EVALUATION OF E-SCOOTER TYRE PERFORMANCE USING DYNAMOMETER-BASED COAST-DOWN TESTS

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ABSTRACT

E-scooters have become a popular form of personal transport with millions of E-scooters used worldwide. This paper details an initial investigation into the relative differences in rolling resistance for a range of e-scooter tyres. Tyre performance was measured using dynamometer-based coast-down tests to determine the coast-down distance and coefficient of rolling resistance of each tyre. Insights from testing showed that e-scooter tyres had coefficients of rolling resistance that were 3.5 to 6 times the coefficient of rolling resistance of a 700x32C bike tyre. Comparisons between tyres of similar specification showed the tyres with solid inserts had more rolling resistance than a pneumatic tyre at the rated pressure. Comparisons of equivalent airless and pneumatic tyres the rated pressure indicated airless tyres had slightly better performance in terms of coast-down distance. The results also show how a decrease in tyre pressure increases rolling resistance, highlighting the importance of maintaining rated tyre pressure to improve e-scooter efficiency. The results from this study provide useful insights into the performance of tyres that can be used on low-powered vehicles.

Keywords: Decision making, Evaluation, Sustainability, mobility devices

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1 INTRODUCTION

Electric kick scooters (e-scooters) are powered by an electric hub motor, they generally have small wheels (outside diameter of approximately 300mm) and the rider stands on a centre deck during propulsion. The motor controller is generally programmed to require the rider to initiate forward motion with an initial push (kick) before electrical power is supplied to the drive motor. E-scooters are cheaper to manufacture than their big-wheel counterparts that employ a more traditional motorcycle geometry, i.e., with a seat. Thousands of e-scooters have been introduced into large cities by ride-share businesses such as Lime, Flamingo, and Beam (Irfan, 2018; Kobayashi et al. 2019; Lime, 2019; Glenn et al. 2020). Subsequently e-scooters are becoming an increasingly popular form of personal transport.

The introduction of e-scooters has, however, proven problematic due to safety concerns. This has resulted in a ban on these devices on footpaths in major cities e.g. West Hollywood (Buckley 2019; Castro 2019). Whilst some cities have attempted to restrict the use of e-scooters, the popularity of these devices remains strong. Consequently, the e-scooter market is growing rapidly. A recent study predicts the market to grow at a compound annual growth rate of 30.3% from 2021 to 2028 to reach \$677.2 billion by 2028 (Wood, 2021).

E-scooters provide a micro mobility solution to replace private vehicle when they are used in conjunction with public transit for first and last-mile travel (Ferguson and Sanguinetti, 2021). Supporters of e-scooters consider the mode of transport to be an environmentally friendly form of transport compared to internal combustion engine vehicles (Gebhardt et al. 2022). However, to accurately determine the environmental effects the full life cycle of the e-scooter must be considered. E-scooters have been found to emit 2.5 to 5.6 grams of CO_2 per kilometre when factoring in average electricity emissions from charging (Chester Energy & Policy, 2021). However, due to the short lifetime of ride-share scooters, a full life cycle analysis suggests emissions are as great as 131 grams per kilometre (Moreau et al. 2020). While this has been shown to be a significant reduction in CO_2 emissions compared to internal combustion engine vehicles (ICEV) in Germany (Gebhardt et al. 2022). Multiple studies suggest that depending on the use case, e-scooters may have a more negative environmental impact than the ICEV transportation methods they are replacing (Hollingsworth 2019; Moreau et al. 2020). Improvements to the energy efficiency of e-scooters will enable reductions in their overall environmental impact.

Legislation is evolving in many countries to control the use of e-scooters. For example, in New Zealand, e-scooters with a power output of less than 300W are classified as "Low-powered vehicles that do not require registration or a drivers licence" (New Zealand Gazette, 2018). However, scooters are sold with motors that have a power output of more than 10 times the maximum allowable under current legislation. Furthermore, the controllers on compliant scooters can be easily modified to exceed 300W. From an enforcement perspective, the power output cannot be easily determined from a simple curbside inspection. If parameters such as tyre rolling resistance are known, then the power output can be measured using a simple dynamometer. Rolling resistance is also a significant parameter to evaluate the efficiency of many low-powered vehicles, not just e-scooters. Decreases in rolling resistance is important for obtaining a good vehicle range, reducing energy consumption and thus the overall environmental impact of the vehicle.

Energy losses due to the rolling resistance of tyres is an important consideration for many vehicles. Tyre selection is particularly important at lower speeds, where the energy losses from rolling resistance make up a larger percentage of the total energy lost, as losses from aerodynamic drag decrease at lower speeds (Petterson and Gooch, 2020). Several studies have investigated the rolling resistance of tyres for personal mobility devices. For example, (Gordon et al. 1989; Sawatzky et al. 2004; Kwarciak et al. 2009) studied the rolling resistance of manual wheelchair tyres, with the finding that airless wheels have greater rolling resistance than pneumatic wheels for increasing loads. Studies have shown that rolling resistance is related to tyre pressure, with results suggesting a decrease in tyre pressure leads to an increase in rolling resistance (Sawatzky et al. 2004; Ott et al. 2022). The energy expenditure of manual wheelchair users was found to increase as the tyre

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pressure decreased, indicating a decrease in rolling efficiency (Pavlidou et al. 2015). Rolling resistance is dependent on the elastic deformation of the tyre, with increased deformation leading to higher rolling resistance (Kauzlarich and Thacker, 1985). Similarly, with increased loads and lower tyre pressures, tyre deformation and surface contact of the tyre increases, thus increasing rolling resistance. A study investigating the differences in the rolling resistance of polyurethane wheelchair tyres compared to solid rubber tyres found that polyurethane tyres had a lower rolling resistance (Kauzlarich and Thacker, 1985). While pneumatic tyres appear to offer rolling resistance and comfort advantages for wheelchairs, airless tyres are a widely the chosen tyre type for e-scooters. Airless tyres require less maintenance, do not puncture, and are replaced less often. Tyre diameter is known to impact rolling resistance, with rolling resistance increasing as the diameter decreases.

Currently, there is a gap in the literature for information detailing the performance and rolling resistance of tyres that are typically used on low powered vehicles such as e-scooters. The intention of this initial study is to investigate relative differences in coast-down distance and rolling resistance for a range of e-scooter tyres and compare them to a typical bicycle tyre. Insights from testing a range of scooter tyres will enable e-scooter users to make better choices about the tyres they use on their e-scooter in terms of energy efficiency. As e-scooters have limited battery capacity, it is important to improve the efficiency of these vehicles so that the energy stored in the battery is used as efficiently as possible. Overall improvements to the energy efficiency of e-scooters can be made through reductions in tyre rolling resistance.

2 THEORY

2.1 Notation

A description of the notation used throughout the paper is included in Table 1.

Table 1: Notation

Symbol	Description	Units
F_T	Tractive Force (drive force at tyre contact patch)	[N]
F_{rr1}, F_{rr2}	Rolling Resistance of the front/rear wheels	[N]
F_{ma}	Inertia force	[N]
F_D	Drag force	[N]
F_α	Ascent resistance force	[N]
RN_1, RN_2	Normal reaction force at the front/rear wheels	[N]
θ	Incline angle	[Radians]
d	Linear distance	[m]
v	Linear velocity	[m/s]
t	Time	[s]
T_{BW}, T_{BD}	Rolling resistance torque for the wheel/drum	[Nm]
r_{w}, r_D	Radius of the wheel/drum	[m]
I_W, I_D	Rotational inertia of the wheel/drum	[kg m^2]
$\ddot{\theta}_W, \ddot{\theta}_D$	Angular acceleration of the wheel/drum	[rad/ s^2]
C_{rr}	Coefficient of rolling resistance	

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2.2 Force analysis

The tractive force, F_T, can be derived by considering the forces acting on a scooter and rider, Figure 1.

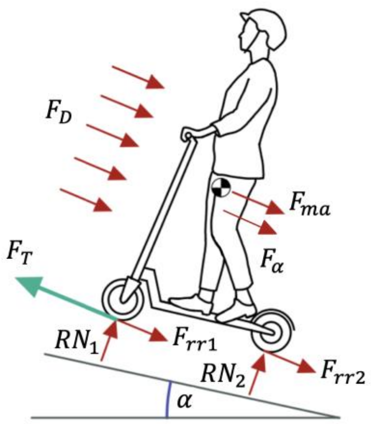
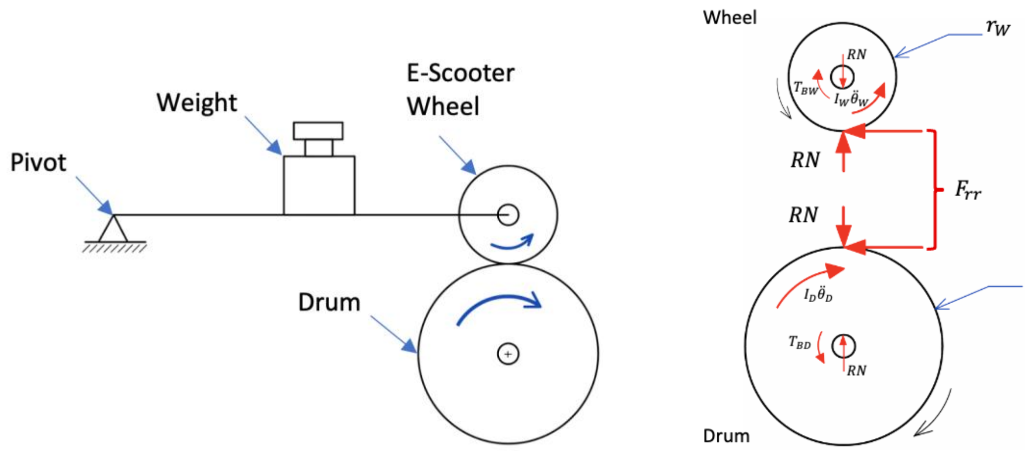


Figure 1. Forces acting on an e-scooter and rider during propulsion

From Figure 1, the tractive force can be derived as:

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

The rolling resistance force, $F_{rr1} + F_{rr2}$ in Equation 1, can be determined by conducting a coast-down test on a drum of known inertia, as shown schematically in Figure 2(a). For the coast-down test F_T, F_D, F_{ma} and F_α equate to zero in Equation 1.



(a) Schematic diagram of proposed test rig *(b) Free body diagrams of wheel and drum*

Figure 2. Theoretical model for coast-down tests

The forces on the wheel and drum for the coast-down test are shown in Figure 2b. Because the drum has a much higher mass moment of inertia, higher windage and higher bearing friction losses, T_{BW} and $I_W\ddot{\theta}_W$ are considered to be small and the acceleration of the drum can be simplified to:

$$\ddot{\theta}_D = \frac{\mathrm{T}_{BD} + F_{rr} r_D}{I_D} \tag{2}$$

For the particular case where the drum is not in contact with the wheel, the resistive torque acting on the drum (from bearing friction and windage) can be calculated as:

$$\ddot{\theta}_D I_D = T_{BD} \tag{3}$$

Once T_{BD} has been established (i.e. from coast-down test with an unloaded drum), F_{rr} can be calculated by rearranging Equation 2, namely:

$$F_{rr} = \frac{\ddot{\theta}_D I_D - \mathrm{T}_{BD}}{r_D} \tag{4}$$

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The coefficient of rolling resistance can be calculated using the well-known relationship detailed in Equation 5 (LaClair, 2006).

$$C_{rr} = \frac{F_{rr}}{\mathrm{RN}} \tag{5}$$

3 METHOD

3.1 Test apparatus description

A coast-down test rig was constructed as shown in Figure 3. The coast-down test rig comprises of a steel drum measuring 255mm in diameter and with a rotational inertia of 0.7132 kgm^2. The dynamometer drum is coupled to a US Digital S1-1000 rotary encoder with a resolution of 1000 counts per revolution. The encoder is connected to a desktop computer. The test wheel is mounted on a steel frame attached to a bearing support. The steel frame has a locating bolt and steel weights can be added to produce the desired normal force between the wheel and the drum. Using the test rig, coast-down tests were completed to compare the rolling resistance of a number of different e-scooter wheels under controlled conditions.

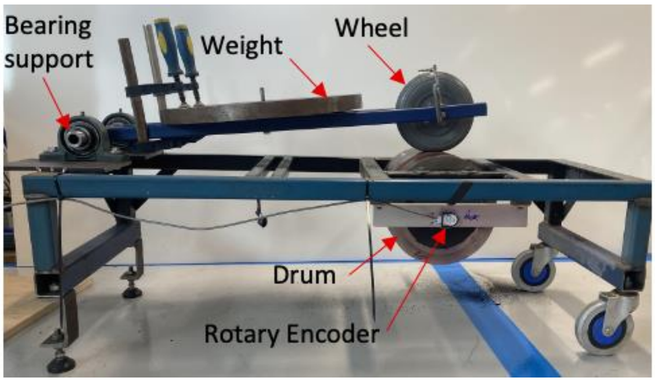

Figure 3: Side view of the apparatus used for coast-down testing

3.2 Test procedure

Starting with the apparatus shown in Figure 3, the drum speed was set to an angular speed that corresponded to a linear scooter speed of approximately 30km/hr. The drive was then decoupled and inertia drum allowed to decelerate to a rest position. The deceleration of the drum was firstly measured without contact with a wheel to establish the resistive torque, T_{BD} , of the drum. For the wheel tests, each wheel was gently lowered onto the drum while rotating at approximately 30km/hr and the coast-down acceleration data captured. The coast-down tests were repeated using three weight variations corresponding to a normal force, RN, of 218N, 365N and 550N. The variety of normal forces are representative of the normal forces that e-scooter users of different sizes would apply to e-scooter tyres when riding. Three normal forces were selected to enable trends of coast down distance to be investigated in terms of applied normal force. The test was repeated three times for each wheel and each load case.

3.3 Data transformations

The encoder data was imported into LabVIEW where the encoder values were sampled at a rate of 10Hz. The data was then exported into MS Excel to determine the coast-down distance and coefficient of rolling resistance. The coast-down distance for each test was measured from the point where the average linear speed of the drum over the past second was 25km/hr. To determine the coefficient of rolling resistance for each wheel, the angular deceleration of the drum at 25km/hr was used. The resistive torque acting on the drum due to windage and bearing losses was calculated using Equation 3. The rolling resistance force and coefficient was then calculated using Equation 4 and 5.

3.4 Tyres selected

Seven e-scooter tyres, Table 1, were selected for comparison of rolling resistance characteristics. All tyres were tested at their rated pressure except for Tyre B which was tested at two pressures to

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investigate the impact pressure has on tyre performance. Please note that the tyre sizes in Table 1 refer to the indicated tyre size specified by the manufacturer.

Table 1. Details of selected e-scooter tyres used in coast-down tests

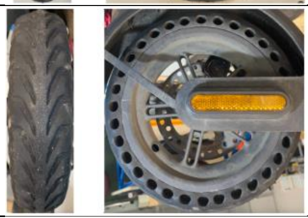
Tyre A		Manufacturer: Cheng Shin Rubber Size: 200 x 50 (inch) Ply rating: 4 P.R. Load rating/pressure: Solid insert
Tyre B		Manufacturer: Cheng Shin Rubber Size: 200 x 50 (mm) Ply rating: 4 P.R. Load rating / pressure: 35 PSI
Tyre C		Manufacturer: unknown Size: 200 x 50 (mm) Ply rating: Unknown Load rating / pressure: 36 PSI
Tyre D		Manufacturer: Yida Size: 8.5 x 2 (inch) Ply rating: Unknown Load rating / pressure: 75kg 340kPa (50 PSI)
Tyre E		Manufacturer: Dubull Size: 8.5 x 2 (inch) Ply rating: Solid/airless with honeycomb Load rating / pressure: unknown
Tyre F		Manufacturer: Cheng Shin Rubber Size: 90mm/65-6.5" Ply rating: 4 P.R. Load rating: 189kg at 350kPa
Tyre G		Manufacturer: Tupda Size: 200 x 85 (mm) Ply rating: Solid Load rating: Unknown

Figure 4 shows a Panaracer Gravel King (700 x 32C) bike tyre on the drum of the test apparatus. Testing of the bike tyre was completed at a pressure 60psi using a load of 550N to enable comparisons between the coast-down distances and coefficients of rolling resistance to be made between a typical bike tyre and each scooter tyre.

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Figure 4: Panaracer Gravel King bike tyre on drum

4 RESULTS

Figure 5 shows the mean coast-down distances of each tyre for the three loads that were tested. The error bars represent one standard deviation of uncertainty. The average linear speed to calculate the coast-down distance and coefficient of rolling resistance for all tests was 25.03±0.09 km/hr (mean ± standard deviation).

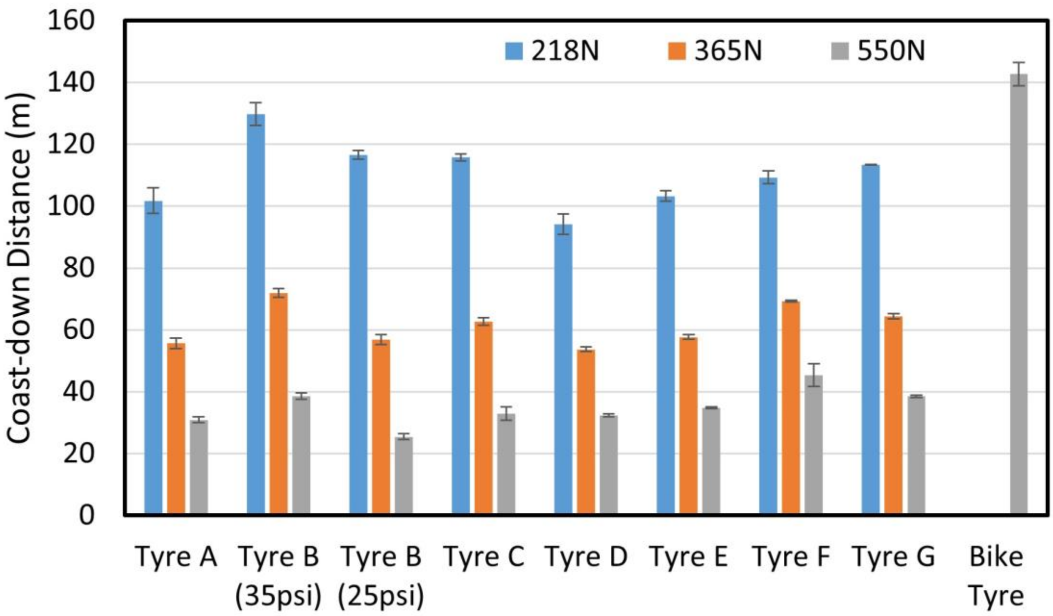

Figure 5: Mean coast-down distances from 25km/hr for each tyre

The coefficient of rolling resistance was calculated for each tyre at a linear speed of 25km/hr. To determine the relative differences in coefficients of rolling resistance, the percentage difference of the coefficient of rolling resistance from the Panaracer bike tyre was used. The results of this are displayed in Figure 6. As the standard deviation was small, error bars have not been included.

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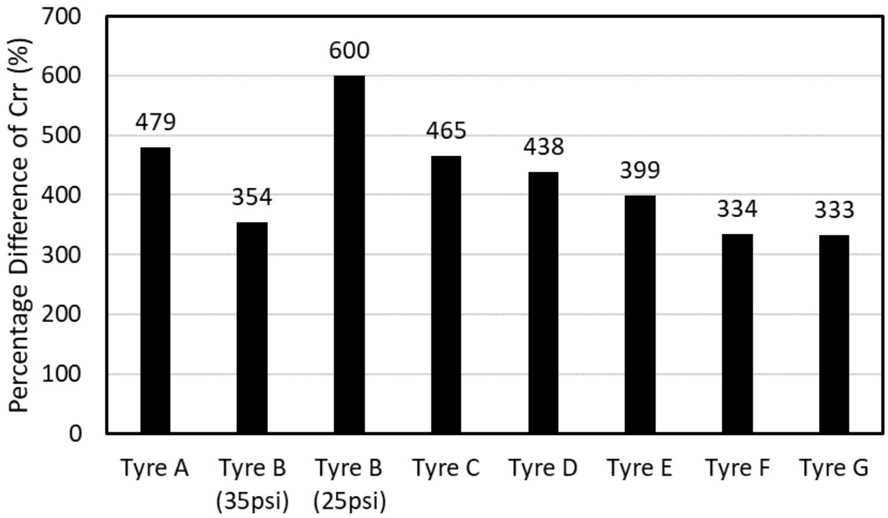

Figure 6: Percentage difference of rolling resistance compared to a Panaracer bike tyre

5 DISCUSSION

The coast-down test method was used to determine the differences in tyre performance of seven e-scooter tyres. Overall the results in Figure 5 show that the coast-down distance is considerably lower for scooter tyres compared with the bike tyre. The results in Figure 5 show that all e-scooter tyres experienced a decrease in coast-down distance with an increase in normal force. When the normal force acting on the tyre was 550N, all scooter tyres had significantly lower coast-down distances and larger coefficients of rolling resistance This result corroborates with results from studies investigating the rolling resistance of wheelchair tyres using coast-down tests (Sawatzky et al. 2004; Kwarciak et al. 2009). This result can be explained by the fact that under higher load, deformation and thus rolling resistance increases. Interestingly, the largest tyre, Tyre F, had the best performance of the scooter tyres with a load of 550N. This result can be explained by two geometrical parameters related to the deformation of the tyre. As Tyre F has a larger tread area, the normal force is spread over a larger area, resulting is less deformation. Tyre F had the largest tyre diameter compared to the other tyres in the study. Increases in tyre diameter have been shown to reduce rolling resistance.

Tyre A and B have the same dimensions and tread pattern. The results from Tyre A (solid rubber insert) and Tyre B (pneumatic tube) provide interesting insights into the impact solid rubber inserts and tyre pressure have on tyre performance. The coast-down distance for each tyre with the 218N load in Figure 5 show that the rubber inserts have a lower coast-down distance (102m) than the results of the pneumatic tyres at both tyre pressures (117m and 130m). Studies using wheelchair tyres had similar results, with pneumatic tyres have lower rolling resistance than their solid equivalents (Gordon et al. 1989; Sawatzky et al. 2004; Kwarciak et al. 2009). This trend holds for all coast down distances when comparing Tyre A to Tyre B at the rated pressure of 35psi. However, comparisons between Tyre A and Tyre B at 25psi show that they have a similar performance of 56m and 57m with a load of 365N. At the highest load of 550N the tyre with solid inserts outperforms the coast-down distance of pneumatic tyre. This result shows that the deformation of the pneumatic tyre at low pressures has a significant impact on the rolling resistance of the tyre at high loads. This observation is highlighted in Figure 6, with the percentage difference of Tyre B at 25psi being nearly twice of Tyre B at the rated pressure of 35psi. This result makes sense, as under heavier loads, the deformation and thus the surface area contacting the drum increase resulting in more rolling resistance. The result of tyre pressure agrees with previous studies that show a decrease in tyre pressure results in increased in rolling resistance (Sawatzky et al. 2004; Ott et al. 2022).
This result highlights the importance of scooter users maintaining the rated tyre pressure to reduce rolling resistance and increase efficiency.

When comparing the results of the Tyre D (8.5 x 2 pneumatic) and Tyre E (8.5 x 2 solid/airless with honeycomb) the performance of the airless tyre was found to be slightly better than the performance of the pneumatic tyre, with larger coast-down distance for all loads and therefore a lower coefficient of

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rolling resistance. This result is interesting, as other studies have found that airless tyres have larger rolling resistances (Gordon et al. 1989; Sawatzky et al. 2004; Kwarciak et al. 2009). As airless tyres cannot be punctured, they are an attractive option as they require less maintenance. Contrastingly, pneumatic tyres often provide a smoother ride due to their ability to absorb shock on uneven terrain. This result suggests that in terms of tyre performance and maintenance, airless tyres are a good option for general purposes. For high-performance applications and it is probably better to have a pneumatic tyre set to the correct pressure.

Figure 6 shows that the performance of scooter tyres are significantly worse than the bike tyre in terms of the coefficient of rolling resistance. The results in Figure 6 show that the coefficient of rolling resistance of the scooter tyres were 3.5 to 6 times higher than the bike tyre. It should be noted that the bike tyre has a higher rated pressure (60psi), larger diameter and smaller section height. Rolling resistance has been shown to increase with decreased tyre diameter. The increased section height and lower pressure of the scooter tyres compared to the bike tyre also helps to explain this difference in the coefficient of rolling resistance. Tyres at higher pressures experience less deformation for a given load. As section height of the tyre increase, the amount of possible tyre deformation also increases. This increased deformation lead to larger energy losses in terms of rolling resistance.

The methodology used in this paper has some limitations. As the mass moment of inertia and windage of the wheels are assumed to be small compared to the drum, this introduces some error into the results. However, as the focus of this paper was to complete an initial analysis of a range of scooter tyres and compare the relative differences in coast-down distance and coefficient of rolling resistance compared to a typical bicycle tyre. The results from this study show that all of the scooter tyres that were tested had significantly higher coefficients of rolling resistance, and thus high energy losses due to rolling resistance compared to a bicycle tyre. Improved tyre selection will enable improvements to the energy efficiency of e-scooters. The results in this paper are useful to provide insights into the performance of a range of e-scooter tyres. Our study used a dynamometer drum to investigate the relative differences in performance of seven e-scooter tyres and one bike tyre. Future work aims to use an updated experimental design so that additional tyres can be used to provide further insight into the effects of different materials, pressures, tread design and surfaces. This will be completed using a refined selection of tyres along with the control of variables such as tyre pressure, tyre materials, tread style and tyre geometry. It is hoped that such refinements may provide further insight into the influence of these parameters on rolling resistance.

6 CONCLUSION

The results from this initial analysis of scooter tyre performance has enabled insights into differences in the coast down distance of a range of scooter tyres. The normalised rolling resistance values compared to a bicycle tyre show that all of the scooter tyres included in this study had significantly higher coefficients of rolling resistance, and thus high energy losses due to rolling resistance. Comparisons between similar tyres showed solid insert had a larger rolling resistance compared to a pneumatic tyre inflated to the rated pressure. However, the rolling resistance of the pneumatic tyres increased when the inflation pressure is reduced, highlighting the importance of maintaining the rated pressure to minimise tyre deformation and thus reduce rolling resistance. The comparison of airless and pneumatic tyres showed that their airless tyres performed better than their pneumatic equivalent (at the manufacturers rated pressure). This result highlights the importance of tyre selection to reduce overall energy losses associated with using low-powered vehicles such as e-scooters as a form of transport.

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