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Abstract

Urban mobility represents one of the most critical global challenges nowadays. Several options regarding design and power sources technologies were recently proposed; among which electric and hybrid vehicles are quite successful to meet the increasingly restrictive environmental targets. This significant goal may affect the perceived vehicle comfort and drivability, especially in everyday urban scenarios. The purpose of this paper is to carry out a comparison in terms of comfort between vehicles belonging to different categories, but all designed for urban mobility: an electric 2-passenger quadricycle used during the demonstration phase of the European project STEVE, an internal combustion engine 2-passenger car (Smart Fortwo), an electric 4-passenger car (Bolloré Bluecar) and an internal combustion engine 4-passenger car (Fiat 500). Leading European car-sharing services use the last three car models. Onboard accelerations at the seat, the feet and the steering wheel are recorded, as suggested by ISO 2631 and ISO 5349 standards. The tests are performed driving on a straight path on two different road surfaces at eight constant vehicle speeds. An optical sensor clamped outside of the vehicle monitors the vehicle speed and the path. The signals coming from the mentioned cars are analysed and compared in the frequency domain to highlight the differences for comfort quality.

Introduction

Over the years, ride comfort has become a challenging aspect in the automotive field. Although the related market is very competitive and affected by many environmental and safety regulations, comfort still constitutes one of the most relevant elements to achieve customer satisfaction. Furthermore, discomfort does not represent the only negative consequence of vehicle vibrations: other critical issues are connected to health and motion sickness. In the scientific literature, many studies have been carried out to demonstrate the correlation between mechanical shocks and damages to humans [1, 2, 3]. Improvements are continuously carried on by automotive manufacturers to guarantee the well-being of users [4] and to avoid health problems [5]. In vehicle design, comfort and vibrations have to be balanced to many different requirements which often go in the opposite direction. In this research activity, the attention is focused only on passenger perceived comfort due to mechanical vibrations.

Traffic congestion, pollution and global warming are nowadays real issues to be unavoidably tackled in the short term. In this context, the European project "Smart-Taylored L-category demonstration Electric Vehicle in heterogeneous urban use cases" (STEVE) aims to study urban sustainable smart mobility, integrating electrified quadricycles of L-category (EL-V) in the urban transportation system. STEVE project involves many partners in public Institutions, Universities, industrial companies and small/medium-sized enterprises located in seven European countries [6]. One of the first project targets consists of achieving the mobility criticalities awareness of controlled user groups. Surveys are distributed to volunteer testers in order to judge quadricycle quality aspects, *e.g.* comfort feeling.

Beyond users perceived feeling, an objective evaluation of the STEVE vehicle comfort is necessary and can be accomplished by comparing other similar vehicles. For this reason, this paper is focused on evaluating ride comfort of the light electric vehicles used in STEVE project versus other vehicles, equipped with different powertrains, used by car-sharing services for urban mobility. The quadricycle strengths are indeed their price and their small size, which lead to advantages in terms of customer appeal and urban mobility. Nevertheless, higher vibrational levels are expected due to their design simplicity, although the electric propulsion should significantly reduce the typical vibrations produced by Internal Combustion Engines (ICEs).

Usually, vibrations are transmitted from the road surface to passengers through a chain of vehicle components [7]: tyres, suspensions, the chassis elements in contact with passengers inside the cockpit (seat, driving pedals, steering wheel angle).

Many efforts are also investigated and implemented to mitigate the disturbances transmitted by road irregularities [8, 9]. Some research activities have already been carried out comparing different types of vehicles in terms of comfort [10]. A recent work also considers the wheel effects into comfort analysis [11]. The seat materials (density, stress-strain relationship and other elements) and its thickness influence the dynamics of the seat (stiffness and damping) and so the perceived vibrations [12, 13]. The seat cushion is designed not only to ensure static comfort but also to minimise its transmissibility [12]. This characteristic also depends on the direction of the vibration input [13]. Another way to reduce the perceived vibrations is acting on elastomeric joints in the suspension systems: a deviation from the designed behaviour can occur because of manufacturing and operative conditions [14]. However, modern electrified quadricycles represent a segment still not deeply investigated, and the present activity aims to provide some initial cues in addressing EL-V comfort targets.

The paper is organised as follows: firstly, details about the vehicles involved in the comparison activity are given in next paragraph. Then, the acquisition setup is described and measured data are processed according to ISO Standard. Finally, results are shown, and conclusions are drawn.

Vehicle Characteristics

The tests are performed on models similar to those available for car-sharing services present in Turin. The four models, shown in Figure 1, are:

1. EL-V used in STEVE project;
2. Smart Fortwo;
3. Bolloré Bluecar;
4. Fiat 500.

They belong to the same segment, i.e. the hatchback microcars suited for urban driving.

FIGURE 1 Vehicles under analysis: STEVE quadricycle (a), Smart Fortwo (b), Bolloré Bluecar (c), Fiat 500 (d).

TABLE 1 General information about the vehicles under analysis.

	STEVE	Fortwo	Bluecar	500
Car maker	JAC	Smart	Pininfarina	Fiat
Fuel type	Electric	Gasoline	Electric	Gasoline
Price [euro]	~8000	~16500	~12000	~15000
Vehicle homologation class	L7e	M1	M1	M1
Number of passengers	2	2	4	4

TABLE 2 Dimensions and weight of the vehicles under analysis.

	Vehicles			
	STEVE	Fortwo	Bluecar	500
Length [mm]	2830	2695	3650	3571
Width [mm]	1500	1663	1700	1627
Height [mm]	1565	1555	1610	1488
Wheelbase [mm]	1815	1873	2430	2300
Track f/r [mm]	1285/1330	1468/1430	1480	1413/1414
Kerb weight [kg]	650	935	1070	950

Some information on the vehicles under analysis are given in Table 1.

As shown in Table 1, the comparison includes two ICE vehicles: Fiat 500 equipped with manual transmission and Smart Fortwo with automatic transmission. Two vehicles are electrified: STEVE and Bluecar. STEVE and Fortwo are 2-passenger cars, while Bluecar and 500 are homologated for 4 passengers. In terms of cost, the cheaper vehicle is STEVE, while the most expensive is Smart Fortwo. Except for the EL-V, all the models fall into M1 homologation class.

The overall vehicle dimensions are reported in Table 2.

In terms of size and mass, Bluecar has the largest values, while STEVE is the lightest. Note that, the mass of the two electric vehicles is heavily affected by the battery pack. STEVE is comparable to Fortwo while Bluecar to 500.

Table 3 deals with the power source of the four vehicles involved.

The autonomy of Bluecar in the urban scenario is approximately twice of STEVE, while the ICE vehicles have the highest autonomy due to the different power source. All the vehicles have similar peak power, except for STEVE which is almost five times lower.

TABLE 3 Powertrain data of the vehicles under analysis.

	Vehicles			
	STEVE	Fortwo	Bluecar	500
Range [km] (urban travel)	~150	~700	~250	~700
Motor	PMS	898 cm^3 3 cyl.	PMS	1200 cm^3 4 cyl.
Rated power [kW]	6.3	-	30	-
Peak power [kW]	12	52.2	50	50.8
Voltage [V]	72	-	300 - 450	-
Battery capacity [kWh]	10.08	-	30	-

Measurement Setup

Ride comfort is evaluated according to vibrational regulations: they indicate how to achieve a correct measure and to predict the consequence of exposure [15]. Vibrations reach passengers through the interface between the human being and the vehicle. The vibrations due to the seating surface, the seat-back and the feet are commonly known as whole-body vibrations. They may cause discomfort, influence human activity or present a health and safety risk [15]. Among the regulations to evaluate human responses to whole-body vibrations, ISO 2631 [15] and BS 6841 [16] represent the most followed references. Even if BS 6841 is the British standard, it has been widely adopted also outside UK; similarly, ISO 2631 is also utilised within the UK. Since they are very similar in the assessment, ISO 2631 is used as reference regulation in this paper.

Beside whole-body vibrations, discomfort can also be caused by other vibration sources, i.e., hand-transmitted vibrations. The steering wheel of the vehicles can cause them. ISO 5349 [17] is used for the assessment of hand-transmitted vibrations.

All four vehicle are equipped with three tri-axial accelerometers placed as close as possible to the interface with the human body. In particular:

1. PCB Tri-axial ICP Seat Pad Accelerometer ISO 10326-1 is placed on the driver seat (texture (a) in Figure 2);
2. PCB Tri-axial accelerometer is placed on the driver floor (texture (b) in Figure 2);
3. PCB Tri-axial accelerometer is placed on the steering wheel (texture (c) in Figure 2).

The seat and the feet accelerometers are oriented using the standard vehicle reference system. The orientation of the accelerometer on the steering wheel represents a crucial point: its position required a compromise among safety factors, measurements as close as possible to the driver hands and coherence factor due to vehicle reference system axes. Weightings and factors for hand vibration assessment are the

FIGURE 2 Accelerometers on STEVE vehicle: on the seat (a), on the floor (b), on the steering wheel (c).

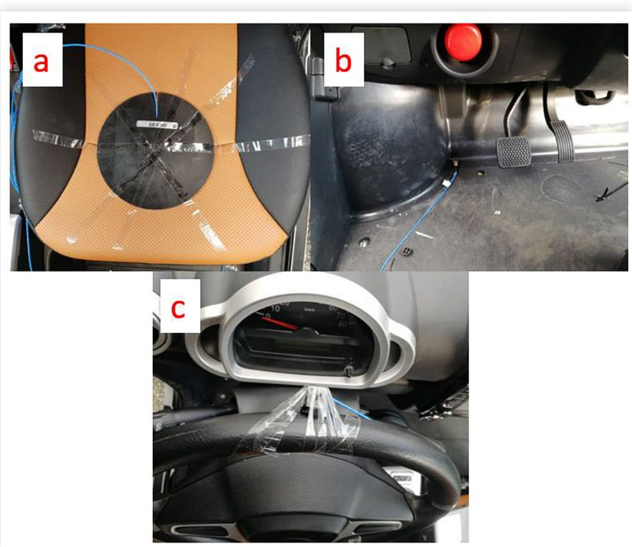


FIGURE 3 Correvit S-Motion on passenger door.

same along X, Y and Z-axes, therefore slightly misalignment do not influence comfort evaluation.

Kistler Correvit S-Motion DTI type 2055A is used to monitor the vehicle speed components. Speed is measured to ensure constant speed and straight-line path. The sensor is mounted on the right side of passenger door using a suction cup clamping system, as shown in Figure 3.

The signals from all sensors are synchronously acquired through a Siemens LMS SCADAS Mobile system. Eleven analogue channels are acquired, three for each accelerometer, and two for the S-Motion sensor, *i.e.* longitudinal and lateral velocities. The acquisition frequency is 8194 Hz.

Test Procedure

The tests are performed with two people inside the vehicles, namely the driver and a passenger who monitors the acquisitions: they are carried out following a straight-line path on two different urban road surfaces: an asphalted one (texture (a) in Figure 4) and a cobblestone pavé (texture (b) in Figure 4).

Each path is travelled at eight different velocities, from 5 km/h to 40 km/h with a step of 5 km/h. The reference speed is monitored using vehicle speedometer; note that the vehicle speedometer overestimates the real vehicle speed and the difference between real and indicated velocity is proportional to the speed.

The longitudinal speeds measured during all the acquisitions are shown in Figure 5. The blue lines are related to the

FIGURE 4 Asphalted (a) and cobblestoned (b) road surfaces.

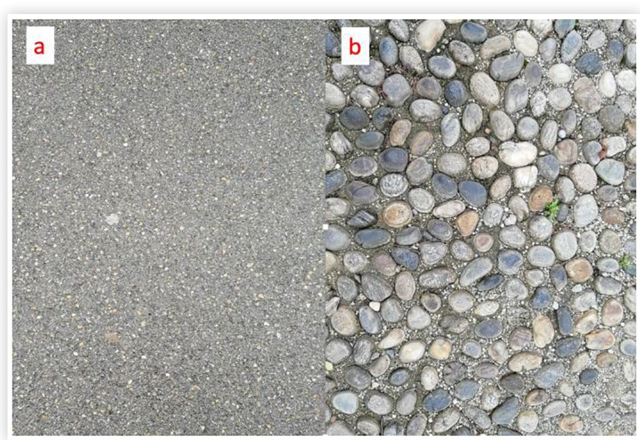
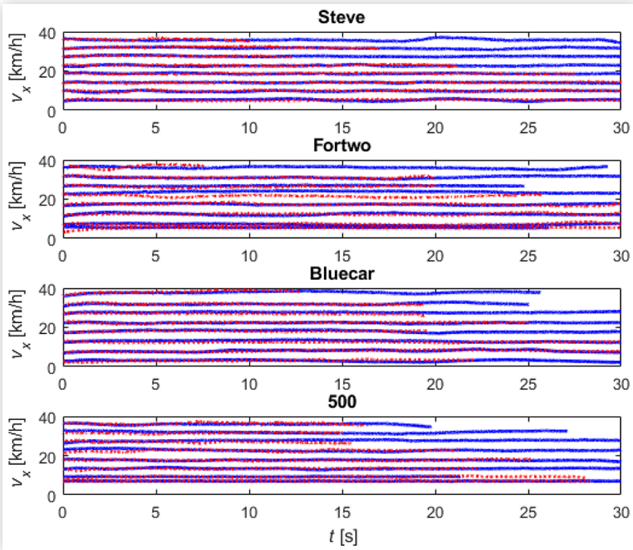


FIGURE 5 Longitudinal speed during the tests.



tests on the asphalted surface while the dot-dot red lines to the cobblestoned surface.

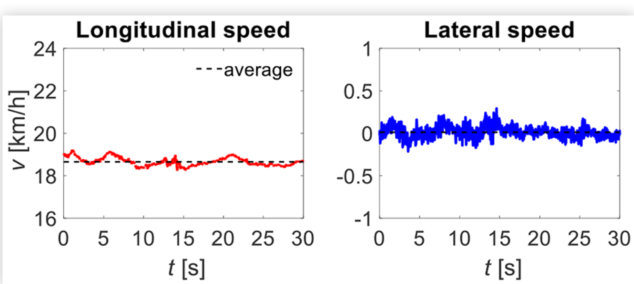
During each test, the driver tries to maintain a constant velocity; however, since tests are performed in an urban scenario, they are affected by small speed variations as visible in Figure 5. Note that the 5 km/h velocity tests cannot be carried out with the vehicles equipped with ICE, i.e., Smart Fortwo and Fiat 500. The lowest speed obtained for them is 7 km/h, engaging the first gear at the minimum engine revolutions per minute (0% acceleration pedal travel). The acquisitions have different time lengths; however, the shortest one is sufficient to post-process the acceleration signals.

Figure 6 shows an example of longitudinal and lateral speed during the tests performed using STEVE quadricycle; in particular, the acquisition performed driving at 20 km/h on the asphalted road.

The lateral speed oscillates around zero. For all the acquisitions, lateral velocities are qualitatively similar. An acquisition is considered valid when the fluctuation around the average value is ± 1 km/h for the longitudinal speed and ± 0.3 km/h for the lateral speed, as shown in Figure 6.

An additional acquisition is carried out holding the vehicle stationary, in key-on position, in order to evaluate the vibrations not due to road excitation.

FIGURE 6 Longitudinal and lateral speeds (test on STEVE vehicle at 20 km/h on the asphalted road).



Data Analysis

The measured data collected from all the 18 tests performed on each of the four vehicles were elaborated in order to assess the vehicle comfort. Matlab is used to process the data.

According to ISO 2631, *i.e.* whole-body vibrations, the range of interest for comfort assessment is between 0.5 Hz and 80 Hz [15]. Note that, considering other vibrational consequences, for instance, motion sickness, the related frequency range changes. According to ISO 5349, *i.e.* hand transmitted vibrations, the range is between 8 Hz and 1000 Hz [17]. The recorded signals are analysed in frequency domain. The time-domain histories are windowed using a 10 second Hanning window with an overlap of 97%. Fast Fourier Transform is applied to each window and energy average of all the time history segments. The frequency-domain data are compensated for the window effect. The frequency resolution is 0.1 Hz.

Filters prescribed in Standard [15, 17] and described in the following: they are directly applied to frequency domain data. According to Standard [15, 17], the acceleration signals need to be weighted: different frequency weightings w are given for each specific vibrating surface, the axes along which the vibration is perceived and its potential effect (health, comfort, perception and motion sickness). Weights w are given in the frequency domain. In this analysis, weightings for comfort assessment are used, as shown in Figure 7 [15, 17]. The Root Mean Square (*RMS*) of the weighed spectrum obtained for each direction are linearly combined using the k factors prescribed in the standard: k factors, given in Table 4 [15, 17]., depending on the kind of assessment and direction. The overall value, obtained using Eq. 1, is an indication of comfort.

$$a_v = \sqrt{\left(k_x a_{RMS,x,w}\right)^2 + \left(k_y a_{RMS,y,w}\right)^2 + \left(k_z a_{RMS,z,w}\right)^2} \qquad (1)$$

where $a_{RMS,i,w}$ corresponds to *RMS* of the weighted acceleration by the related weight w on the i-th axis and k_i is the correspondent factor, where $i = x, y, z$.

FIGURE 7 Weightings trends in function of the frequency [15, 20].

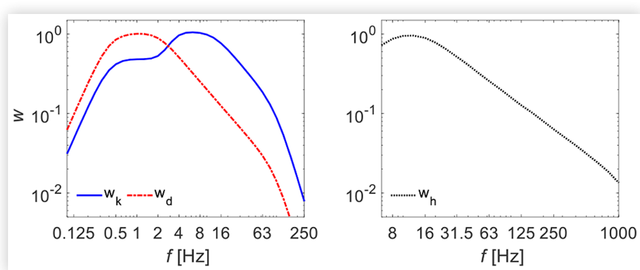


TABLE 4 Weightings and factors for comfort assessment.

Location	Direction	Weightings w	Factor k_i
Supporting seat surface	X, Y	w_d	1
	Z	w_k	1
Feet	X, Y	w_k	0.25
	Z	w_k	0.4
Steering wheel	X, Y, Z	w_h	1

The *RMS* value of acceleration is also used in [21], together with acceleration peak, to assess the gearshift noise.

The weights modify the measured acceleration based on human perception. Generally, the first whole-body resonance lies between 4 and 6 Hz [15]. However, the maximum values for w_k, w_d and w_h are at almost 6.3 Hz, 1 Hz and 12.5 Hz. Hence, according to ISO 2631, the maximum perception of z-acceleration occurs close to 6.3 Hz while for x and y-accelerations close to 1 Hz. The BS 6841 recommends two slightly different sets of weightings, thus giving less importance to low frequencies and more to high ones than the ISO. Moreover, the BS 6841 combines the three acceleration of the seat with the one of the backrests, while ISO considers the two sources of vibrations separately. Griffin [1] compares the two methods: according to the author, BS 6841 represents a clearer and more consistent guide for the whole-body vibration assessment. ISO Standards are employed in this activity even if weightings are widely criticised in the scientific literature since they do not seem to be consistent with the real perception thresholds. Different points of view exist on the frequency weightings, also because the biodynamic response is highly nonlinear: the higher the magnitude, the lower the resonance frequency is [19]. For instance, Morioka [18] considers the unweighted vertical acceleration as a better predictor of human perceptions and detected a perception higher than the standards [19]. Furthermore, the human response to a mechanical oscillation does not depend only on frequency but also on exposure duration and magnitude [20]. The weightings should also consider these two crucial aspects.

Figures 8 shows the effect of frequency weighting on seat signals coming from STEVE vehicle test on the asphalted road

FIGURE 8 Accelerations on the seat in frequency domain (test on STEVE vehicle at 20 km/h on the asphalted road).

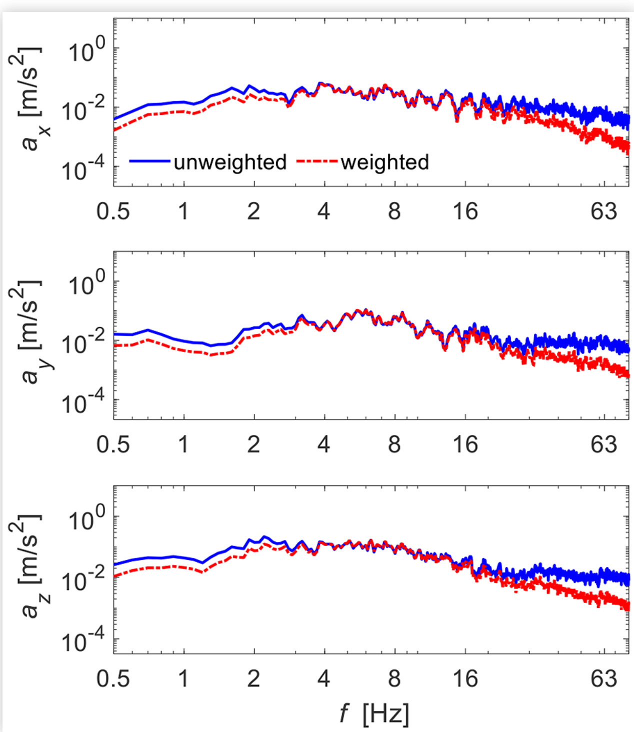


TABLE 5 Comfort bands [15].

Comfort reaction	Acceleration band [m/s^2]
Not uncomfortable	< 0.315
A little uncomfortable	0.315 - 0.63
Fairly uncomfortable	0.5 - 1
Uncomfortable	0.8 - 1.6
Very uncomfortable	1.25 - 2.5
Extremely uncomfortable	> 2

at 20 km/h. The blue line corresponds to the unweighted signals while the red line after the weighting application.

The comfort level is evaluated by using the global value a_v in Eq. (1). The comfort levels related to the overall weighted *RMS* for whole-body vibrations are reported in Table 5.

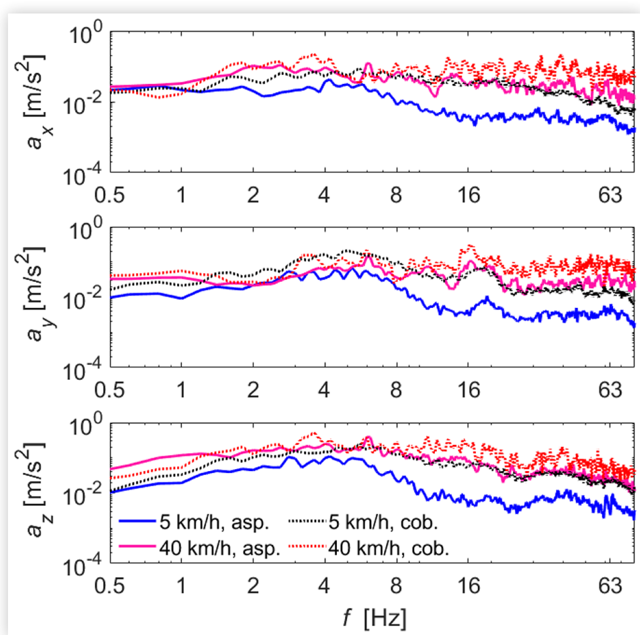
The comfort limits are not precisely defined, since the bands overlap each other. The lower values of each band are used to carry out the worst-case scenario for all the vehicles. Since equivalent comfort bands do not exist in the ISO 5349, the same bands are also used for comfort assessment of hand-transmitted vibrations.

Results

Spectrum Analysis

The behaviour of STEVE quadricycle is mostly studied, being the focus of the European project. The frequency spectra for STEVE quadricycle are shown in Figures 9-11. Logarithmic scale is used in order to underline the trends. Only the lowest and the highest vehicle speed are considered for greater clarity.

FIGURE 9 Unweighted Spectrum of the signals acquired on the floor.



In the feet accelerometer signals, a great frequency content can be identified in all the three directions between 2 and 6 Hz. Same peaks are also evident on the seat. The content is also relevant around 30 Hz on the *x*-axis while close to 19, 38 and 62 Hz on the *y*-axis. The amplitude of vibration on the *z*-axis is almost 4 times larger than the values on the other directions, as expected. Driving on cobblestoned road surface causes the presence of the new peaks at high frequency on *x* and *y*-axes. The amplitude on the *z*-axis is higher, but in proportion less than the other directions. In Figures 9-10, trends referred to cobblestoned at 40 km/h test have more noise than the other ones.

FIGURE 10 Unweighted Spectrum of the signals acquired on the seat.

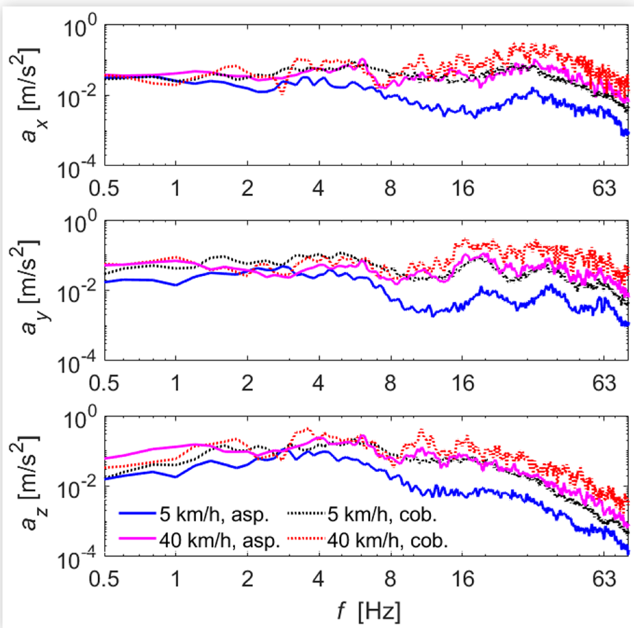
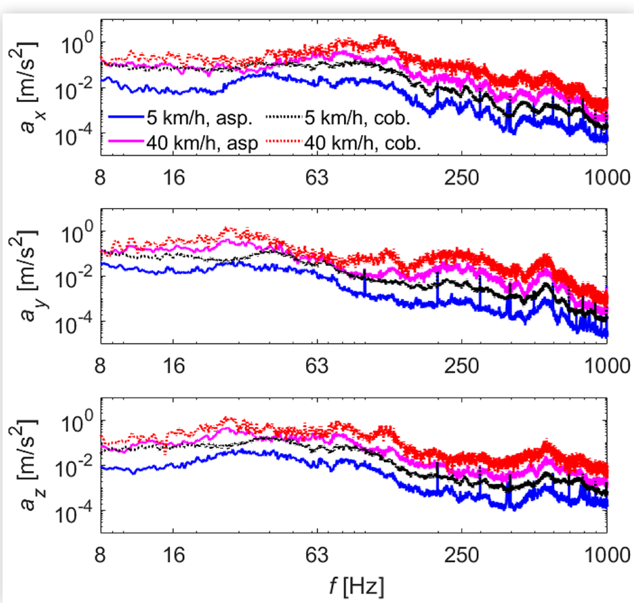


FIGURE 11 Unweighted Spectrum of the signals acquired on the steering wheel.



In the steering wheel signal, many peaks are evident, probably due to the resonances of the steering system; the first one fall in the first 50 Hz.

The spectrums of the other vehicles are not reported, but are qualitatively the same, with the following differences.

In Bluecar, the feet signal FFT on *x* and *y*-axes are flat using *y*-logarithmic scales. On *z*-axis, some peaks around 4 Hz occur and are still evident in the seat (1 Hz less than Steve). On *x* and *y*-axes of seat sensor, some peaks are visible at 3, 5, 17 and 38 Hz. The first peak in steering wheel signal is lower than 25 Hz in all the three directions (almost half of what happens for the quadricycle).

As regard Fortwo, the seat and the feet trends are quite flat. A peak at almost 4 Hz is identifiable only driving on the cobblestoned road for the *z*-axis: it is slightly higher than the Bluecar ones. The first peaks of the steering wheel spectrum fall in the first 30 Hz, similarly to Bluecar.

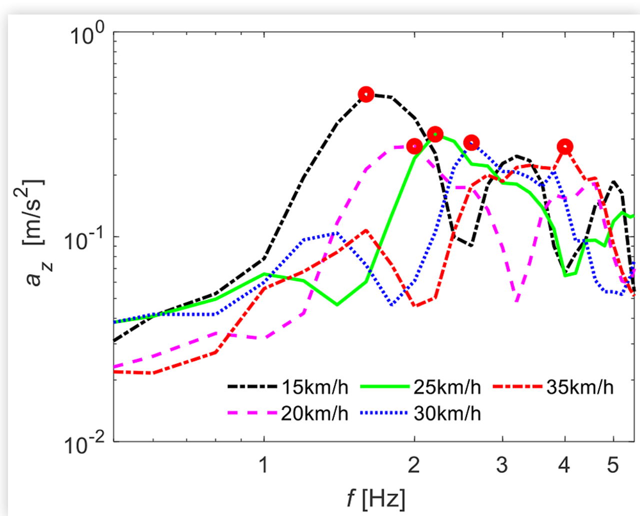
In 500, the first feet peak in all the three directions, as visible in Figure 12 for *z*-axis, seems to be more dependent on speed than the other vehicles.

The peak (red point in Figure 12) moves towards higher frequency and lower amplitude, increasing the speed. It moves from 1.8 Hz at 15 km/h to 3.8 Hz at 40 km/h. The peak values at 5 km/h and 10 km/h do not respect this trend, thus they are not reported in the chart. This behaviour is more evident on the cobblestoned surface and in-seat signals and is probably the effect of wheelbase filtering.

At speed higher than 20 km/h, another peak dependent on speed appears at lower frequencies: even this one moves towards higher frequency but higher amplitude with speed. It is not evident at 15 km/h.

As for feet and seat signals, a further peak is evident at almost 10 Hz. At the same frequency, contrary to other vehicles, there is the first peak also in the steering wheel FFT.

FIGURE 12 First peak trends in Fiat 500 seat vibration Spectrum on *z*-axis varying the vehicle speed driving on cobblestoned surface.



Comfort Assessment

The global value a_v at different longitudinal speeds, according to Eq. (1) are provided in Figure 13 and Figure 14. They refer to the asphalted and cobblestone roads, respectively. The two charts also report the standard bands according to Table 5.

The comfort level decreases when the speed is increased, as expected, and this behaviour is the same for the four vehicles in all the measurement points. The higher values occur at the steering wheel, while the lowest at the feet: this is not due only to the real vibration values, but also to the weightings and the factors used in the assessment.

The seat comfort level of Fortwo, Bluecar and 500 is always within the first two bands; therefore, they objectively result quite comfortable. Their trends are overlapped, and a slight difference is appreciable only at speed higher than 20 km/h where Fortwo has the best quality, 500 the worst and Bluecar is placed in the middle. The electric quadricycle is the less comfortable: in fact, it seems to be fairly uncomfortable at speeds higher than 25 km/h. Its trend has a gap from the others.

Looking at the feet signal trend, all the four vehicles remain in the first band (not uncomfortable); again, STEVE has the highest values; however, the gap with respect to the other vehicles is small. The patterns of the three vehicles on the market are very similar. At 40 km/h, Fortwo is the best, Bluecar is in the middle while 500 has the value nearest to Steve quadricycle. Contrary to expectations, the two ICE vehicles have lower vibrations than the two electric cars at zero speed.

FIGURE 13 Weighted overall vibration in function of the vehicle longitudinal speed driving on asphalted road.

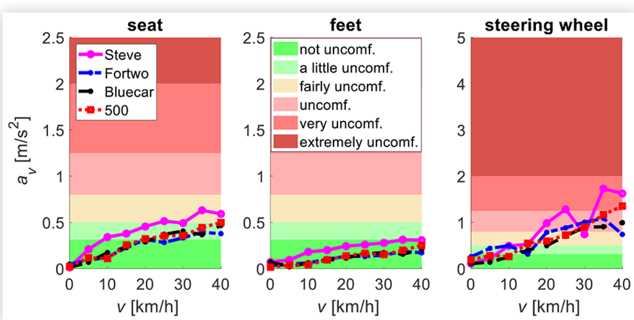
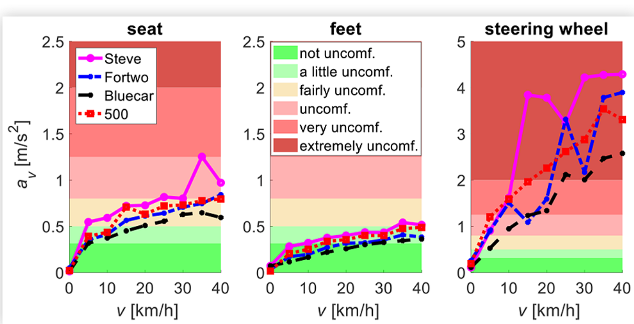


FIGURE 14 Weighted overall vibration in function of the vehicle longitudinal speed on the cobblestones.



The trends of Fortwo, Bluecar and 500 are more similar in the feet chart than in the seat one. This could mean that the suspension subsystem is well optimised for urban mobility. For STEVE vehicle, the design simplicity and low material cost justified by the fact that it is a quadricycle, can be responsible for the higher values. The difference between STEVE and the other vehicles is stronger on the seat, where vibration damping is less effective.

With regards to the steering wheel chart, all the vehicles seem to be fairly uncomfortable at speeds higher than 15 km/h. This can be explained considering that the bands are prescribed for whole-body vibrations, thus they are not well suited for hand transmitted vibrations. The trends are increasing for all the vehicles. The lower vibrations are achieved on Bluecar; then 500 and Fortwo. Over 15 km/h, Steve has the highest vibrations. Some values (i.e. STEVE at 30 km/h, Fortwo at 15 km/h and 40 km/h) do not follow the trend: these tests should be repeated and more accurately investigated in order to find the cause. As expected, but contrary to the feet diagram, the starting point of the curves (0 km/h) of the two electric vehicles is lower than the ones of the two ICE models.

Resuming the comfort results, except for the EL-V, which is the worst, it is challenging to define a ranking of the other three vehicles. As for the seat and the feet comfort, the difference is appreciable over 20 km/h and Fortwo achieves the best quality. Nevertheless, all the four vehicles have good behaviour on asphalted surface. Bluecar results to be the most comfortable regarding the hand-transmitted vibrations.

Considering the cobblestone road surface, the values are generally higher than the previous case in all the three charts: this is expected and due to the different vibrational input coming from the ground.

Considering the seat chart, STEVE trend goes from the fairly uncomfortable band at 5 km/h to the uncomfortable one at 40 km/h. At 35 km/h, the value seems to be out of the trend (it results very uncomfortable). Fortwo and 500 trends at 40 km/h are at the limit between the third and the fourth band, while Bluecar is always inside the first three bands. A significant difference compared to the seat chart achieved on the asphalted surface is that the trends of the three M1 vehicles are not overlapped.

For the feet chart, the trends are well outlined and confirm the considerations discussed for the seat: all of them fall in the first two bands. The trends in the feet chart are closer to each other than the ones in the seat diagram. All the four vehicles have good feet comfort on cobblestoned surfaces at urban speed.

The steering wheel chart presents trends that are not clearly defined, in particular, for the two-passenger vehicles. It is also challenging to find the speeds at which the overall value comes out the pattern. STEVE seems to be the most uncomfortable: it falls in the last comfort band over 15 km/h. 500 owns the second worst trend: it reaches the last band over 20 km/h. Fortwo reaches higher vibrations after the 500 in some cases, since the out of trend values. The Bluecar seems to show lowest values of a_v with respect to other vehicles, also reaching the extremely uncomfortable band for higher speeds.

Conclusions

An experimental comparison for comfort quality assessment of urban vehicles is performed. Four different vehicles were analysed at different speeds on two different road surface in urban scenario. The following general conclusion can be drawn:

1. as expected, regardless of the vehicle and the road surface, increasing the vehicle speed, vibrations on the seat, at the feet and the steering wheel tend to rise;
2. a less smooth road surface leads to more relevant vibrations;
3. following ISO Standard for whole-body comfort assessment, seat vibrations are stricter than feet ones.
4. comfort bands prescribed by ISO 2631 (whole-body vibrations) are not suitable for the handle vibration assessment;
5. in order to characterise the comfort quality of a vehicle, driving on a cobblestoned surface is more useful since it underlines better the differences between vehicles.

As for the comparison between the vehicles under analysis, it was found that:

1. the EL-V is the less performing vehicle: the difference compared to the other tested vehicles is clear. Nevertheless, in an urban scenario characterised by smooth roads and by low vehicle speeds (for instance in heavy traffic conditions), it proves to be quite comfortable and constitutes an excellent alternative to traditional ICE vehicles. On the other hand, it is not suitable for irregular roads.
2. Smart Fortwo represents the best compromise between compactness and comfort quality: its behaviour is quite good even at high speed on asphalt and at low speed on cobblestoned roads.
3. Fiat 500 shows comfort quality very similar to the other two vehicles on the market, driving on the asphalted road. Driving on cobblestoned surface, it proves to be the least performing among these three models.
4. Bluecar is the vehicle which has performed best, both on asphalted and cobblestoned roads, even at high velocities.

Please note that the presented results are valid only for the specific tested vehicles and cannot be assumed in general extendable to the car models.

Acknowledgment

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Definitions/Abbreviations

STEVE - Acronym of the European project: "Smart-Taylored L-category demonstration Electric Vehicle in heterogeneous urban use cases."

EL-V - Electric vehicle of L-category

ICE - Internal Combustion Engine

RMS - root mean square

PMS - Permanent Magnet Synchronous

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