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Skid Resistance Analysis of Urban Bike Lane Pavements for Safe Micromobility

Martín López-Molina, David Llopis-Castelló *, Ana María Pérez-Zuriaga, Carlos Alonso-Troyano and Alfredo García

Highway Engineering Research Group (HERG), Universitat Politècnica de València, Camino de Vera, s/n, 46022 Valencia, Spain

* Correspondence: dallocas@upv.es; Tel.: +34-963877374

Abstract: The use of micromobility vehicles is considerably growing in cities worldwide. As a result, crashes involving these vehicles are also increasing, with single-bicycle crashes accounting for a significant percentage. In most infrastructure-related crashes, the road surface was slippery. In this context, the study of pavement skid resistance is crucial to improve micromobility safety. In this research, the British pendulum tester was used to test the skid resistance of 5 different types of pavements on 17 bike lane locations in Valencia (Spain). Additionally, micromobility users' speed was collected to analyse users' behaviour. The results showed that asphalt, concrete, and rough painted tile pavements had the greatest skid resistance, whereas painted cobble and smooth painted tile pavements presented poor skid resistance. These values were compared with the limits set by the few guidelines that includes skid resistance thresholds. Moreover, skid resistance variability was also studied, with asphalt pavement being the most homogeneous. Based on the results of the research, several recommendations are proposed for the pavement to be used in the micromobility facility according to its typology. To this end, the investigatory level of skid resistance and the minimum braking distance required were also defined for each type of pavement and bike lane. The findings of this study contribute to the consideration of micromobility safety from the construction stage to the pavement management.

Keywords: skid resistance; pavement; bike lane; micromobility; road safety; crash occurrence; British pendulum

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1. Introduction

A paradigm shift is taking place in mobility in cities worldwide, especially boosted by the COVID-19 pandemic. Eco-Counter, that operates automatic bicycle trip counters at key locations in European and North American cities, showed a considerable variation in percentage changes in cycling levels between 2019 and 2020 among EU countries as well as among regions of the USA and Canada [1]. Not only has bicycle use increased, but there has also been an exponentially growing trend in urban micromobility, especially including e-scooters. E-scooters, both shared and owned, have become a first-mile/last-mile transport mode, helping cities reduce crowded public transport while enabling social distancing, sustainability, and mobility resilience [2].

This increase in active means of transport was possible thanks to the measures undertaken by many city governments to accommodate and encourage increased cycling during the pandemic. Many cities expanded their cycling facilities in 2020, shared by the different micromobility vehicles. Furthermore, the expansion and improvement of cycling facilities was already included in long-term plans, although COVID-19 accelerated implementation [1].

This significant increase in micromobility vehicles use in recent years has also led to a growing number of crashes involving them [3–5]. The ETSC [6] found out that 53% of all cyclist deaths in the European Union are the consequence of an impact with a passenger car, and that 16% of cyclists died in single-bicycle crashes (SBCs). Those are the percentages according to police records. However, several studies have found that, although the SBCs reported by the police account for only about 10% of all crashes involving cyclists, hospital records show that SBCs represent from 60 to 95% of all crashes involving cyclists [7,8]. Therefore, to improve micromobility safety is not only necessary to prevent crashes with motorized vehicles, but also SBCs.

In Sweden, one of the most common main causes of SBCs is road maintenance deficiencies, including slippery surfaces, uneven surfaces, temporary objects, and road edges [7,9]. Considering all causes, and not only the main one, the most common causes of SBCs are skidding due to ice/snow, kerbstones/edgings, grit, mainly from winter maintenance, evasive action to avoid collision with other users, and making a turn/taking a curve. In Finland, 62.9% of SBCs were related to the infrastructure and, in the majority of infrastructure-related crashes, the road surface was slippery [10]. In countries with less probability of the presence of snow and ice on the pavement, such as Australia, 37% of SBCs were classified as loss-of-control events [11]. Loss-of-control events commonly occurred due to sudden braking to avoid collision with another vehicle or cyclist, losing control on a dry descent, or losing control in wet/slippery conditions.

Therefore, good surface riding quality is essential for micromobility users' safety (cyclists and other personal mobility vehicles users), as well as users' comfort. Almost all cycling design standards state that cyclists need a smooth riding surface, i.e., not undulating and with adequate skid resistance [12,13]. However, most of them do not include a threshold level either for the roughness or for the skid resistance [14]. To our knowledge, only NSW Roads and Maritime Service (Australia) [15], NZ Transport Agency (New Zealand) [16], and Consejería de Fomento y Vivienda de Andalucía (Spain) [17] provide some guidelines on these values.

In fact, Qian et al. [18] highlighted that there remains a significant gap in knowledge in terms of defining what types of measurements are critical determinants of the quality of a bicycle ride, how these determinants of the quality are associated with perceptions of ride quality and safety, and how to best specify the relationship between the critical determinants and the traditional pavement rating tests. This gap is even higher when considering e-scooters. Several studies have studied the influence of the bike lane pavement on riding quality, focusing on mean texture depth (MTD) [18], international roughness index (IRI) [19], and vibrations experienced by cyclists and e-scooter users [20–24]. However, there are few studies on skid resistance.

Gao et al. [25] characterized the pavement–tire interface via the following nine parameters: contact area, unit bearing, stress intensity, stress uniformity, kurtosis, spacing, maximum peak spacing, radius ratio, and fractal dimension. They highlighted that stress characteristics have a direct influence on the skid resistance of road surfaces. However, they did not delve into this topic and recommended further research to establish design and evaluation criteria that include skid resistance.

Offei et al. [26] evaluated the friction and texture characteristics of five green-colored bicycle lanes. Results indicated that several factors, such as pavement surface type as well as the type of green bike lane material applied, and the presence of traffic wear, have a significant influence on the friction values.

Friction depends not only on the properties of the tires and pavement materials but also on the environment and the interfacial medium between the materials. Rekilä and Klein-Paste [27] measured the actual braking friction of bicycles in winter conditions by measuring deceleration and braking distance, and compared the results to friction measurement devices. They concluded that the bicycles experienced at least as much or more friction from the road surface, compared to the readings of the friction measurement devices.

Similarly, Bergström et al. [28] used a portable friction tester to measure friction on bikeways with diverse types of asphalt pavements under different surface conditions—bare and wet—in winter. A low difference in friction was found between the different pavement surfaces, which was associated with the fact that the same type of pavement was evaluated, namely asphalt concrete.

In this context, this research is aimed at evaluating the skid resistance on different types of bike lane pavements. To do this, the study is divided into five stages, as follows: (i) bike lane network analysis, (ii) definition of the variables to be observed, (iii) field data collection, (iv) analysis of skid resistance and micromobility users' speed, and (v) proposal of suggestions and recommendations. The outcomes of this study will help designers and administrations in the construction and maintenance of micromobility facilities to improve users' safety.

The research method of the study is presented in Section 2, and includes the location of the field data collection and the description of the methods proposed for measuring skid resistance and micromobility users' speed. Section 3 describes the results of data collection in terms of skid resistance and its relationship with micromobility users' speed and stooping sight distance. Section 4 shows a discussion of the findings of the study. Finally, the main conclusions, limitations, and further research are presented in Section 5.

2. Materials and Methods

This section presents the characterization of the bike lane network in the city of Valencia (Spain), the identification of the methods used for the measurement of pavement skid resistance, and the description of the field data collection.

2.1. Bike Lane Network

The bike lane network of the city of Valencia was characterized by identifying the most common types of bike lanes in terms of the materials of which the pavement is made up. To do this, the existing bike lanes were analysed through images from Google Maps and Google Earth as well as the information available in the Geoportal of the City Council of Valencia (https://visor.gva.es/visor/ (accessed on 17 September 2021)).

As a result, the following types of pavements were identified (Figure 1):

- Asphalt pavement;
- Concrete pavement;
- Painted cobble pavement;
- Rough painted tile pavement;
- Smooth painted tile pavement.

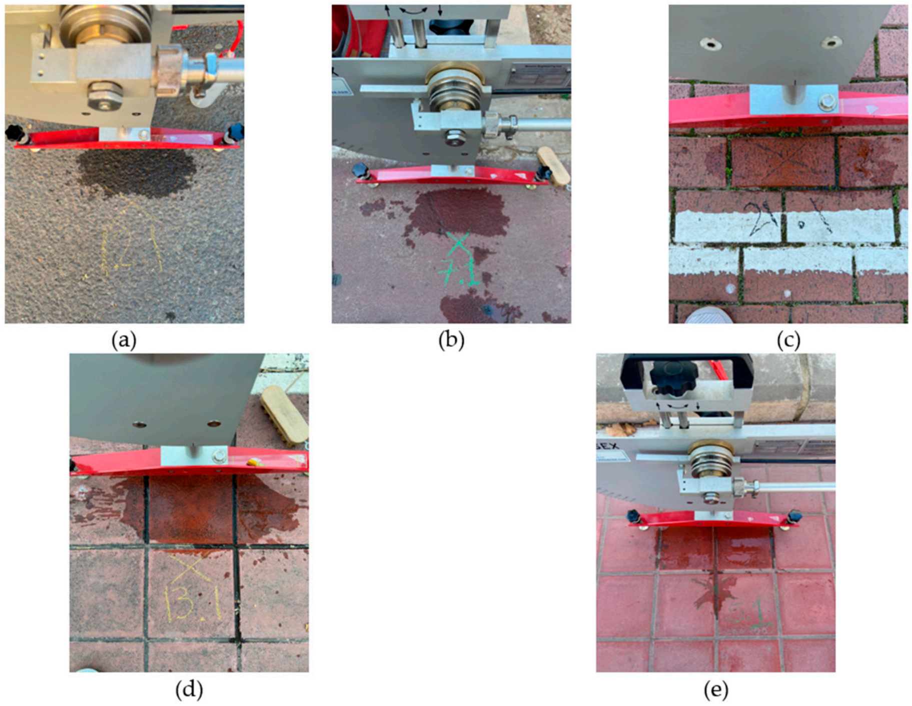

(a) (b) (c) (d) (e)

Figure 1. Types of pavements in bike lanes. (**a**) Asphalt pavement; (**b**) concrete pavement; (**c**) painted cobble pavement; (**d**) smooth painted tile pavement; and (**e**) rough painted tile pavement.

2.2. Skid Resistance and Micromobility Users' Speed

Friction between the pavement and the tire is based on the mechanisms of hysteresis and adherence that occur at the tire–pavement contact. While adherence is associated with pavement microtexture, hysteresis is a consequence of energy loss due to tire deformation and is, therefore, related to macrotexture.

Microtexture influences the magnitude of tire friction, interacts with the tire on a molecular scale, and provides adherence. In this way, microtexture has a greater influence on friction as speed decreases. Likewise, this influence increases when the pavement is dry and plays an essential role in vehicle braking processes. By contrast, macrotexture affects the friction–velocity gradient. It is particularly important in wet conditions, reducing water splashing and preventing aquaplaning. However, it is also responsible for generating more or less noise in the–pavement interaction.

Due to the weight of the micromobility vehicle and the user as a whole and their low speed, microtexture is critical in micromobility safety and can be directly related to the skid resistance. This pavement feature is generally measured as a friction number or coefficient [29] using the following devices:

- Grip number determined from the GripTester—continually measured by a towed device, which can also be pushed by hand in narrow areas;
- British pendulum number (BPN)—measured by the British pendulum (BP), a portable device which tests a small and discrete area of surface;
- Sideways force coefficient (SFC)—continually measured with a device known as SCRIM (mounted on a heavy commercial vehicle), although the 50 km/h test speed and significant clearance requirements generally exclude the use of this equipment on bikeways.

All three devices measure the skid resistance on a wet surface. The most appropriate testing device for bikeways should be the British pendulum or GripTester [29].

In this study, the skid resistance was measured according to the UNE-EN 13036-4 standard that is based on the British pendulum tester (Figure 2). The test measures skid resistance when a rubber slider on a 20 in (508 mm) pendulum arm contacts a test surface. A drag pointer on a 0–150 scale measures friction.

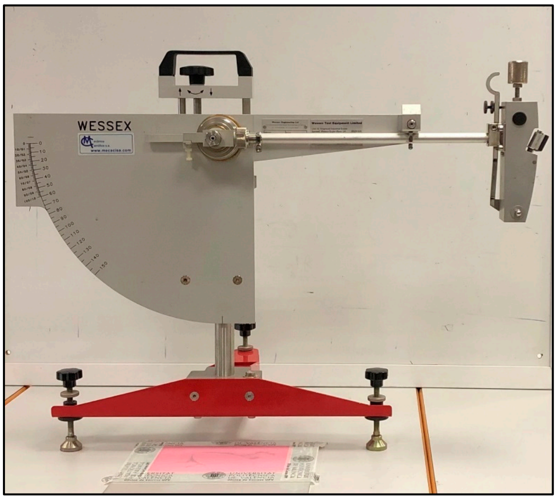


Figure 2. British pendulum tester.

The procedure of the measurement of skid resistance can be divided, after the calibration of the pendulum in the lab, into six phases, as follows: (i) cleaning of the pavement surface and temperature measurement, (ii) leveling of the pendulum, (iii) calibration of the 0, (iv) preparation of the pendulum arm to slide 126 mm, (v) wetting of contact surface, and (vi) performing five measurements. The value of the skid resistance for the observation point is calculated as the average of the five measurements.

The speed of micromobility users were also measured through video recordings. For this purpose, the operation of micromobility users at each of the studied locations were recorded by Garmin Virb Elite video cameras placed on a tripod. These video cameras allow recording at a resolution of 1920 × 1080 pixels and at 30 fps, with a field of view of 120°. The speed of each user was estimated considering the time required by the user to cover a known distance.

2.3. Field Data Collection

Figure 3 shows the 17 sampling points in which the skid resistance was measured. Data collection was carried out in November and December 2021.

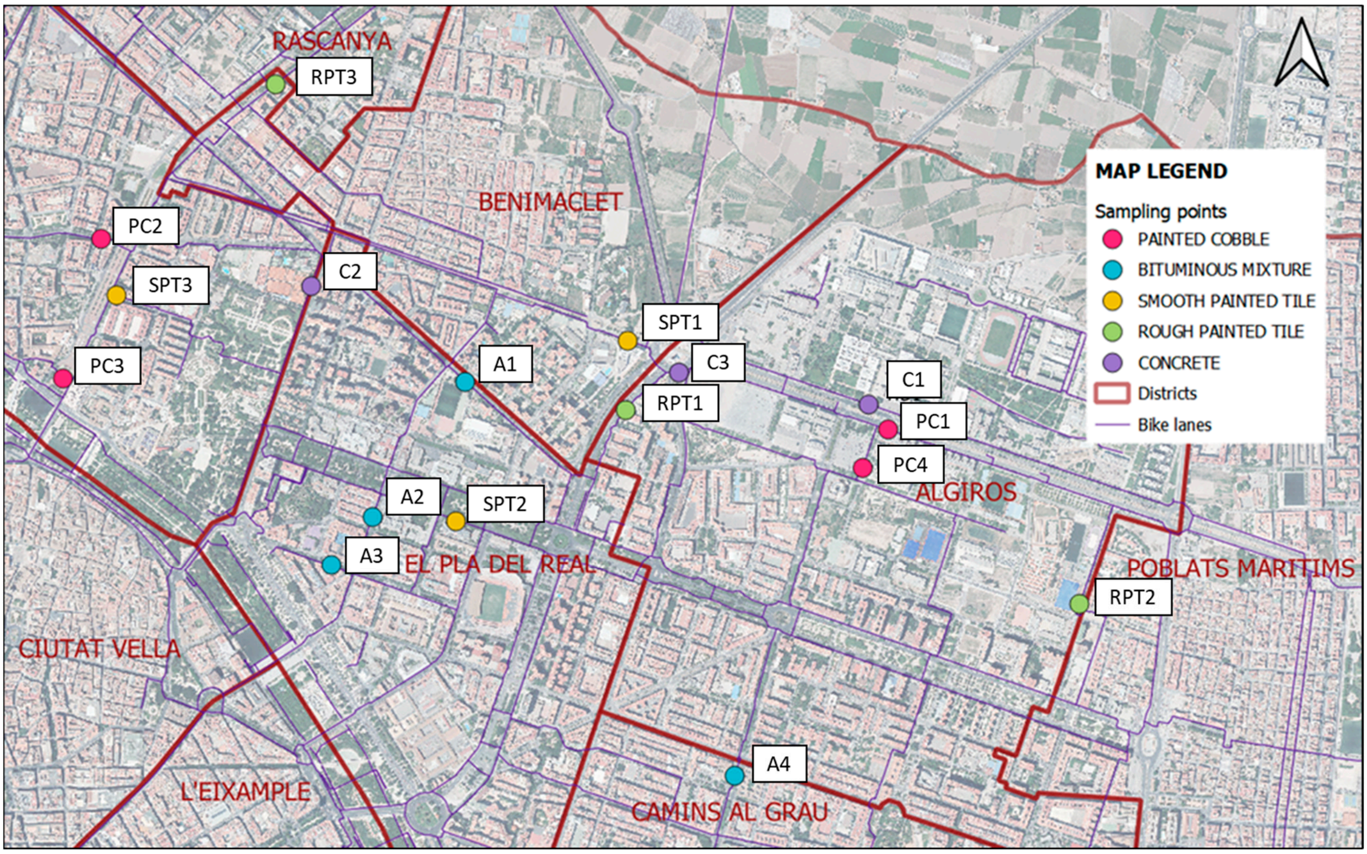


Figure 3. Sampling points location.

The location, type of pavement, type of bike lane, and skid resistance of each sampling point are included in Table 1. Regarding the type of bike lane, sidepath refers to off-street bikeways that are built as extensions of the sidewalk, with a complete physical separation from cars except at intersections with cross streets.

As can be observed, a minimum of three sampling points by type of pavement were selected to ensure reliability results. Additionally, all sampling points presented good pavement conditions—without pavement distresses—so as to minimize the influence of external factors. The value of the skid resistance for every location was calculated as the average of the skid resistance obtained at four different locations no more than 0.400 m apart on the same pavement section.

Table 1. Characteristics of sampling points.

Id	Location	Pavement Type	Type of Bike Lane	Skid Resistance
A1	Primat Reig Ave.	Asphalt	Protected bike lane	65
A2	Doctor Moliner St.		Protected bike lane	60
A3	Micer Mascó St.		Protected bike lane	62
A4	Manuel Candela St.		Sidepath	57
C1	Naranjos Ave. (UPV)	Concrete	Protected bike lane	70
C2	Cavanilles St.		Sidepath	62
C3	Roundabout Cataluña Ave.		Sidepath	58
PC1	Naranjos Ave. (UV)	Painted cobble	Sidepath	45
PC2	Argenter Suárez St.		Sidepath	36
PC3	Almazora St.		Sidepath	38

PC4	Alabat del Tarongers St.		Sidepath	36
RPT1	Cataluña Ave.	Rough painted tile	Sidepath	75
RPT2	Campillo Altobuey St.		Sidepath	60
RPT3	Alfauir St.		Sidepath	55
SPT1	Dr. Vicent Zaragoza St.	Smooth painted tile	Sidepath	24
SPT2	Blasco Ibáñez Ave.		Protected bike lane	33
SPT3	Convento Carmelitas St.		Sidepath	52

At the same time, micromobility users' speeds were observed at 11 of the sampling points using a Garmin Virb Elite video camera placed in a tripod. For speed measurement, two points were taken as reference, before measuring the distance between them in the field. Later, the speed of every micromobility user was estimated by identifying the difference in time to cover the distance between the reference points.

Table 2 shows the number of observations, mean speed, and standard deviation of the speed in each location for every type of micromobility vehicle, including private bicycle, e-scooter, and public bicycle sharing.

Table 2. Statistical summary of the speed of micromobility users.

Micromobility Vehicle	Number of Observations	Mean Speed (km/h)	Standard Deviation (km/h)
A1			
Private bicycle	68	18.45	4.15
E-scooter	49	22.72	3.98
Public bicycle sharing	21	15.09	2.87
Other	1	18.90	-
A2			
Private bicycle	135	17.95	4.02
E-scooter	79	21.32	3.51
Public bicycle sharing	27	16.20	2.87
Other	5	12.28	2.36
A3			
Private bicycle	224	11.48	3.60
E-scooter	125	12.89	2.52
Public bicycle sharing	88	11.45	3.56
Other	3	12.35	0.58
A4			
Private bicycle	256	11.30	2.52
E-scooter	189	17.57	4.61
Public bicycle sharing	86	10.87	1.91
Other	10	11.45	1.30
C1			
Private bicycle	383	12.96	3.38
E-scooter	124	14.90	2.66
Public bicycle sharing	60	12.56	2.99
Other	6	13.43	1.37
C2			
Private bicycle	209	18.43	3.41
E-scooter	79	22.89	3.52
Public bicycle sharing	38	16.03	3.24

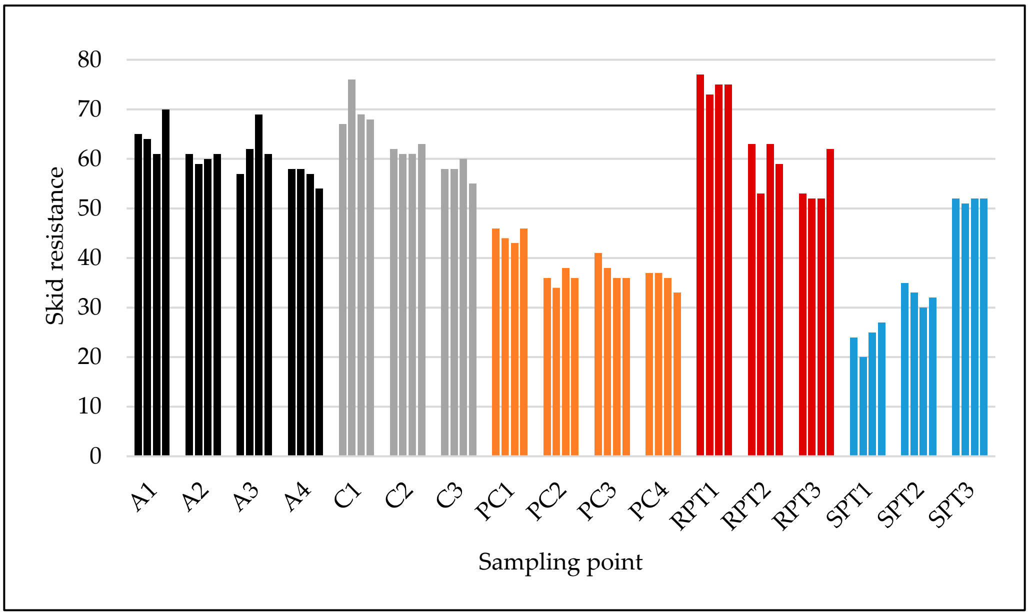
Other	5	14.76	1.39
PC4			
Private bicycle	59	19.22	3.76
E-scooter	16	22.76	5.09
Public bicycle sharing	60	17.02	2.76
Other	-	-	-
RPT1			
Private bicycle	350	12.01	2.70
E-scooter	109	12.92	2.59
Public bicycle sharing	40	11.70	2.45
Other	9	11.95	1.98
RPT2			
Private bicycle	130	11.20	2.12
E-scooter	87	16.38	4.07
Public bicycle sharing	55	10.15	1.62
Other	7	11.92	1.01
SPT1			
Private bicycle	509	12.67	2.63
E-scooter	164	15.59	2.95
Public bicycle sharing	91	10.80	2.81
Other	2	13.32	2.95
SPT2			
Private bicycle	77	18.22	3.68
E-scooter	57	22.19	3.66
Public bicycle sharing	44	15.76	3.49
Other	-	-	-

3. Results

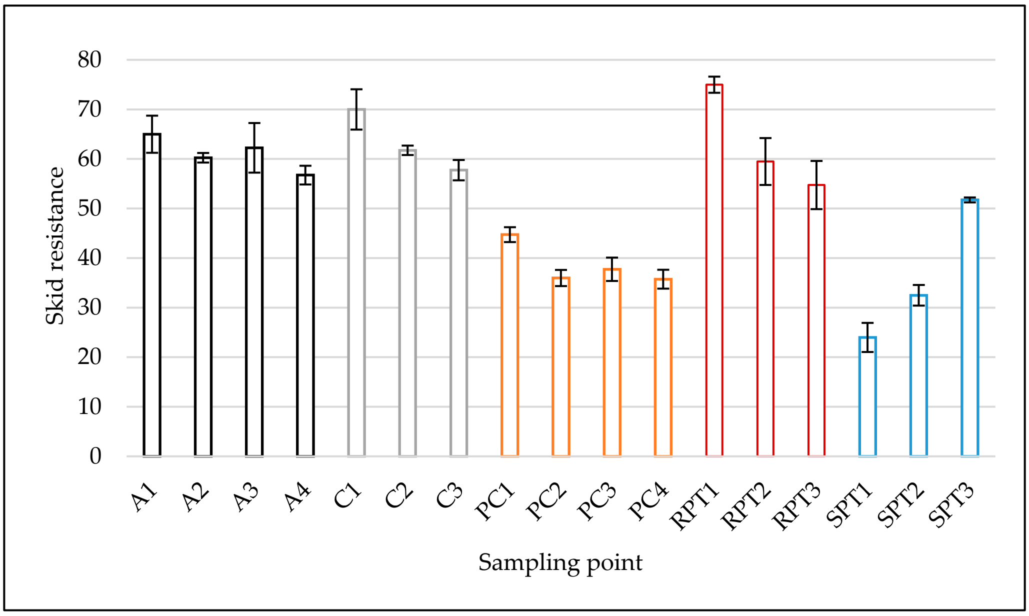
This section presents the results of the skid resistance per type of pavement and micromobility users' speed. Moreover, the stopping distance is calculated for every type of pavement based on pavement friction and the speed of micromobility users.

3.1. Skid Resistance

Figure 4 shows the values of all measurements of the British pendulum tester and the mean value and the standard deviation of the skid resistance at each sampling point. As mentioned above, at each sampling point, the skid resistance was measured at four different locations no more than 0.400 m apart (Figure 4a). In this way, the skid resistance at each sampling point, estimated as the mean of the skid resistance of its four locations, is included in Table 1 and represented together with the standard deviation in Figure 4b.



(**a**)



(**b**)

Figure 4. Results of the British pendulum test at each sampling point. (**a**) Skid resistance at each observation point no more than 0.400 m apart at each sampling point, and (**b**) mean and standard deviation of skid resistance in each sampling point.

Overall, the variability in skid resistance at each observation point was low (<5) regardless of pavement type. This fact indicates that the pavement properties are quite homogeneous along the studied bike lanes. However, some pavement types, namely concrete and rough and smooth painted tile pavements, showed a large variability in skid resistance among the different sampling points.

For asphalt pavement, four sampling points were established, including a total of 16 measurements of the skid resistance, i.e., 4 measurements per sampling point. The maximum value of the skid resistance was 70, the minimum was 54, and the mean skid resistance was equal to 61. In addition, the variability in the skid resistance between the sampling points was very low.

Although the mean values of the skid resistance for concrete pavement and rough painted tile pavement were very similar to that obtained for asphalt pavement, the variability in the skid resistance for both type of pavements was greater than that observed for asphalt pavement. This variability cannot be associated with pavement condition since all selected bike lanes were in good condition. Therefore, this variability is an indicator that the construction of bike lanes with these materials—concrete and rough painted tiles—could lead to pavements with quite different surface characteristics. Specifically, these type of pavements presented higher maximum values of skid resistance (76 and 77, respectively) than asphalt pavement. However, the minimum skid resistance was very similar between these three types of pavements.

On the other hand, the mean skid resistance for painted cobble pavement was similar to that identified for smooth painted pavement. However, the variability in the skid resistance between the sampling points associated with smooth painted tile pavement was much greater than the variability observed for painted cobble pavement. In light of these findings, the pavement condition of the three sampling points consisting of smooth painted pavement was analyzed. While the sampling points SPT1 and SPT2 showed clear evidence of polishing or wear, sampling point SPT3 had some roughness and evidence of recent painting, which is in accordance with the results obtained.

3.2. Micromobility Users' Speed

The speed of a total of 4136 micromobility users was estimated (see Table 2). The users riding their own bikes accounted for 58% of the total of micromobility users, whereas the public bicycle sharing system was used by 15% of the users (Figure 5). In turn, one out of four micromobility users were riding an e-scooter.

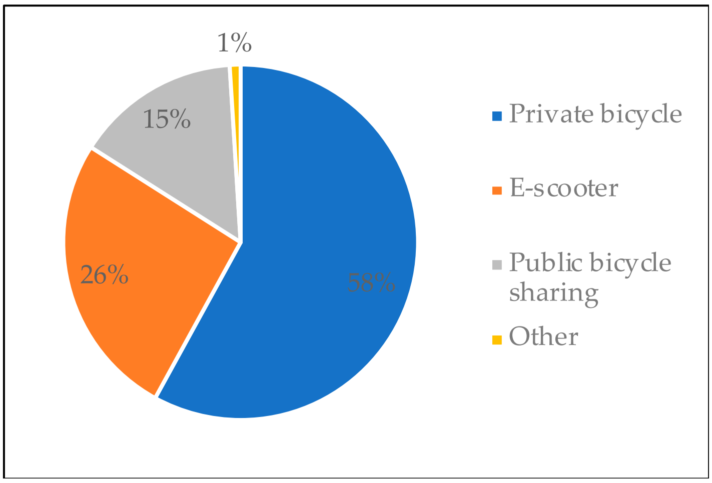


Figure 5. Distribution of micromobility users.

The mean speed of micromobility users riding an e-scooter is greater than the mean speed of micromobility users riding a bicycle—private or public—at each sampling point (see Table 2). Moreover, the mean speed associated with private bicycles was slightly higher than that experienced by the users of the public bicycle sharing system. Regarding the speed variation among users, the highest standard deviation was observed for private bicycles.

It was also identified that the micromobility users' speed does not seem to depend directly on the type of pavement (Figure 6). There are other important factors that would be influencing micromobility users' behaviour, such as pavement condition, urban furniture, including containers, benches, etc., separation elements, including flexible posts, concrete curbs, etc., the type of bike lane, and the volume of motorized and non-motorized--including pedestrians—traffic.

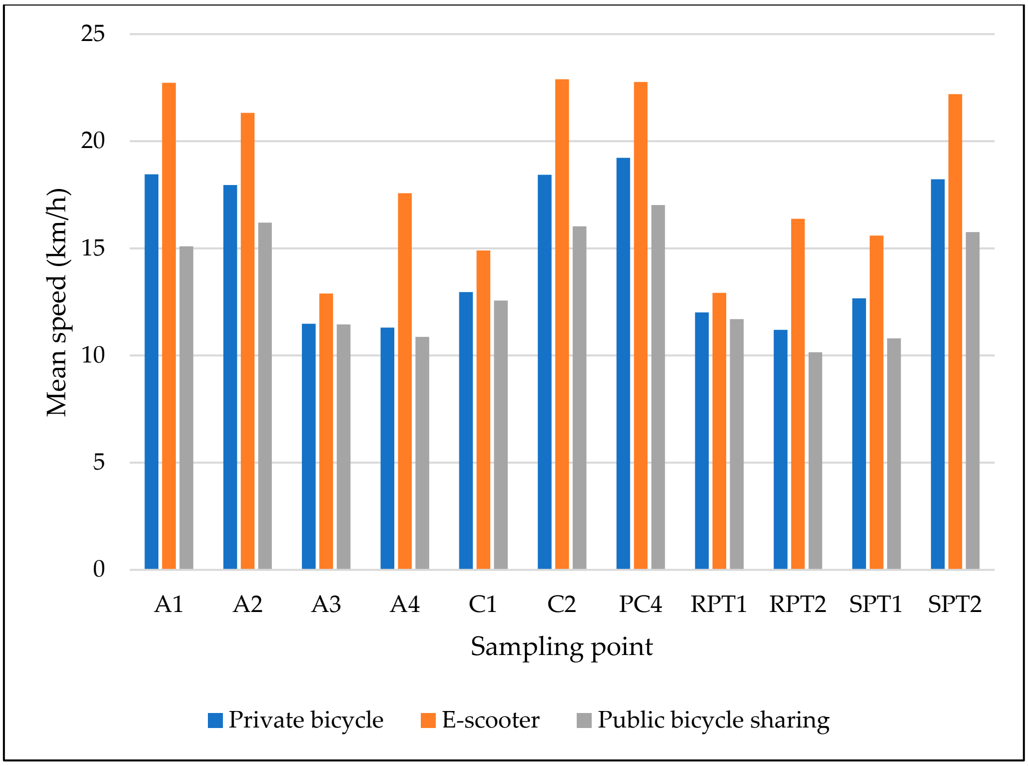


Figure 6. Micromobility users' speed.

3.3. Stopping Sight Distance

The stopping sight distance is the distance travelled between the time when the driver decides to stop the vehicle and the time when the vehicle stops completely. In this way, the stopping distance consists of (i) the thinking distance, that is, the distance travelled while the driver notices a hazard and applies the brakes, and (ii) the braking distance, that is, the distance while the vehicle comes to a full stop from its initial speed.

The minimum stopping sight distance can be calculated using the following Equation (1) [13]:

$$S = \frac{V^2}{254 \cdot (f + G)} + \frac{V \cdot t_p}{3.6} \tag{1}$$

where S is the stopping sight distance (m); f is the coefficient of friction; G is the longitudinal grade; V is the speed (km/h); and t_p is the perception and brake reaction time (s).

Before applying Equation (1), the coefficient of friction must be determined for each type of pavement. Table 3 includes the coefficient of friction for the pavement types considered in this study, which have been estimated from their mean skid resistance through the following Equation (2) [30]:

$$f = \frac{3 \cdot SR}{330 - SR} \tag{2}$$

where f is the coefficient of friction and SR is the skid resistance.

Table 3. Coefficients of friction.

Pavement Type	*F*
Asphalt	0.6803
Concrete	0.7079
Painted cobble	0.4021
Rough painted tile	0.7079
Smooth painted tile	0.3673

Figure 7 shows the stopping distance for each pavement type considering a perception and break reaction time of 2 s and a flat terrain (*G* = 0%).

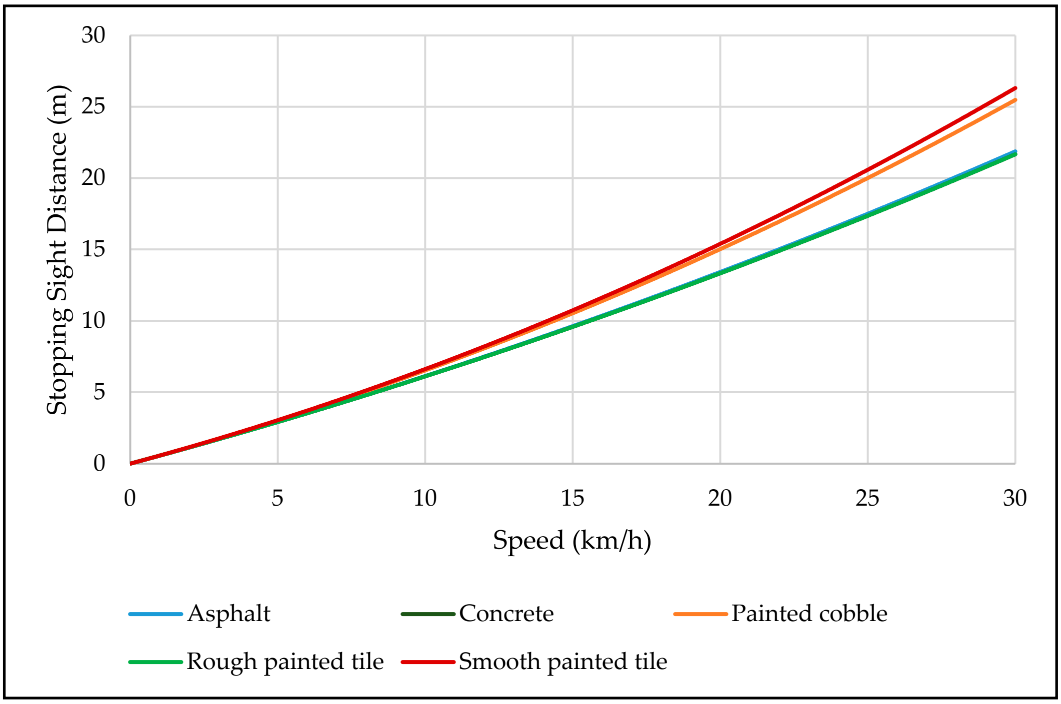


Figure 7. Minimum stopping sight distance by pavement type.

The use of asphalt, concrete, and rough painted tile pavements reduces the required minimum stopping sight distance by 5% at 10 km/h and by 10% at 30 km/h. On the contrary, smooth painted tile pavement increases the required minimum stopping sight distance from 4% to 9%, which could lead to risky situations mainly under wet conditions.

4. Discussion

Pavement quality and bike lane conditions are critical for micromobility users' safety as well as for riding comfort. Focusing on safety, skid resistance is one of the surface characteristics that has more influence on it, since it allows for accelerating, braking, and maintaining the trajectory of the bicycle or e-scooter without risk of slipping or skidding.

This characteristic is often included in cycling pavement management systems at an investigatory level. In this way, the level of skid resistance at or below which a site investigation is undertaken is defined, and the information of that level is used as a priority indicator for programming treatment.

The investigatory level recommended by the Government of South Australia [29] for bikeway pavement with a 60 km/h maximum vehicle speed is a grip number of 0.40. Considering that the appropriate conversion from British pendulum no. (BPN) to grip no. (GN) is GN = 0.01·BPN [29], the investigatory level would be a BPN of 40.

The NSM Road and Maritime Service [15] recommends a minimum slip or skid resistance value (SRV), measured in units of British pendulum number (BPN), to be at least 55 for normal applications and 65 for high skid risk applications.

The NZ Transport Agency [16] states that the investigatory level for skid resistance in units of equilibrium SCRIM coefficient (ESC) is 0.35. Considering that SC = 0.0071·BPN + 0.033 [31], an ESC of 0.35 is equivalent to a BPN of 44.64.

Likewise, Consejería de Fomento y Vivienda de Andalucía [17] recommends a skid resistance value measured in units of British pendulum number of not lower than 45.

The results of the analysis of data collected in this study show that only asphalt, concrete, and rough tile pavement present higher SRVs than the abovementioned thresholds—61, 63, and 63, respectively—whereas the SRV of painted cobble pavement (39) and smooth painted tile pavement (36) are considerably lower. Standard deviation was also studied, since high variability may be an indicator of the sensitivity of the pavement type to boundary conditions. In this sense, the variability in skid resistance for both concrete and rough tile pavement was greater than that observed for asphalt. Therefore, we can conclude that asphalt pavement provides a more homogeneous skid resistance along the riding surface, so it could be recommended as the default provision for cycling in accordance with Transport for London [12]. They also recommend paving slabs/flags and cobbles (pebbles in concrete) to be avoided for general cycling use due to their poor wet skid resistance, which is also in line with the outcomes obtained in this research.

The greatest variability was found on smooth painted tile pavement. For this case, the pavement in location SPT3 presented an SRV considerably greater—52—than the other two, which were 24 and 33, respectively. Sampling point SPT3 presented evidence of recent painting, so it can be concluded that the conditions of the paint play an essential role for skid resistance in this type of pavement, which decreases over time. Therefore, it is suggested that the tests be repeated yearly to ensure that the surface continues to meet the requirements, especially for this type of pavement.

Moreover, skid friction and speed are the factors that determine the required minimum stopping sight distance. In Valencia, bike lane speed limit is set according to the type of bike lane as follows: 30 km/h for shared roadway; 20 km/h for striped, buffered, and protected bike lane; and 15 km/h for sidepaths [32].

Given that micromobility users can reach higher speeds along shared roadways and striped/buffered/protected bike lanes, the pavement used for these types of bike lanes should provide higher skid resistance than those used for sidepaths. Thus, micromobility users would have the necessary friction to stop in safety conditions. To do so, it is necessary to provide the adequate stopping sight distance. The AASHTO [13] considered a coefficient of friction of 0.16 in its calculation, whereas Consejería de Fomento y Vivienda de Andalucía used a 0.25 value [17]. Minimum stopping sight distance should be calculated based on the coefficient of friction corresponding to each type of pavement (Table 3).

According to the results of the study, the following good practices are proposed:

- For roadways shared by motorized vehicles and micromobility users, the surfacing material should be asphalt, since this is the most common material used in roadways. The investigatory level should be a SRV of 65 measured in units of BPN one month after construction to comply with Spanish highway regulations [33]. Given that the travel speed is lower in urban areas, the investigatory level could be reduced;
- For striped/buffered bike lanes in Valencia, the speed limit is 20 km/h. The recommended surfacing material is asphalt, especially to give continuity to the attached roadway. The proposed SRV investigatory level is 55. Considering this speed limit and SRV, the required minimum stopping sight distance is 13.7 m;
- For protected bike lanes in Valencia, the speed limit is 20 km/h, but, unlike the striped and buffered bike lane, these bike lanes have an edge element to separate micromobility users and motorized vehicles. The recommended surfacing material is asphalt by default, but concrete pavement could also be used. Given that the risk on this type of bike lane is lower, the proposed SRV investigatory level is 45. Considering this speed limit and SRV, the required minimum stopping sight distance is 14.5 m;
- For sidepaths in Valencia, the speed limit is 15 km/h because of the close presence of pedestrians. In this case, where the desired speed is lower, the recommended pavement is rough tile pavement, since the vibrations experienced by users could encourage them to reduce the speed. The proposed SRV investigatory level is 45. Considering this speed limit and SRV, the required minimum stopping sight distance is 10.2 m.

- Painted cobble and smooth painted tile pavements must not be used as surfacing materials for micromobility facilities due to their low and variable skid resistance and vibrations.
- Near intersections, it is suggested to have an SRV of at least 65 to ensure safety, applying a surface treatment when necessary.
- The skid resistance should be tested one month after construction, and repeat testing every year to ensure that the surface still meets the requirements is highly recommended.

5. Conclusions

This research analyses the skid resistance on micromobility facilities with different types of pavements using the British pendulum tester. In addition, micromobility users' speeds were measured at different locations so as to characterize users' behaviour and describe some recommendations based on the concept of stopping sight distance.

The results of the skid resistance indicated that asphalt, concrete, and rough painted tile pavements provide an adequate friction for micromobility users. The values of the skid resistance for these pavements range between 55 and 75, which are higher than the required skid resistance established by existing guidelines. However, asphalt and concrete pavements are preferred over rough painted tile pavement because the former presented less variability among the sampling points and provide lower vibrations to micromobility users, i.e., a more comfortable operation.

On the other hand, both painted cobble and smooth painted tile pavements showed a poor skid resistance of below 45. Therefore, the use of these types of pavements could lead to riskier micromobility users' maneuvers, increasing the likelihood of crash occurrence and the number of traffic conflicts between micromobility users and between these users and pedestrians and motorized traffic.

In addition, the required stopping sight distance for every type of pavement was estimated considering a range of speed between 0 and 30 km/h. While the pavements providing a greater adherence—asphalt, concrete, and rough painted tile pavements—allow a reduction in the required stopping distance up to 10%, smooth painted tile pavement increases the required stopping sight distance by 9% when travelling at 30 km/h.

As a conclusion, several recommendations have been proposed related to the use of the different types of pavements depending on the type of bike lane. Moreover, SRV investigatory level and required minimum stopping sight distances have also been proposed to ensure safety not only for micromobility users but also for pedestrians and motorized vehicles.

Finally, it should be noted that this research only considers pavements in good condition. Further research is needed to analyze how pavement condition influences skid friction. The influence of the type of the paint used on tile pavements should also be studied, since rough and smooth painted tile pavements showed a large variability in skid resistance. Moreover, the skid resistance of pavement markings and the loss of skid resistance over the time should also be studied.

The results of this study can be the basis for improving safety in micromobility facilities, decreasing single-bicycle crashes. In addition to the fact that low skid resistance could be the cause of a cyclist or e-scooter user slipping, it could also be a dangerous situation for pedestrians, who could be injured or could even cause traffic crashes. Therefore, the improvement of skid resistance is worthy for all road users.

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