and each point of $\widehat{a_{lat}^{+}}^{j}$, $\widehat{a_{lat}^{-}}^{j}$, $\widehat{a_{long}^{+}}^{j}$ and $\widehat{a_{long}^{-}}^{j}$ was derived from an average of 27,767 points. Interestingly, Fig. 7 shows three findings.

First, the ride comfort perceived by passengers may mainly be attributable to the positive component of acceleration, *i.e.*, accelerations and right curves in the route, whereas breaking and left curves affect the OBCL less. The result of the two-sample t-test between means show that differences between the left and right accelerations are significant ($p<0.001$).

This peculiar phenomenon may be explained by observing the passenger's posture and the path characteristics, according to some remarks of a handful of researchers ([58], [59]). Besides, in this study, this phenomenon may be explained as follows. Almost all sitting passengers are oriented in the longitudinal direction and are confined by seatbacks and the lateral bus body. Since the bus seating layouts are asymmetric, with doors on the right and many seats on the left, there are more passenger confined to the left. The standing passengers are oriented mainly in the transversal direction. Their feet, aligned in longitudinal direction, can prevent movements from braking rather than lateral accelerations. Moreover, it can be observed that the road pavement has a transversal slope. Consequently, the bus is transversally sloped on the right and the passengers looking towards the right windows or waiting at the door can have a worse perception of the right accelerations. The right wheel path presents rutting and irregularities that can increase this effect. Nevertheless, as no specific experiment has been reported so far, more future research is recommended to confirm the differences between the left and right accelerations

TABLE VI

COMPARISON OF THE $\widehat{a_{lat}}$ AND a_{long} THRESHOLDS FOR SOME COMPARABLE STUDIES

Source	Comfort range $\widehat{a_{lat}}$ [m/s²]	Comfort range $\widehat{a_{long}}$ [m/s²]
Present study	$-0.372 \leq \widehat{a_{lat}} \leq 0.412$	$-0.514 \leq \widehat{a_{long}} \leq 0.499$
Barabino *et al.*, 2018, [13]	$-2.000 \leq \widehat{a_{lat}} \leq 2.000$	$-2.000 \leq \widehat{a_{long}} \leq 2.000$
Hoberock, 1977, [14]	-	$1.078 \leq \widehat{a_{long}} \leq 1.470$
Castellanos and Fruett, 2014, [17]	$\widehat{a_{lat}} \leq 7.848$	$\widehat{a_{long}} \leq 6.867$
Prashanth *et al.*, 2013, [30]	-	$\widehat{a_{long}} \leq 0.570$

when asymmetrical vehicles are used. This represents a new research challenge.

Second, while accelerations strongly affect the OBCL, braking does not seem to have any effect. This may be explained considering the strong acceleration from the bus stops and it confirms the result of [11], since at CTM, the drivers were also trained in a full-blown fuel-efficient driving style. Nevertheless, according to the results of Fig. 7, one may infer that passengers mainly perceive the driving style in term of the positive component of the longitudinal and transversal accelerations.

Third, as shown in Table VI, the values of $\widehat{a_{lat}^{+}}^{j}$, $\widehat{a_{lat}^{-}}^{j}$, $\widehat{a_{long}^{+}}^{j}$ and $\widehat{a_{long}^{-}}^{j}$ present stricter OBCL thresholds than those of [13] and [14]. Moreover, the thresholds for an uncomfortable ride are also stricter than those of [17] and [30]. Therefore, in our case study, the passengers seem to be more sensitive to the driving style in terms of their perceived comfort.

D. Recommendations

The findings help us provide some recommendations.

- The close collaboration between the PTC and the research team has been very useful, and it greatly helped the research team plan the route to be measured, provided useful suggestions to gather data of the passenger population, and so on. Moreover, different PTC business units shared and compared their experiences to better plan the data collection, both for the objective and subjective data.
- A limited paper-and-pencil interview survey at reduced costs is enough to acquire a representative sample, as a base for the linking with objective data of accelerations and evaluating the comfort in worse conditions.
- The recent use of smartphones helps for ease in the measurement, and results in quite reliable objective data.
- The inclusion of the time dimension when matching objective and subjective data may help build how many scales how many time periods are considered. The PTC may set up the most suitable scale according to the different time periods of a day.

V. Conclusions and Future Research

Bus comfort is a key factor in transit service quality. Measuring the OBCL can support public transport companies for the monitoring, evaluation and implementation of specific actions to improve their services. Nevertheless, since the OBCL may be measured in different ways, the studies used attributes that reflect the scope of their research. Most of the previous research relied on the passengers' perceptions, which provided a too subjective measure, and on kinematic parameters (*e.g.*, acceleration, speed), which rarely are linked to the passengers' perceptions. In addition, among bus operators, there is a significant interest in building a comfort scale in order to assess and monitoring the transit service quality, as in the case of railway operators which have their scale.

The contributions of this paper are twofold, as follows:

1) The proposal of an innovative framework to assess the OBCL in urban bus transit services by a gradual and real-time scale, which shows the trend of the RMSWA values according to passengers' perceptions.
2) The geographical link of the OBCL to allow bus drivers to monitor the real-time quality of a bus ride.

This framework identifies different objective comfort thresholds, which are associated with a scale of judgment, and identifies where passengers experience comfort/discomfort conditions that are associated with the driving style of the bus drivers. This framework was tested on a real case study using approximately 300 judgments (subjective data) and approximately 200,000 pieces of raw data of the kinematic parameters (objective data) collected on several routes of an Italian bus operator. These results may help public transport companies obtain both an offline evaluation of comfort and an online (real-time) one.

Nevertheless, this is a preliminary step in the authors' research agenda, and thus, further research is suggested. First, in this experimentation, the authors identified a gradual comfort scale without differentiating between young and old passengers or sitting and standing passengers. Since these characteristics are expected to cause variations in the comfort perceptions, a more challenging comfort scale may be derived that considers these characteristics. In this way, a new and more comprehensive comfort scale may be derived. Second, in the experimentation, the vertical component of the acceleration was disregarded, since subjective evaluations were not performed. In future work, adding this new evaluation may help build a new scale, which would consider the pavement roughness. Finally, more advanced econometric models may be calibrated (*e.g.*, multinomial logit) to examine the impact of various sociodemographic and journey characteristics on the ratings.

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