Accelerated wear testing shows that thermoplastic bushings could be a cost-effective and durable alternative to traditional bearings for wheelchair caster use

Jack J Fried¹,², Jon L Pearlman¹,² and Anand A Mhatre²,³

Abstract

Introduction: Wheelchair caster bearings often suffer high-risk failures that lead to adverse consequences such as user injuries, suggesting that design improvements are necessary. This study aimed to compare thermoplastic bushings to standard roller bearings for potential improvements in durability and cost-effectiveness.

Methods: The durability and cost-effectiveness of two thermoplastic bushing models and two metallic ball-bearing models were tested using a standard lab-based accelerated wear testing protocol. Bushings and bearings were installed on a standard 8” caster, and four samples per model underwent testing (16 total samples).

Results: All failures were experienced by the stem rolling element. The thermoplastic bushings experienced higher mean durability than the standard ball-bearings. There were significant differences in durability across the tested models, $F(3,12) = 3.88, p = 0.04$. The durability of thermoplastic bushing #2 was higher than the standard type ZZ shielded deep groove ball bearings, $p < 0.05$. There were significant differences in cost-effectiveness across the tested models, $F(3,12) = 7.64, p = 0.004$. The cost-effectiveness of both thermoplastic bushings were significantly higher compared to type 2RS sealed deep groove bearings, $p < 0.05$.

Conclusions: The use of thermoplastic bushings can lower product cost and potentially reduce caster failures in the community that are associated with adverse consequences including user injuries.

Keywords
Caster, cost-effectiveness, design, durability, quality, standards, wheelchair

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80 years or older will triple. While wheelchairs play a significant role in the lives of people with disabilities and the aging population, they are known to breakdown frequently. More than 50% of wheelchairs suffer a breakdown every 6 months in resourced settings and every 3 months in the adverse environments typically observed in rural areas of resourced settings and low- and middle-income countries (LMICs). One-third of these breakdowns result in consequences for wheelchair users including injuries, being stranded in the street, or loss of access to work and/or school. Without a functional wheelchair, the user may have to stay in the home in a regular chair or bed which makes them vulnerable to development of pressure injuries and rehospitalization as found in a recent study. Wheelchair breakdown can also lead to total abandonment of their wheelchair and isolation from social circles and mental health resources. The downward spiral of social and health outcomes following breakdowns can negatively impact the user’s quality of life and mental health while increasing the public health burden.

Of all failures reported for wheelchair parts, nearly one-third are front wheel or caster failures. Recent wheelchair failure data collection studies have found that caster stem bearings fracture within 2 years of use in adverse environments as well as in resourced settings. Models like Matching Person and Technology highlights that a lack of consideration for an individual’s needs can lead to improper use, total abandonment, or injury. These premature and frequent failures of wheelchair caster bearings can be attributed to a lack of consideration of individuals’ specific environments during product design, testing, and assessment. Cost-reduction engineering practices in the wheelchair industry may have led to design and selection of low-cost, substandard caster parts that experience different failure modes including seized bearings, damaged bolts, fractured wheels and forks and worn-out tires and fasteners. Stem and axle bearings are subjected to rapid fatigue and stress as wheelchairs are exposed to corrosion, shocks, high temperatures, and dirt especially during use in adverse environments. Bearing fractures can lead to a cascade of high-risk failures with caster stems, bolts, and forks as they experience stresses higher than the ultimate tensile strength of their materials. This can cause the stem to fracture, the wheelchair to tip, and the user to sustain injuries.

Motivated by the high rates of caster failures in the community, the standards working group of the International Society of Wheelchair Professionals (ISWP) and a team at the University of Pittsburgh Department of Rehabilitation Technology led the development of the ISO 7176-32 Caster Durability Testing Protocol. Exposing casters to the factors of shock, abrasion, and corrosion through this protocol show that bearings are inadequate in their quality and design. They fail on the standard test that requires casters to complete two-years’ worth of equivalent test cycles. Such congruent findings from the community and laboratory-based standard testing studies motivated the authors to investigate the bearing designs that may prove to be more effective in the environments they are used.

The development of more dependable, low-cost stem and axle bearings for wheelchair casters used in adverse environments is crucial to reduce bearing failures and ensure user safety. Thermoplastic bushings can be less susceptible to corrosion and wear during operation and provide a possible design improvement for casters which motivated this study. More specifically, we sought to compare the durability of traditional caster bearings with thermoplastic bushings and proposed the two hypotheses:

1. Durability:
   a. Null hypothesis ($H_0$): Casters with thermoplastic bushings would not have significantly higher durability than those with traditional ball bearings based on a standardized lab-based test.
   b. Alternative hypothesis ($H_a$): Casters with thermoplastic bushings would have significantly higher durability than those with traditional ball bearings based on a standardized lab-based test.

2. Cost Effectiveness:
   a. Null hypothesis ($H_0$): Thermoplastic bushings are not significantly more cost-effective, based on their cost-per-cycle, than traditional ball bearings used on casters.
   b. Alternative hypothesis ($H_a$): Thermoplastic bushings are significantly more cost-effective, based on their cost-per-cycle, than traditional ball bearings used on casters.

**Methods**

**Selection of testing materials**

One caster model was selected to be tested with each bearing and bushing model to control and isolate the durability of the bearings and bushings. A standard 8” soft urethane caster model seen in Figure 1, widely used on multiple wheelchair models provided around the world, was chosen for the testing study.

Four models – two bearing models and two bushing models were selected for comparative testing as shown in Table 1. The standard type ZZ caster ball-bearings selected are the bearings supplied by the caster manufacturer. Type ZZ double shielded bearings have unremovable, no-contact metal shields in the outer ring to protect the rolling elements inside and represent a commonly selected low-cost bearing for wheelchair casters in LMICs. The balls of the bearings are covered but not completely sealed, so debris and humidity still infiltrate the bearing. Type 2RS double-sealed
chrome steel deep-groove radial bearings were also selected so that the full range of bearing durability could be established in the study for bushing comparison. These type 2RS bearings have a nitrile rubber seal that protects the balls of the bearings from the environment.

The bushing materials were selected based on recommendations from wheelchair experts from the ISWP Standards Working Group. Both bushing materials in Table 1 were selected because of their self-lubrication, lower wear rate, low coefficient of friction, resistance to corrosion and chemicals, large range of operating temperatures, and low humidity absorption. The two manufacturers chosen provided samples of the materials that were machined to the bearing dimensions with press-fit tolerances recommended by the manufacturers.

Sixteen total samples underwent the ISO testing protocol, with 4 different bearing/bushing models for the stem and axle as shown in Table 1. Unit cost for the bushings were calculated using web calculators from the respective manufacturers and the standard dimensions of the bushings. Dimensions for each stem and axle bearing/bushing are shown in Table 2. An ABEC tolerance rating of 5 or higher (Outer Diameter/Inner Diameter: +0.0000/−0.0002 in., Width: +0.0000/−0.0010 in.) was required for each bearing and bushing chosen. Both bearings had ABEC 5 ratings, and the bushings were machined and verified to be within ABEC 5 tolerances. These tolerances also cover ABEC 7 tolerances as well.

**ISO 7176-32 caster durability testing**

The ISO Caster Durability Testing Protocol, ISO 7176-32, includes corrosion testing in a salt fog chamber (as per ASTM B117) that exposes the casters to corrosive fog at temperatures of over 35°C and durability testing on ISWP

![Figure 1. Standard caster.](image)

**Table 1. Bearing/bushing models tested in the study.**

| Bearing/bushing model                             | Stem bearing/bushing | Unit cost | Axle bearing/bushing | Unit cost |
|--------------------------------------------------|----------------------|-----------|----------------------|-----------|
| Standard type ZZ double-shield deep groove caster ball-bearings | Model | $0.99 | Model | $0.99 |
| Type 2RS Chrome Steel Double-sealed deep groove caster ball-bearings | | $11.85 | | $8.88 |
| Thermoplastic bushing #1 | | $1.15* | | $1.15* |
| Thermoplastic bushing #2 | | $1.15 | | $1.15 |

*The manufacturer did not disclose the unit cost, so it was assumed to be the same as bushing #2 for cost analysis.*
Chakra as seen in Figure 2. Durability testing includes exposure to shock and abrasion and simulates 2 years of equivalent use per testing cycle. Table 3 details the caster testing protocol. Figures 3 and 4 show the corrosion and durability testing conducted with the caster models in this study. The testing was repeated but limited to an exposure equivalent to 6 years of wheelchair use as most of these bearings fail within this time period in adverse environments and need replacement according to previous work. Wheelchairs are usually replaced in a 5-year time period, so testing for 6 equivalent years was the closest to this timeframe while also completing the full testing protocol. It also would show if any of the bushings or bearings lasted for 5 years or more on average. This would indicate the rolling element could last the entire lifetime of the wheelchair. Testing of a sample was discontinued following a bearing/bushing failure or caster failure. Durability

**Table 2.** Dimensions for the stem and axle used for each bearing/bushing type.

| Bearing/bushing type | Flange thickness (in.) | Outer diameter (in.) | Inner diameter (in.) | Width (in.) | Dynamic load capacity (lbs) | Static load capacity (lbs) |
|----------------------|------------------------|----------------------|----------------------|-------------|-----------------------------|---------------------------|
| Stem                 | 0.062                  | 1.125                | 0.50                 | 0.3125      | 884                         | 501                       |
| Axle                 | N/A                    | 0.866                | 0.315                | 0.276       | 750                         | 315                       |

**Figure 2.** ISWP chakra (left) and salt-fog chamber (right).

**Table 3.** ISWP caster testing protocol simulating 2 years of outdoor use.

| Exposure                        | Testing cycles | Equivalent test cycles | Slat height | Number of slats | Speed |
|---------------------------------|----------------|------------------------|-------------|-----------------|-------|
| Wet corrosion                   | 200 h          | 400 h of corrosion testing | NA         | NA              | NA    |
| Dry corrosion                   | 200 h          | NA                     | NA          | NA              | NA    |
| Low magnitude shocks and abrasion | 9000 turntable rotations | 18000 equivalent test cycles | 0.5 in     | n = 2           | 1 m/s |
| High magnitude shocks and abrasion | 3000 turntable rotations | NA                     | 0.75 in     | n = 1           | 1 m/s |

**Figure 3.** ISWP corrosion testing.
is determined by the number of shock testing cycles completed in the ISO 7176-32 Caster Durability Testing Protocol. Cost-effectiveness is calculated as a test cycles-per-dollar ratio. The cost included the combined cost of two stem and two axle bearings/bushings.

**Data analysis**

One-way ANOVA statistical analysis was performed using IBM SPSS Statistics 28 to test the hypotheses. If significance was found, a Tukey post-hoc test was used to reveal where the significance lay within the bearing and bushing models. A significance level of $\alpha = 0.05$ was used.

**Results**

Failures encountered during testing are shown in Table 4 below. Failure modes are shown in Figure 5. The axle bearings and bushings for all samples did not encounter any failure. Stem bearings as opposed to axle bearings are subjected to thrust forces and since, both are of similar quality, the stem bearings typically experience failures during field use and lab-based standards testing. Most bushing samples either remained intact or exhibited a stem failure, with the stem bushings usually breaking at the flange. The flange intersection with the bearing cross-section experiences the highest stress and hence, it is common to experience flange failures during field use and standards testing. Cycles to failure and cycles/dollar of the bearings and bushings are shown in Figure 6.

There was a significant difference in durability across the models, $F(3,12) = 3.88, p = 0.04$. The Tukey post-hoc test showed that the durability of thermoplastic bushing #2 was significantly higher than the standard double-shield ball bearing, $p < 0.05$. There was a significant difference in cost-effectiveness across the models, $F(3,12) = 7.64, p = 0.004$.

The Tukey post-hoc test showed that the cost-effectiveness of thermoplastic bushing #1 and #2 respectively was significantly higher than the double-sealed bearings, $p < 0.05$.

**Discussion**

Results from the comparative testing study demonstrate that thermoplastic bushings are viable for use in wheelchairs as they are significantly durable and cost-effective compared to metallic bearings. Though this study focuses on adverse environments, a rolling element that is more durable and cost-effective can benefit users in any environment. Ideal casters for wheelchair application should have a high load bearing capacity and tight tolerances to absorb road shocks and impacts as well as material properties that resist corrosion. Thermoplastics are often superior to metals in their corrosion resistance because they are not as easily oxidized due to their strong halogen bonds. Hence, these materials were chosen for investigation.

Both thermoplastic bushings lasted beyond the minimum quality requirement of the ISO/DIS 7176-32. As per the study results, samples from both models survived twice the number of equivalent test cycles listed in the protocol with one exception. One sample of thermoplastic bushing #1 failed prematurely in testing at 2455 cycles, leading to lower durability on average and higher range of results for those bushings. It is difficult to pinpoint why this one-off failure occurred. This could be due to the manufacturing variability in the bushing material or tolerancing of the flange section of the bushing. Such one-off failures are common in product testing and hence, testing of four samples was considered. Other than this, thermoplastic bushing #2 demonstrated the least variation in durability or number of test cycles completed, indicating the consistency of their potential durability and reliability in the community.
Table 4. Stem bearing and stem bushing failure photos.

| Bearing/bushing model                                                                 | Failure photos |
|-------------------------------------------------------------------------------------|----------------|
| Standard type ZZ double-shield deep groove caster ball-bearings                      | ![Image](image1) |
| Type 2RS chrome steel double-sealed deep groove caster ball-bearings                 | ![Image](image2) |
| Thermoplastic bushing #1                                                            | ![Image](image3) |
| Thermoplastic bushing #2                                                            | ![Image](image4) |
On average, the double-shielded caster ball-bearings failed to meet the minimum quality requirement of the ISO/DIS 7176-32 which is two-years of simulated outdoor use. These bearings are low-cost bearings that have been shown in previous literature to fail prematurely and are overall unsuitable for adverse environments. The double-sealed products are used on certain wheelchairs in high-income settings and based on testing results, certainly exceed the strength requirements of a typical manual wheelchair caster bearing. Caster and bearing failures shown in Table 4 are typically encountered in the community and during standards testing.

Resistance to corrosion and related wear down improve the longevity of the thermoplastic materials as witnessed in our study. Our results suggest that thermoplastic bushings can be both cost-effective and durable even in adverse environments. Additionally, bushings may offer a low-cost alternative because they can be mass produced using processes like injection molding which further reduces the total product cost and improves part availability. The
cost-effectiveness was calculated using unit costs, so it is worth noting that the overall price per bushing will most likely decrease when manufactured in bulk. Bushings may also be manufactured using 3D printing technology that is gaining traction in the global assistive technology sector and will further facilitate easy access. 26 These methods are especially important in LMICs where access to wheelchair parts is challenging. 14 Since bearings are typically treated as consumables or parts that frequently require maintenance or replacement, and bushings are cost-effective, a wheelchair provider can include additional bushing samples during wheelchair provision.

The minimal amount of corrosion on the bushings’ surface did not impede its natural wearing and rolling ability. On the contrary, the corroded bearings did experience obstruction to rolling and consistently higher amounts of tire wear in the ball-bearing samples, which is consistent with recent evidence. 27 Such obstruction can increase the rolling resistance experienced by the user and lead to poor real-world performance as well as health issues like upper extremity injuries. 27 A future study could be to test the relative increase in rolling resistance of ball bearings versus bushings using these identical methods. 27 If rolling resistance is lower for thermoplastic bushings, it would indicate potential for real-world performance as well as for durability and cost-effectiveness as shown in this study.

This is the first study to compare bearings and thermoplastic bushing materials for application in wheelchairs. The authors plan to conduct further investigation into the design of cost-effective rolling elements and support the wheelchair sector with new knowledge and design innovation. Improved durability and cost-effectiveness of bearings and bushings is vital to raise the quality of wheelchairs in the community and reduce the frequency of wheelchair breakdowns and adverse consequences to the user.

Conclusion

Wheelchair caster bearing failures are commonplace in adverse environments. The ISO 7176-32 caster testing protocol has been instrumental in informing design improvements and guidelines for wheelchair casters. This comparative testing study utilized the testing protocol for comparative testing of caster bearings and bushings. The results suggest that thermoplastic bushings could serve as a durable, corrosion-resistant, and cost-effective alternative to bearings. The authors look forward to developing additional evidence to inform selection of wheelchair rolling components based on the application of use and thereby, reducing bearing failures and wheelchair breakdowns in the community through design and quality improvements.

Limitations

Due to the length of time required for testing and cost of testing, the sample size of this study is relatively small. With further testing, addition of testing samples would aid in the validity of the results. The length of time required for testing and usual lifetime of casters and wheelchairs led us to cap the testing at 6 years of equivalent cycles. Both thermoplastic bushing models, as well as the double-sealed bushings, all had samples that survived beyond this mark, but were not tested further. Only one type of caster was used in this study to isolate the effect of the bushings and bearings on durability and cost-effectiveness, so the consistency of this effect across different models is unknown. Debris infiltration from dust and dirt could also heavily impact both bushings and bearings, so a lack of this type of environmental testing affects the outcome of this study. The cost-effectiveness for the samples was based on unit costs that did not consider savings on large-quantity orders. Though this study has established the quality of these bushings, it did not evaluate its real-world performance. Aspects such as rolling resistance and overall speed were not analyzed in this study and impact the usability of the product by the user.

Future work

Our results suggest that bushings may be a more durable and cost-effective alternative to roller bearings, and therefore reduce the incidence of bearing failure in the community. However, there is additional work required to reinforce these findings. Along with rolling resistance tests, there are additional environmental conditions that must be examined to fully evaluate bearing and bushing performance as well. Though high temperatures did not influence tire aging as seen in preliminary studies, we do plan to conduct further high temperature (as seen in coastal and tropical climates) and dust testing evaluations in the future, and these factors could be included in bearing/bushing testing. Thermoplastic bushings were chosen for comparison instead of thermoplastic bearings because their solid design resists contamination and seizing from debris. Though contamination was not tested in this study, we recognized it as an advantage that bushings may have over bushings. This advantage needs to be validated further through dust testing and comparison to thermoplastic bearings. Testing of these thermoplastic bushings on multiple different caster models is also necessary to validate their full applicability. Following this, use of these bushings in the community through a clinical study could be conducted to get a sense of real-world performance. Continued use of tools such as the Caster Failure Inspection Tool (C-FIT) as well as others like Psychosocial Impact of Assistive Devices (PIADS) and Quebec User Evaluation of Satisfaction with Assistive Technology
(QUEST) during these studies would aid in understanding their effect on user outcomes. 12,28,29

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Guarantor
AM.

Contributorship
AM and JP conceptualized the study. JF conducted the preliminary testing with his senior design team members. JF performed the testing and data analysis in this study. AM and JP reviewed the study findings and provided feedback on them and this manuscript.

ORCID iDs
Jack J Fried https://orcid.org/0000-0002-5601-4853
Jon L. Pearlman https://orcid.org/0000-0003-0830-9136

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