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Comparison of e-scooter tyre performance using rolling resistance trailer

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Abstract

E-scooters are a cost-effective means of urban transport, however, there have been questions about their safety, performance, and energy efficiency. This paper investigates the rolling resistance of scooter tyres so that the performance of scooters can be more accurately determined. A rolling resistance trailer was manufactured to directly measure tractive force and closely approximate the rolling resistance force for nine commonly used scooter tyres at low speed on a smooth concrete surface. The results of this study will enable a better understanding of the energy losses of these devices.

Keywords: sustainability, sustainable design, energy efficiency, rolling resistance, e-scooters

1. Introduction

1.1. Background

By 2050, the proportion of the world's population who live in urban areas is predicted to increase to 68 % (Ritchie and Roser, 2018). With this growth, urban transport technology has developed a range of light electric vehicles (LEVs) to act as micromobility solutions to meet the increasing demand for transportation solutions (Mesimäki and Lehtonen, 2023, Kostareli et al., 2021). Micromobility generally refers to a number of lightweight (less than 500 kg) and small human or electric powered vehicles including electric kick scooters (e-scooters), e-bikes, shared bikes, electric skateboards, hover boards, segways and electric mopeds (Abduljabbar et al., 2021, Zarif et al., 2019). E-scooters are a stand-up scooter that comprises of an electric hub motor, two wheels, a central deck and a steering handle. The simplicity and convenience of e-scooters as an urban transportation method in terms of availability, price and lack of parking requirements has led e-scooters to rapidly gain popularity and become a significant means of transport for citizens in cities all over the world (Liew et al., 2020, Bloom et al., 2021).

One benefit of e-scooters as a mode of transport is their ability to significantly reduce the energy consumption of urban transportation when e-scooters are used instead of passenger cars (Weiss et al., 2020). The use of e-scooter can also have a positive impact on urban air quality, noise pollution and congestion by reducing private vehicle usage and facilitate the use of public transport (Orozco-Fontalvo et al., 2023, Abduljabbar et al., 2021, Ferguson and Sanguinetti, 2021). However, in terms of CO2 emissions, the savings compared to the emissions produced by a car are highly dependent on the general conditions of the use cases that are considered (Gebhardt et al., 2022). Studies which have completed a life cycle assessment (LCA) to investigate the environmental impact of shared e-scooters over their life have found that e-scooters tend to have a higher impact than the transportation modes they replace. This is mainly due to the environmental impacts related to material production and manufacture of e-scooters in combination with the short lifespan of shared e-scooters, which is often shortened due to scooter damage associated with misuse and vandalism (Orozco-Fontalvo et al., 2023, Hollingsworth et al., 2019). Abduljabbar et al. (2021) highlighted that targeted policies and strategies to increase the life of scooters are required to reduce the overall environmental impact of this mode of transport.

Another way to reduce the environmental impact of e-scooters is to increase their energy efficiency by reducing the losses associated with the vehicle during use. As many micromobilty vehicles have a limited battery capacity, improvements to the energy consumption will have a positive effect on the vehicle range. Similarly, tyre selection is an important consideration for small off-road vehicles to reduce rolling resistance and increase vehicle range (Petterson and Gooch, 2020). Factors such as comfort, puncture resistance, maintenance, rolling resistance, grip and wear rate should be considered when selecting an appropriate tyre for use on an e-scooter. During operation, the total energy requirements are dependent on a number of factors such as the total frontal area, combined mass of the rider and vehicle, wind speed, slope grade, motor and transmission efficiencies and tyre performance (Hieu and Lim, 2023, Jansson, 2022). Analysis of the power requirements to overcome the aerodynamic resistance of an e-scooter with a rider have been completed using steady-state computational fluid dynamics (CFD) analysis (Acarer et al., 2021). At a velocity of 25 km/hr, the simulation calculated the longitudinal drag force to be 12.5 N for a system with a total mass of 90 kg. However, at low speeds, energy losses from tyre rolling resistance become an important consideration. Although a range of tyres are available to be used on e-scooters, quantitative details of tyre rolling resistance coefficients are lacking from the literature.

Previous work used dynamometer-based coast-down tests to compare the performance of a range of e-scooter tyres to a standard bicycle tyre (Stilwell et al., 2023). The results of this study highlighted the rolling resistance of e-scooter tyre is significantly higher than the rolling resistance of a standard bicycle tyre. The results showed that equivalent non-pneumatic and pneumatic tyres had similar drum coast down distances. In recent years, there have been several developments for non-pneumatic tyres which use elastic polymer supports (often a cellular lattice structure) or fillers to replace pneumatic tyres (Deng et al., 2023). This type of tyre design eliminates the possibility of the tyre going flat due to a puncture and the need to maintain the tyre's air pressure. Research has been completed to compare the design of cellular lattice structures of non-pneumatic tyres that have been designed to mimic a similar sized pneumatic tyre (Kim et al., 2013). Improvements to non-pneumatic tyre technology has led to an interesting trade-off for e-scooter designers and users to consider when selecting an appropriate tyre for their vehicle.

The objective of this study is to present new tyre performance data for e-scooter tyres in terms of rolling resistance. This information is important to determine power requirements and energy efficiency of micromobility devices such as e-scooters. Currently, there is limited information available for the performance of tyres that are typically used on e-scooters. In particular, there is a lack in knowledge about the performance differences of non-pneumatic tyres, which have the potential to offer both environmental and performance advantages over traditional pneumatic tyres (Sardinha et al., 2023). The results from this study have the potential to enable e-scooter designers (and users) to make informed decisions when selecting a tyre for improved energy efficiency in terms of tyre rolling resistance.

2. Methodology

2.1. Tractive effort theory

The tractive force (F_T) of an e-scooter can be determined by considering the general forces outlined in Figure 1. Resistive forces include aerodynamic drag (F_D), rolling resistance (F_{rr1} and F_{rr2}), inertia (F_{ma}), and the incline force (F_α).

Using the forces shown in Figure 1, the tractive effort of an e-scooter on an incline is defined as:

$$F_T = F_D + F_{rr1} + F_{rr2} + F_{ma} + F_\alpha \tag{1}$$

The focus of this study is the rolling resistance force, which is caused by energy lost due to hysteresis of the tyre when it is loaded and unloaded (Kauzlarich and Thacker, 1985). The general relationship between the coefficient of rolling resistance (C_{rr}), normal force (F_N) and rolling resistance force is independent of the velocity of the vehicle as outlined in Equation 2 (LaClair, 2006).

$$C_{rr} = \frac{F_{rr}}{F_N} \tag{2}$$

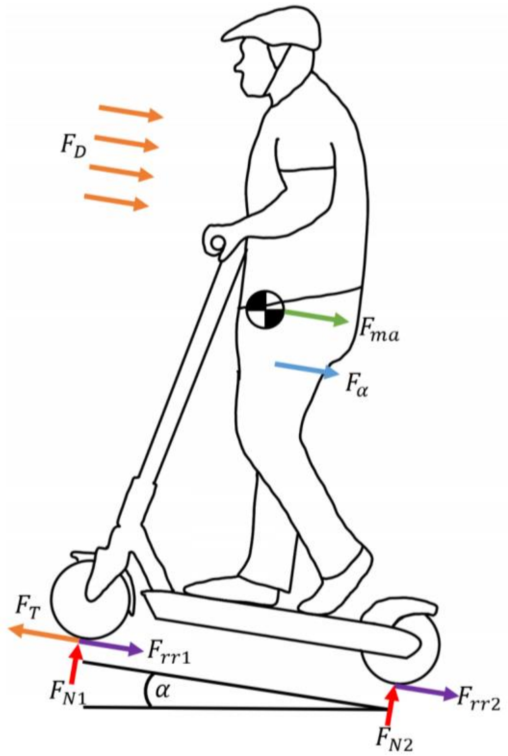

Figure 1. Forces acting on an e-scooter and rider during propulsion on an incline

2.2. Rolling resistance trailer

To determine the rolling resistance force of e-scooter tyres, a rolling resistance trailer was developed, as shown in Figure 2. The trailer was connected to an additional subframe that was added to a Segway Ninebot F Series F40 Kick Scooter via a universal joint. A calibrated 200 kg load cell (YZC-516C) was installed near the universal joint. A total of three axles were made for the trailer to accommodate scooter bearings with inner diameters of 10 mm, 11 mm, and 12 mm. To ensure each tyre had the same normal force during testing, a balance weight was made after the weight of each tyre and axle was measured. A mobile data acquisition unit was used to record the trailer towing force at a sampling rate of 20Hz using LabVIEW. Prior to testing, data was recorded with the load cell in two perpendicular orientations to ensure the orientation of the load cell did not impact the results.

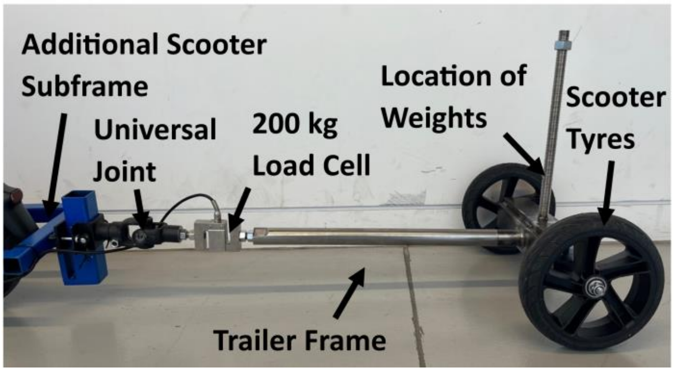

Figure 2. Detail of rolling resistance trailer

Figure 3 shows a simple free-body diagram (FBD) of the forces acting on the rolling resistance trailer during testing. Provided testing is completed a constant low speed, the inertial force (F_I), the aerodynamic drag force (F_D) and resistance force from the wheel bearings (F_B) considered small and can neglected during testing. These assumptions have been made by other similar studies which have investigated the rolling resistance of wheelchair wheels (Vinet et al., 1998, Bascou et al., 2017). As the trailer does not have an enclosure to reduce windage, aerodynamic drag would need to be considered at high speeds. Similarly, e-scooters typically have an inline tyre arrangement compared to the open arrangement of the rolling resistance trailer. To reduce the impact of these differences, all tests were complete at a fast walking speed of 6 km/h. The recorded towing force (F_{tow}) is assumed to be equivalent to the total tyre rolling resistance force.

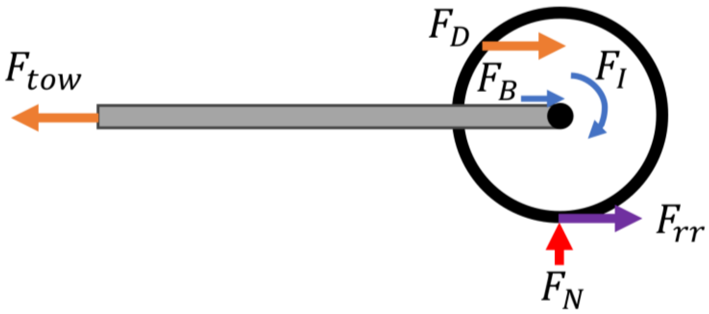

Figure 3. Simple FBD of forces acting on rolling resistance trailer

2.3. Test procedure

Testing was completed indoors on and on a flat painted concrete surface. The indoor test was chosen for initial testing as it was a controlled environment that was level and out of the wind. Before recording data, the masses and balance weight were added to achieve the desired total mass of either 20 kg, 40 kg, 60 kg and 80 kg for each specific test. The start and finish line were marked 50 m apart from each other. This ensured that the procedure for each test was consistent, and that data was recorded over the same points. To improve the accuracy of the recorded data, the test was completed four times in both directions at a constant speed of 6 km/h. The scooter was at the desired speed of 6 km/h when the start line was crossed. All of the tests were completed for each pair of identical tyres before gathering data for the next tyre type.

2.4. Data processing

The recorded data was processed in Microsoft Excel to determine the median towing force for each of the tyres and test scenarios. The recorded data points for each test were graphed as a scatter plot and overlaid on a single plot to enable a visual inspection of the data before a detailed analysis was completed. This enabled obvious outliers to be removed from the analysis. Due to noise in the data caused by the vibration of the trailer, the median towing force was used. The coefficient of rolling resistance was determined for each tyre using the 80 kg data using Equation 2. The calculation of the coefficient of friction assumes that weight is shared equally between each wheel. Equation 2 was also used to estimate the rolling resistance force of each tyre supporting a total system mass of 90 kg to allow comparisons to previously reported drag force values from Acarer et al., (2021).

2.5. Tyre selection

In total, nine e-scooter tyres were tested using the rolling resistance trailer. This selection included a range of pneumatic and solid tyres that would fit commonly available e-scooters from brands such as Segway, Xiaomi and VSETT. All pneumatic tyres were tested at their rated pressure. The key details for each tyre are included in Table 1.

Table 1. Details of tyres used in study

Tyre A		Manufacturer: MMG Size: 216 x 51 mm (8.5 x 2 inch) Type: Solid/airless with honeycomb Load rating / pressure: unknown
Tyre B		Manufacturer: WL Size: 216 x 51 mm (8.5 x 2 inch) Type: Pneumatic Load rating / pressure: 75 kg 340 kPa (50 PSI)
Tyre C		Manufacturer: VSETT Size: 216 x 76 mm (8.5 x 3 inch) Type: Pneumatic Load rating / pressure: 65 kg 310 kPa (45 PSI)
Tyre D		Manufacturer: Yida Size: 200 x 50 mm Type: Solid Load rating: Unknown
Tyre E		Manufacturer: Chuancheng Size: 216 x 51 mm (8.5 x 2 inch) Type: Solid/airless with honeycomb Load rating: Unknown
Tyre F		Manufacturer: Yuan Xing Size: 254 x 54 mm (10 x 2.125 inch) Type: Pneumatic Load rating / pressure: 75 kg 350 kPa (50 PSI)
Tyre G		Manufacturer: KTA Size: 200 x 35 mm Type: Solid/airless with honeycomb Load rating: Unknown
Tyre H		Manufacturer: For You Size: 210 x 35 mm Ply rating: Solid Load rating: Unknown
Tyre I		Manufacturer: TUOVT Size: 255 x 80 mm Type: Pneumatic Load rating / pressure: 85kg 345 kPa (50 PSI)

3. Results

The median towing force for each tyre and load at a speed of 6 km/h are shown in Figure 4.

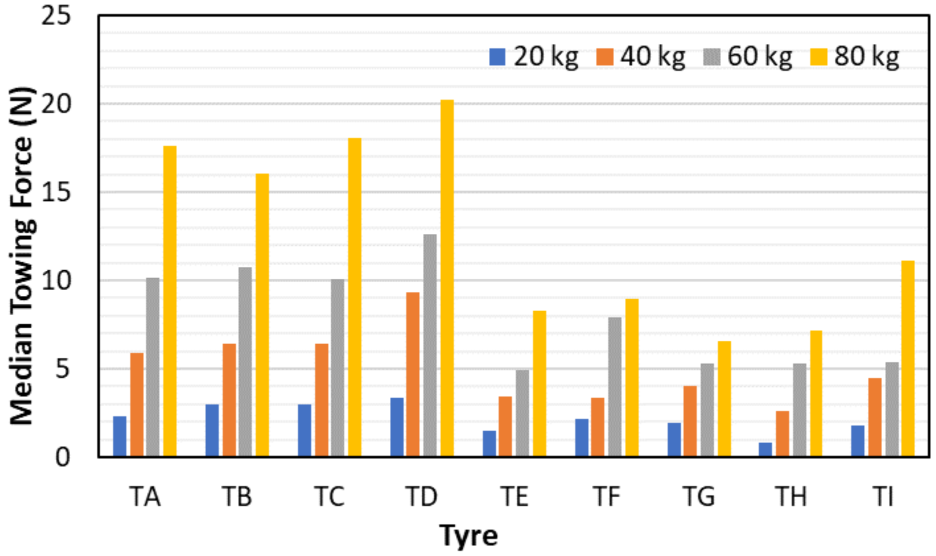

Figure 4. Median towing force for each e-scooter tyre

The values of the coefficient of rolling resistance for a single tyre with a normal force of 392 N are detailed in Table 2.

Table 2. Coefficient of rolling resistance for each tyre on painted concrete at 6 km/h

Tyre	A	B	C	D	E	F	G	H	I
C_{rr}	0.022	0.020	0.023	0.026	0.011	0.011	0.007	0.009	0.014

Using Equation 2 and the coefficients of rolling resistance in Table 2, estimates of the rolling resistance force were calculated for a system (scooter and rider) mass of 90 kg. This calculation assumes that the rolling resistance force is the same for the front and rear tyre on the scooter. The resulting total rolling resistance forces are included in Table 3 to two significant figures.

Table 3. Estimated rolling resistance force for total vehicle mass of 90kg on painted concrete

Tyre	A	B	C	D	E	F	G	H	I
F_{rr} (N)	20	18	20	23	9.4	10	7.4	8.1	13

4. Discussion

The focus of this study was to present new tyre performance data for a range of e-scooters. The novel rolling resistance trailer was a convenient tool to record the towing force for a selection of scooter tyres on painted concrete at 6 km/h for four different normal forces. The data gathered from these tests enabled the coefficient of rolling resistance to be determined for each tyre using the normal force of 392 N. This result provides quantitative insights into the energy efficiency of each tyre in terms of rolling resistance to enable comparisons of losses associated tyre selection to other vehicle losses such as aerodynamic drag.

The median towing force for each tyre in Figure 4 provides a useful comparison of the performance of different tyres as the normal load is increased. As expected, towing force increased with normal force. The trend of these results is supported by results of previous studies (Stilwell et al., 2023, Bergiers et al., 2012) which used coast down tests to evaluate tyre performance. Of the nine tyres, seven had a linear increase in towing force with load, with Tyre F and Tyre I not having a linear relationship between the towing force and the load. These results show that the linear relationship detailed in Equation 2 is a valid approximation for determining the rolling resistance force of each tyre for a range of normal loads at a constant velocity on painted concrete.

It is interesting to compare the performance of similar tyres such as Tyre A, Tyre B and Tyre E, which are the same size of 216 x 51 mm. These tyres have the same dimensions as they are sold as possible tyres for the Xiaomi e-scooter range. Comparisons between the results of Tyre A and Tyre B show that they have a very similar performance, with Tyre A requiring 9.5 % larger towing force for the 80 kg case. The results for Tyre E had a significantly lower towing force than Tyre A and Tyre B. This is an interesting result as it shows that Tyre E requires approximately half of the towing force of Tyre A and Tyre B. The comparison of the results from Tyre A, B and E highlight that tyre selection cannot be made purely off the type of tyre as Tyre A and E are both a solid/airless tyre with a honeycomb structure. Overall, these results suggest that Tyre E, a solid/airless with honeycomb tyre type, is the best tyre to select for users of a Xiaomi e-scooter who wish to reduce the rolling resistance of their e-scooter. However, there will be a trade-off in ride comfort when selecting a tyre with the lowest rolling resistance, as harder tyres will yield a bumpier ride. This is an important consideration for e-scooters that will be used on uneven terrain.

Tyre F is the standard tyre for much of the Segway e-scooter range. Compared to the standard tyre for Xiaomi scooters (Tyre B), the Segway tyre required a similar towing force than that of Tyre E. This difference may be partly explained by Tyre F having a larger diameter, which is associated with lower tyre deformation and thus a decrease in rolling resistance (Kauzlarich and Thacker, 1985). However, as both Tyre B and Tyre F both have a load rating of 75 kg, this difference is a valuable result. Tyre G and H also required a lower towing force than Tyre A, B and E. This result may be caused by reduced tyre deformation for Tyre G and H due to these tyres being narrower (35 mm) than Tyre A, B and E (50 mm) which have a similar diameter. This result makes sense as a narrower tyre has a small contact patch, which leads to reduced rolling resistance. To investigate these differences further, future work could look to incorporate compression testing of each tyre to provide more detail into the load displacement response and energy loss due to material hysteresis. Use of compression testing would also enable the possibility to develop and compare 3D printed non-pneumatic tyre structures to existing tyres that are available on the market.

The results in Table 2 show the coefficient of rolling resistance for each tyre for the case when each tyre had a normal force of 392 N. This normal force is similar to the force that would be expect on the rear tyre of scooter during operation. The results show that the coefficient of rolling resistance varies from 0.007 for Tyre G to 0.026 for Tyre D. The results show that Tyres A-D has approximately double the rolling resistance of Tyres E-I. This result highlights that tyre selection makes a large difference in tyre performance in terms of coefficient of rolling resistance. The results in Table 2 show that the solid narrow tyres, Tyre G and H, had the best performance in terms of rolling resistance. In this study, there are principally three structural configurations of the e-scooter tyres used in this study. These are pneumatic, and non-pneumatic (Solid/airless with honeycomb and solid). In each case, there was a marked difference in the measure rolling resistance value. The results shows that tyres with a similar structure and dimensions can have considerable difference in their efficiency in terms of rolling resistance. The trends of the results do not suggest that one structural configuration is superior in terms of losses due to rolling resistance.

The results in Table 3 give indicative values of the rolling resistance force for each of the tyres that were tested using the rolling resistance trailer. The results show that for a total vehicle mass of 90 kg, the rolling resistance force varies from 8.1 to 23 N. The size of the rolling resistance forces can be benchmarked against the aerodynamic drag forces of a scooter and rider (90 kg) with a frontal area of 0.53 m^2 at 25 km/hr of 12.5 N, as calculated by Acarer et al., (2021). This comparison highlights the importance of tyre selection, as the resulting resistive force can have a similar magnitude to the resistive force from aerodynamic drag at a velocity of 25 km/hr. The variation of the rolling resistance force in 216 x 51 mm tyres (Tyre A, B and E) emphasises this point, with Tyre A and B resulting in 20 N and 18 N of rolling resistance force which is more than twice the rolling resistance force of Tyre E (9.4 N). As Equation 2 is independent of the velocity of the vehicle, at lower velocities, losses from tyre rolling resistance will become more significant as the losses from aerodynamic drag decrease.

One of the limitations of this study is that testing was only completed on a level painted concrete surface. In reality e-scooter will be used on other surfaces such as footpaths, cycle ways and roads. As the roughness of these surfaces will be larger than painted concrete, future work should use the rolling resistance trailer to investigate tyre performance on a variety of surfaces. Road surface roughness has been shown to be an important consideration when investigating the rolling resistance of car tyres (Bergiers et al., 2012). Another limitation of the study was that all data was gathered at a speed of 6 km/h. This speed was chosen to reduce the impact of aerodynamic drag and windage and tyre arrangement on the results. The initial results from this study provide insight into difference in tyre performance at this velocity. If future work wishes to investigate the difference in the losses associated with open tyres compared to tyres that are partially shielded from being in an inline arrangement the rolling resistance trailer would need to be updated. One way to do this would be to incorporate existing scooter features such as mudflaps over the tyres into the rolling resistance trailer. The development of the trailer enables future work to investigate how the rolling resistance of e-scooter tyres changes with parameters such as surface type, test velocity and windage effect the towing force and coefficient of rolling resistance. Using this data, improvements could be made to the general equation for tyre rolling resistance detailed in Equation 2. Overall, the information presented in this study provides useful insight into the e-scooter tyre performance in terms of rolling resistance that was not readily available before this study was completed.

5. Conclusion

This study has presented the development of a rolling resistance trailer to evaluate the performance differences of a variety of e-scooter tyres. This initial study evaluated a selection of nine e-scooter tyres on a painted concrete surface. The results presented in this study provide designers with valuable information about the performance of the tyres in terms of their coefficient of rolling resistance. The comparison of resistive force associated with aerodynamic drag and rolling resistance revealed that they are of similar magnitude for a total system mass of 90 kg. This result highlights the importance of tyre selection to help improve the overall energy efficiency and thus reduce the environmental impact of these micromobility devices. The results corroborate that the required towing force typically increases linearly with normal force. The coefficient of rolling resistance for the tyres in this study varied from 0.007 for Tyre G to 0.26 for Tyre D. The comparison of the 216 x 51 mm tyres (Tyre A, B and E) showed that Tyre E should be selected if the user wishes to reduce the rolling resistance of their device. However, the variation in the results show that simple assumptions based on tyre dimensions and construction methods are not necessarily a good predictor of tyre rolling resistance. This highlights that testing is essential to establish the rolling resistance of e-scooter tyres, especially when designers and users want to consider the environmental impacts of their device. Future work should investigate the performance of these tyres in more detail by incorporating further parameters such as surface type and test velocity.

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