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Assessing e-scooters safety and drivability: a quantitative analysis

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Abstract: E-scooters are now massively present in urban environments as a shared last-mile solution. Their apparent ease of drivability favored their diffusion, but also actually raises safety concerns. In this work, we propose a data-driven approach to map e-scooters mechanical specifications to drivability and safety metrics, the latter appropriately defined and computed based on experimental data. An ad-hoc HW/SW platform was designed for this purpose, so as to be portable and installed on seven different e-Scooters that were tested in trips carried out in the city of Milan. The proposed approach allowed us to characterize both stability and comfort metrics on the different vehicles, and compare them also with a qualitative driving test carried out by a journalist making driving tests. The quantitative analysis matched the impressions of the human driver, and it disclosed an interesting mapping between the perceived risk and the vehicle characteristics evaluated according to the two metrics proposed.

Keywords: E-scooters; drivability; safety; comfort; vehicle dynamics.

1. INTRODUCTION AND MOTIVATION

Since their first introduction in California in 2017, dockless electric scooters (e-scooters) received wide acceptance from users, quickly becoming undisputed players in urban micro-mobility. According to recent outlooks from the International Energy Agency (Agency, 2019), worldwide, e-scooters sales increased by 800% over the past five years. Also, (Prescient and Intelligence, 2021) reports that, in Europe, the number of sharing e-scooters increased by 200% between 2018 and 2019. According to (Smith, 2019), e-scooters became the leading choice to cover the so called "last-mile" path, *i.e.,* the distances that are too long to walk but too short to justify using a car. This is due to the fact that they are easy to retrieve, drive and park, as well as cheap and efficient. In addition, the growing awareness regarding environmental issues, together with the recent health emergency, has further supported the diffusion of this transport means, environmentally friendly and for individual use. However, despite their undisputed advantages, risk factors cannot be ignored, and still discourage several people from adopting them. Indeed, several studies, as those proposed by (Trivedi et al., 2019b; Nellamattathil and Amber, 2020), reveal that a high percentage of e-scooter riders are victims of accidents. Even if the most frequent consequences are fractures and head injuries, (Schneeweiss et al., 2021) show that severe trauma may occur, leading to surgical interventions and death.

Because the introduction of these vehicles is reasonably recent, several risk factors associated with e-scooters are still to be investigated. To date, most of the studies in the literature, such as (Ma et al., 2021; Trivedi et al., 2019a), focused on rider behavioral factors, such as alcohol intoxication, high speed, and helmet usage; however, as highlighted by (Schneeweiss et al., 2021), little research has been conducted on the influence of the e-scooters mechanical specifications. In this context, two studies provide significant contributions. The first one was presented by (Cano-Moreno et al., 2021): in this work, starting from analyses carried out in the literature for other transport means by (Cossalter et al., 2006; Singh, 2019), the authors present a methodology to study the repercussions of the vibrations generated while driving an e-scooter on human health, carrying out simulations on a multi-body dynamical model. The obtained results reveal that the size and material of the wheels, and the shock absorber, when available, are the main factors in determining the magnitude of the vibrations, acting in a multiplicative and independent way. The second work was presented by (Kim, 2021), and focused on the effects of the whole-body vibrations perceived at the handlebar. The results reveal that they cause irreversible damage to the rider balance sensory systems, also leading to chronic muscholosketal pains. As key factors, Kim identifies the wheels' size and the road profile quality. Finally, (Jogi, 2018) demonstrates that large vibrations cause e-scooters' wear, posing additional risk to user safety and increasing maintenance costs. According to these results, we can say that the vibrations generated threaten both the rider's health and the e-scooter's status. The key factors currently identified are wheel material and size, shock absorbers, and the quality of the road profile. However, existing works mainly focus on the vibrations' repercussions on the riders rather than identifying an optimal set of features to provide practical guidelines for e-scooters design. Moreover, the reported evidence was obtained through simulations; however, several works in the literature, as (Passigato et al., 2020), prove that, especially when considering twowheeled vehicles, frame compliance, and rider mobility are difficult to model correctly, limiting the reliability of simulation results.

Therefore, in this work, we provide a data-driven method to investigate the relationship between e-scooters mechanical specifications and riders' well being and risk. To this purpose, the analysis dimensions were quantified mathematically by means of two metrics:

- Comfort, which considers the magnitude of the vibrations generated while driving along the vertical vehicle dynamic;
- Stability, which considers the magnitude of the oscillations perceived at the handlebar.

To gather the needed data, a global positioning system (GPS) and a 6-axis inertial measurement unit (IMU) were integrated into an ad-hoc designed embedded device. This allowed us to include seven different on-the-market e-scooters in our analysis. To determine the most suitable conditions to estimate comfort and stability metrics, we exploit the results of an experimental analysis conducted considering different combinations of road profiles and driving speed ranges. Thus, this work aims at providing a practical tool to investigate the relation between e-scooters' mechanical specifications and riders' risk. This paves the way for defining effective guidelines to maximize riders' safety and favor e-scooters design.

2. SENSORS AND VEHICLE SETUP

Since the experimental campaign conducted in this study involved many different e-scooters models, an easily portable acquisition device was necessary. Therefore, we realized an integrated hardware system, detailed below.

2.1 Acquisition System

To effectively conduct the experimental campaign, we built a stand-alone hardware setup, shown in Figure 1, which embeds the sensors of interest. The designed system is small and lightweight, easily connected to the vehicle frame, and has low power consumption. The Raspberry Pi Zero W was chosen as a processor, representing the best trade-off between performances and size. Also, it provides a Wi-Fi module, facilitating data downloading operation. In detail, two sensors were connected to the Raspberry:

- An u-blox 7 family GPS, which provides vehicle speed, longitude, and latitude with a 10Hz sampling frequency;
- A 6-axis IMU BMI 160 by Bosch, which provides tri-axial accelerations and angular rates with a 100 Hz sampling frequency.

The whole system was enclosed within a protective heat-shrink tube, and has negligible weight and small size, measuring only 88x38x38mm. During the campaign, it was easily anchored to the vehicle's deck with plastic ties. Also, it was designed to be powered either by the vehicle battery or an external power bank. In the first case, the Raspberry was connected via a DC/DC converter to the e-scooter's battery. As this solution is advantageous when several acquisitions must be performed on a single vehicle, it was adopted for the preliminary analysis data collection.

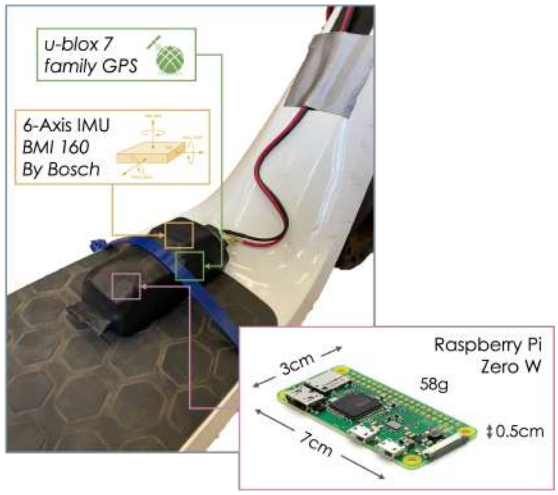


Fig. 1. Stand-alone acquisition setup. The designed device embeds a GPS and a 6-axis IMU, whose recordings are logged by a Raspberry Pi Zero W. Collected data are easily downloaded connecting to the Wi-Fi module of the Raspberry Pi.

Alternatively, an external power bank can be connected to the USB port of the Raspberry. This solution was adopted to collect data on different shared e-scooters that were rented to perform the needed tests.

2.2 Target E-scooters

Our analysis considered seven on-the-market e-scooters, two mainly tailored for personal use and five available for sharing in the city of Milano, the mechanical specifications of which are reported in Table 1. It can be noticed that their wheels are of different materials, *i.e.*, honeycomb, solid rubber, or air chambered, and their diameter ranges from 8 to 12 inches. Nominal engine power ranges from 250W to 500W, while the weight ranges from 13kg to 32kg. Also, most e-scooters have a double front shock absorber, except for Lamborghini and Dott, which have a single one, and Xiaomi Mi2 Pro, which has no shock absorber at all. The top reachable speed ranges from 20km/h to 25km/h.

3. PRELIMINARY DYNAMIC ANALYSIS

To define effective comfort and stability metrics, the operating range in which the e-scooter vertical dynamic was excited enough to reveal the dynamic characteristics of interest was needed. To determine it, tests were conducted to investigate the vertical e-scooter behavior with different combinations of road profile and vehicle speed, which are described in the following.

3.1 Experimental Campaign

This preliminary analysis was carried out on the two private e-scooters we own, *i.e.,* Mi2 and Lambo. The other vehicles were then only more briefly tested to check consistency of the results, which was always obtained. These vehicles were driven by an experienced rider, a woman of 35kg, on three straight asphalt road profiles. Each one was 200m long, and the quality of the road surface ranged from good (smooth alsphalt), to medium, and bad (a rather

Table 1. E-scooter specifications. This Table reports the mechanical specifications of the e-scooters considered in the analysis.

E-scooter Model	Sharing	Weight [kg]	Wheels		Engine Nominal Power [W]	Maximum Speed [m/s]	Front Shock Absorber
			Diameter [inches]	Material			
Mi2	✗	14.2	8.5	Air-Chambered	300	25	N/A
Lamborghini	✗	13.0	8	Honeycomb	350	25	Single
Lime	✓	19.5	10	Honeycomb	250	25	Double
Bit	✓	17.6	10	Solid Rubber	450	20	Double
Dott	✓	15.0	12	Air-Chambered	500	20	Single
Voi	✓	32.0	10	Solid Rubber	350	20	Double
Helbiz	✓	22.5	10	Solid Rubber	350	20	Double

disconnected cobblestone surface), respectively. The rider covered each road three times, at a constant speed of 12km/h, 16km/h, and 20km/h, respectively. The collected dataset thus contains 9 trials. For each one, GPS and IMU signals were acquired using the device described in Section 2, directly powered by the e-scooter battery.

3.2 Vibration-level Assessment

To assess the frequency ranges of interest for the characterization of comfort and stability of the vehicles, a vibration analysis was conducted, considering the power spectra of the acquired signals. A preliminary step of resolution equalization was required, linearly interpolating the GPS time-series up to the IMU sampling frequency, *i.e.,* 100Hz. In addition, for each recording, the initial acceleration and final deceleration phases were removed, maintaining only the constant speed frame identified considering longitudinal acceleration and GPS speed. For the selected time windows, the power spectrum of the vertical acceleration a_z was computed as

$$S_{a_z}(f) = \frac{|a_z(f)|^2}{N}, \quad (1)$$

where N is the signal length, and $a_z(f)$ is the discrete Fourier transform of a_z, computed as:

$$a_z(f) = \frac{1}{N}\sum_{k=0}^{N-1} a_z(k) \cdot e^{\frac{i2\pi kn}{N}}, n \in \mathbb{Z}, \quad (2)$$

where i is the imaginary unit and N is the length of the signal.

The obtained results are shown in Figure 2 for the Mi2 e-scooter and in Figure 3, for the Lambo one. For both vehicles, one may notice that, considering the same road profile, the vibrations along the vertical direction increase proportionally to the e-scooter speed. Considering trials performed in the same conditions, the Mi2 and Lambo spectra differs in shape and magnitude. This is consistent with our prior knowledge that the spectrum shape depends on the specific vehicle mechanical structure. In both cases the results are consistent with those presented by Cano-Moreno et al. (2021), which assessed that e-scooters start to be uncomfortable for the rider from 16km/h, and constitute a real health risk above 23km/h, even for short trips. On the other hand, considering the produced vibrations as a function of the road profile, it turns out how it significantly affects their magnitude. Indeed, with no potholes or bumps, the good quality road profile generates negligible vibrations compared to the bad one. These results allow us to effectively define the experimental conditions for the campaign reported in Section 4. In particular, as optimal range to compare comfort and stability of the different e-scooter selected, we chose speed values larger than 16km/h and profiles characterized by potholes and irregularities.

4. COMFORT AND STABILITY ASSESSMENT

This Section presents the proposed approach for estimating the risk for an e-scooter related to its users' safety and health, depending on its mechanical specifications. In detail, two metrics are defined to evaluate the vehicle's comfort and stability, respectively. The experimental campaign is initially described; then, the data pre-processing and the metrics formulation are detailed.

4.1 Experimental Campaign

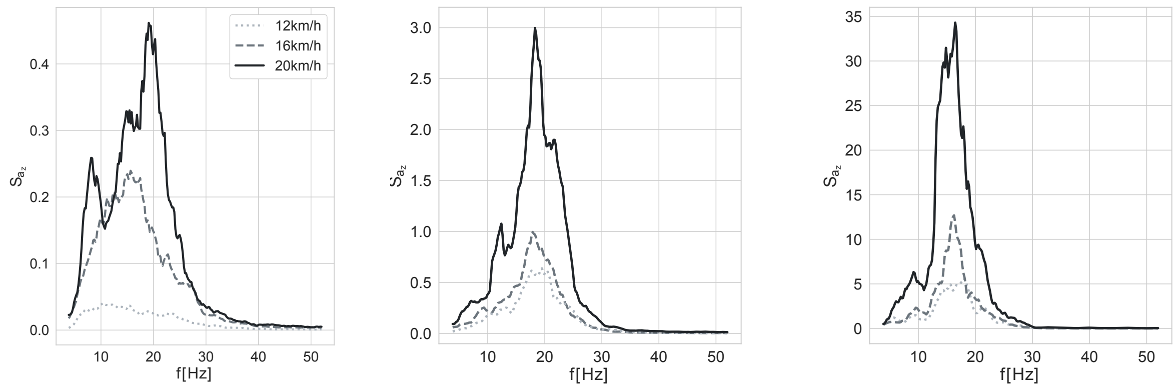
Considering the results obtained in the preliminary analysis described in Section 3, the experimental campaign for the estimation of comfort and stability was conducted with two riders, a 35kg woman and a 73kg man, who rode at a constant speed of 20km/h a 200m straight asphalt road profile of bad quality. Each rider covered the selected route twice for each of the e-scooters included in the analysis. Thus, the collected dataset contains 28 recordings, 14 for each volunteer. For each of them, the GPS and IMU time series were acquired.

4.2 Data Pre-Processing

Resolution equalization was first performed according to the preliminary vibrational behavior analysis procedure, interpolating the GPS time series to 100Hz. Also, the IMU signals were filtered by applying a first-order low-pass filter, whose cut-off frequency was set to 30Hz. Then, only the 10 seconds referred to the most uneven portion of the road profile, characterized by the highest vertical accelerations, were considered for each recording. The extracted windows, highlighted in Figure 4, are then considered to estimate the e-scooter comfort and stability.

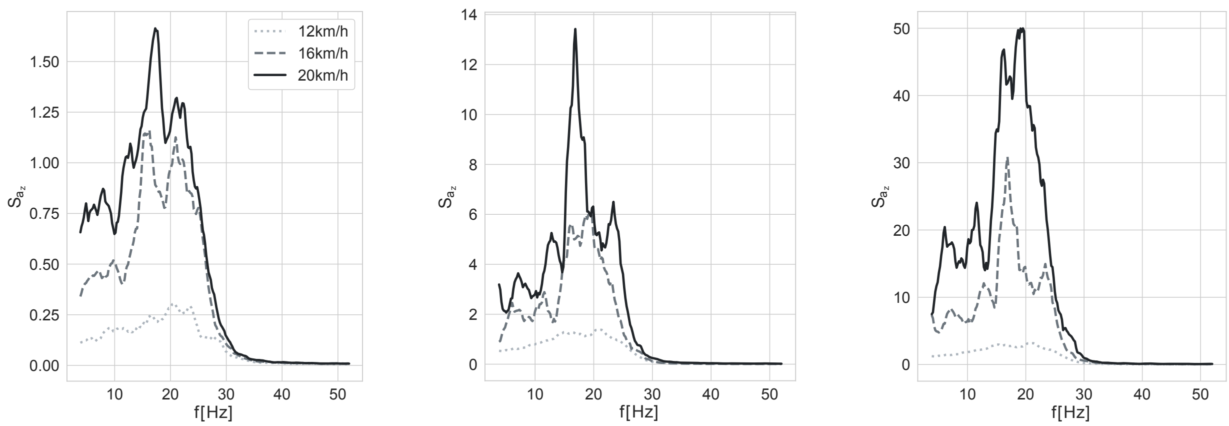
4.3 Comfort and Stability Formulation

When the e-scooter covered a rough road profile oscillations are perceived, which most involves vertical and lateral dynamics. It follows, that the rider experiences solicitations along vertical dynamics, and looses vehicle driveability due to the vibrations perceived at the handlebar. To define metrics capable of effectively quantifying



(a) Good (b) Medium (c) Bad

Fig. 2. Preliminary vibration analysis: Mi2 results. The power spectra of the vertical acceleration recorded during the different combinations of road profile and e-scooter speed considering a rider of 35kg. The spectra of the trials performed at 12km/h, 16km/h, and 20km/h are reported for three different road profiles, 200m long, of good (left), medium (middle), and bad (right) quality.



(a) Good (b) Medium (c) Bad

Fig. 3. Preliminary vibration analysis: Lambo results. The power spectra of the vertical acceleration recorded varying the combination of speed and road profile conditions. In detail, each plot reports the spectra for the vertical acceleration recorded in the trials performed at 12km/h, 16km/h, and 20km/h, and it is referred to a specific road profiles, 200m long, corresponding to good (left), medium (middle), and bad (right) quality.

vehicle comfort and stability, we inspected the IMU signals' trend over time for all the collected trials, aiming at identifying the most informative. It turned out that vertical acceleration and yaw rate were the most affected by the traveled road quality. This result reveals that, considering comfort and stability assessment in an e-scooter, the set of relevant signals is consistent with the one characterizing other classes of vehicles, such as passenger cars. Indeed, in the case of suspension design, lateral wheel slip and oscillations perceived along the vertical axis are the key performance indicators, estimated monitoring signals as vertical acceleration and yaw rate Cartwright (1986).

It follows that the comfort metric was formulated ad-hoc to quantify the vibrations generated while driving. Therefore, it was defined as the reciprocal of the vertical acceleration spectrum area, defined as $A[S_{a_z}(f)]$, calculated according to Equation (2):

$$\eta = \frac{1}{A[S_{a_z}(f)]}. \tag{3}$$

Its real-time computation is carried out leveraging a sliding window. For each, the area was approximated according to the trapezoidal approximation method as:

$$\eta = \left(\frac{1}{2} \sum_{n=0}^{N-1} \left[S_{a_z}(n+1) + S_{a_z}(n) \right] \cdot \left[f(n+1) - f(n) \right] \right)^{-1}$$

where f is the frequency vector associated with the spectral density.

Stability, instead, is defined to quantify the magnitude of perceived oscillations at the handlebar. Therefore, the yaw rate was considered as the most relevant signal, and the yaw rate spectrum was defined as

$$S_\psi(f) = \frac{|\psi(f)|^2}{N}, \tag{4}$$

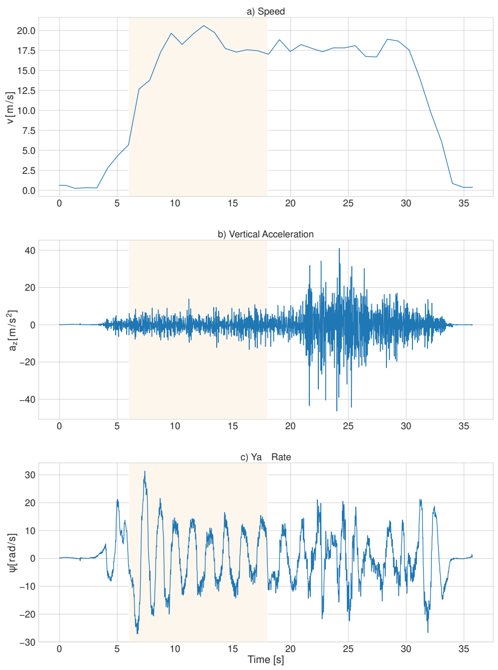


Fig. 4. Window extraction. This Figure reports the e-scooter speed, vertical acceleration, and yaw rate recorded during a trial. In yellow is enhanced the 10s window considered for computing the comfort and stability metrics, *i.e.,* the one referred to the most uneven road portion.

where N is the signal length, and $\psi(f)$ is the discrete Fourier transform of the time-series ψ, computed as:

$$\psi = \frac{1}{N} \sum_{k=0}^{N-1} \psi(k) \cdot e^{\frac{i2\pi kn}{N}}, n \in \mathbb{Z}, \tag{5}$$

Finally, the stability index was estimated as:

$$\sigma = \frac{1}{A[S_{\psi}(f)]}, \tag{6}$$

where ψ is the yaw rate, and computed in real-time as:

$$\sigma = \left(\frac{1}{2} \sum_{n=0}^{N-1} \left[S_{\psi}(n+1) + S_{\psi}(n) \right] \cdot \left[f(n+1) - f(n) \right] \right)^{-1}$$

We will now discuss the evaluation of these metrics on the 7 selected e-scooters and show their consistencies in describing their driveability characteristics, and their link to the vehicle mechanical specifications.

5. EXPERIMENTAL RESULTS AND DISCUSSION

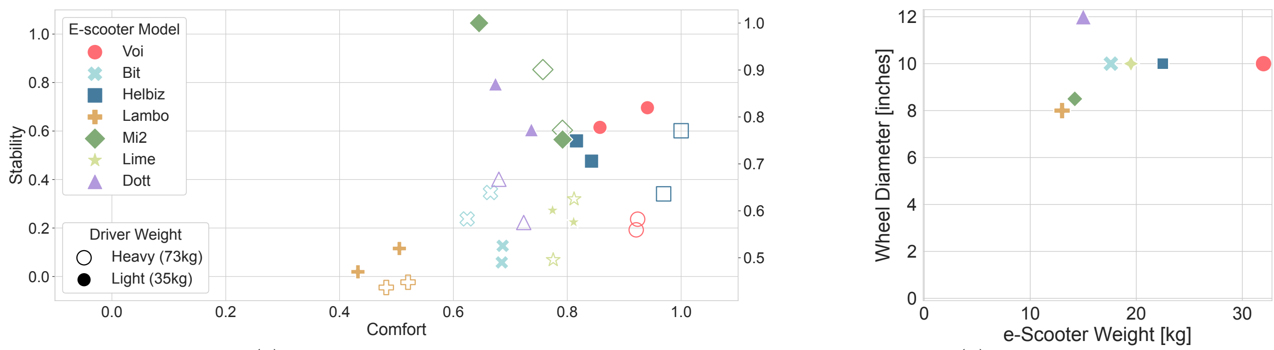
To discuss the obtained results, let us consider Figure 5(a), which reports the so-called *comfort-stability* map . In this graph, each observation represents the value of the comfort and stability indexes, η and σ, computed in the windows selected from each test, according to the method described in Section 4. To ease readability, each metric was normalized with respect to its maximum value. The absolute values are reported in Table 2. In addition, Figure 5(b) shows the *weight-diameter* chart. For each vehicle, four observations are reported in the comfort-stability chart, two for each driver, and one for each e-scooter in the weight-diameter chart. In the comfort-stability chart, the filled markers refer to 35kg driver's trials, the empty ones to 73kg driver's ones.

Table 2. Quantitative and qualitative results. This Table reports for each trial the comfort (η) and stability (σ) metrics computed. Also, it is reported the qualitative score referred to the driving experience presented in (Pinter, 2021)

Trial Number	Driver Weight [kg]	e-Scooter Model	Metrics		Qualitative Score (Pinter, 2021)
			η	σ	
1	35	Helbiz	5.87	13.47	9
2	35		5.69	13.223	
3	73		6.97	13.61	
4	73		6.76	11.24	
5	35	Voi	6.56	14.48	9
6	35		5.98	13.74	
7	73		6.44	10.29	
8	73		6.42	9.89	
9	35	Mi2	5.52	13.29	N/A
10	35		4.50	17.67	
11	73		5.52	13.64	
12	73		5.28	15.92	
13	35	Lime	5.66	10.18	7.5
14	35		5.40	8.76	
15	73		5.66	11.05	
16	73		5.41	8.76	
17	35	Dott	5.14	13.66	8.5
18	35		4.70	15.38	
19	73		5.04	10.16	
20	73		4.64	11.30	
21	35	Bit	4.79	9.28	8
22	35		4.77	8.66	
23	73		4.74	11.79	
24	73		4.35	10.30	
25	35	Lamborghini	3.52	9.19	N/A
26	35		3.01	8.31	
27	73		3.63	7.92	
28	73		3.36	7.72	

Regardless of the driver mass, Helbiz and Voi achieve the best results in terms of comfort, while Mi2 and Dott obtain the highest stability. The weight-diameter chart allows to investigate further these results, mapping comfort and stability metrics to the vehicle mechanical specifications. In particular, we notice how comfort is closely related to the e-scooter weight. This result is physically explainable as, considering the same road profile, the vehicle has a greater capacity to dampen the vibrations generated as its weight increases. Considering e-scooters with the same wheels' size while traveling on the same surface, the heavier are also more stable, which is the case of Bit, Lime, Helbitz and Voi. Moreover, it can be noticed that stability is also affected by the wheels' size and material. Air-chambered wheels confer more stability than solid rubber and honeycomb ones; accordingly, Dott and Mi2 turns out to be the most stable vehicles. Therefore, air-chambered wheels are preferable to more rigid alternatives such as honeycomb or solid rubber as their elastic properties allow for improving e-scooter drivability. Considering vehicles with the same wheels specifications and shock absorber configuration, as Bit and Helbiz, also the weight-to-power ratio presents a direct correlation with stability.

Finally, our analysis results were evaluated against the comparative analysis presented by (Pinter, 2021). This riding test considered the same sharing e-scooters included in our experimental campaing, and provides a qualitative score, on a scale from 1 to 10, expressing the driver experience perceived during a trip in the Municipality of



(a) Comfort-stability chart

(b) Weight-diameter chart

Fig. 5. Comfort-stability analysis results. The left chart compares the comfort and stability metrics computed for each recording; the right one shows the mechanical specifications of the considered e-scooters.

Milan, varying driving speed and traveled road surfaces. The scores, reported in Table 2, turned out to be consistent with the quantitative results obtained in our analysis. This evidence demonstrates that the presented comfort and stability metrics correctly represent the rider's perception.

6. CONCLUDING REMARKS

This work presented an analysis of e-scooters' driveability and safety levels, relating them to their mechanical specifications. A quantitative definition of the considered cost functions was provided using two metrics: comfort and stability. Furthermore, considering vehicle vibrational behavior as a function of speed and road profile, a preliminary analysis was conducted to identify the most appropriate working conditions within which the proposed metrics should be evaluated. Accordingly, seven on-the-market e-scooters were compared. The results confirm the importance of wheel size and material in ensuring driver safety, and identify as key design factors the vehicle weight and the weight-to-power ratio. This work paves the way for further experimental research aimed at defining a set of optimal specifications to maximize the safety of the riders by optimizing the vehicle design features.

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