D-51-6AA
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Positioning Tweel™ Caster and Power Drive Wheel for the Wheelchair Market

Stakeholder Viewpoints and Experiences

June 2006

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EXECUTIVE SUMMARY

Product Concept

A one-piece caster assembly and one-piece drive wheel assembly, constructed with a shear band and flexible fins or spokes that seeks to provide users with the characteristics of a pneumatic ride on a non-pneumatic caster and drive wheel

Study Purpose and Objectives

The overall project addressed several aspects of wheelchair caster and drive wheel design, including specific tests of the Tweel™ technology. This report covers the subjective findings based upon the experiences and perceptions of stakeholders (power wheelchair users, manual wheelchair users, clinicians and vendors). The study included surveys, focus groups and field trials. Stakeholder experiences and perceptions were collected on 1) current caster and drive wheel products, 2) product requirements for new and ideal casters and drive wheels, 3) Tweel™ prototypes, and 4) the performance of Tweel™ prototypes affixed to power wheelchairs.

Survey Key Findings

The survey collected feedback on experiences with current caster and drive wheel technology. The most common problem reported by survey respondents (n=78) was foreign matter getting caught in casters and drive wheels. For power wheelchair respondents, drive wheel wear was a significant problem. Manual wheelchair users identify wear as an important issue. Respondents indicated that gravel/dirt, ice and grass were the most difficult surfaces to roll over. Gravel caused the most damage to casters. Respondents indicated that functionality and performance were the most important features for casters and drive wheels. Cost, regardless of how casters and drive wheels were paid for, was not a deciding factor. Power wheelchair users tended to replace casters more frequently than manual users. Power wheelchair users also tended to receive more help from clinicians and vendors when choosing replacements. Manual users replaced their casters less frequently, but replaced bearings more frequently. Manual users relied more on their own past experiences or information from other users when choosing replacement casters.

Focus Group Key Finding

Outdoor surfaces and barriers presented the most difficult challenges. Participants (n=49) complained about rough rides over hard, uneven surfaces like bricks, cobblestones, cracked and broken sidewalks. Participants complained about jarring rides and vibration so severe that their posture and seating position was impacted. Some experienced caster breakage and tires rolling off the wheel rims. Caster and drive wheel traction on slopes and soft surfaces, such as sand and grass, also presented difficult challenges. Participants reported significant maintenance and

cleaning problems with debris getting caught in casters and between caster and forks. This debris affected caster operation and increased rolling resistance. Some users reported having to clean debris on a weekly basis. Caster and drive wheel wear varied widely and was affected by type of caster and drive wheel materials, user activity level, environments of use, adjustment and maintenance. Flat tires were the most exigent; they caused operational failure and can pose health and safety risks. Participants experienced a significant amount of bearing wear and reported replacing bearings more frequently than casters. While bearings are an inexpensive part, labor charges associated with changing bearings is costly and usually not reimbursed by insurance. While discussing caster and power drive wheel selection, participants expressed frustration by the trade-offs they had to make. For example, manual wheelers generally selected small diameter, solid casters to achieve maximum maneuverability, but in so doing had to trade-off comfortable rides over rough surfaces. Power users generally selected larger, wider casters to absorb impact over rough, uneven surfaces, but gave up maneuverability in tight places. Based on these experience and problems, a need for innovation is apparent. Participants appeared were frustrated because prices kept going up and quality and choice didn't seem to improve.

Important Caster Product Requirements

The IDEAL caster gives a smooth, level ride and absorbs shock, is self-cleaning, requires no maintenance or adjustment, is durable, grips wet and icy surfaces, turns/ maneuvers well in tight spaces, is convertible (can vary the caster shock absorption characteristics), is one-piece construction with a quick-release mechanism, is available in multiple diameters and widths, is lightweight, is available in multiple colors that will not mark flooring, is stylish with effects and doesn't make noise when rolling across floors.

Important Power Drive Wheel Product Requirements

The IDEAL power drive wheel gives a smooth ride and absorbs shock, grips wet and dry indoor and outdoor surfaces, is durable, is self-cleaning, doesn't require maintenance, is available in multiple diameters and widths, is available in multiple colors that will not mark flooring, looks sporty and is lightweight.

Initial Impression of the Tweel™ Prototypes

Participants were most impressed with the airless features of the Tweels™ technology. The Tweels™ technology appeared to give a pneumatic-like ride without constant maintenance and failure problems. Both caster and drive wheel prototypes appeared to provide a smooth, comfortable ride. Participants felt that the prototypes would offer good shock absorption with power wheelchairs, but thought the caster prototype was too stiff for manual wheelchair use. Participants liked the single piece construction of the prototypes, but raised doubts about the durability of the fins and drive wheel tire material. They were concerned that the fins would lose their 'resiliency,' affecting the overall ride and shock absorption characteristics. Durability of the caster bearings was widely discussed, although

group consensus was reached about the importance of bearing operation and durability. Participants felt that the wide, flat caster design appeared to provide better traction on wet surfaces, but they still wanted a small amount of tread. Drive wheel tread and traction appeared to be adequate. Finally, participants told us that the Tweels™ must improve patient/client outcomes in indoor activities, on indoor surfaces to be medically justified and they must come as standard parts of the wheelchair from the original equipment manufacturer (OEM), not as options.

Field Trial Key Findings

Field Trial subjects (n=9) were satisfied with the performance of the Tweel™ casters and drive wheels over the 4 week field trial. Several of the needs identified in the focus groups were corroborated or explained by experiences during the field trials. Gravel and loose dirt surfaces, foreign matter caught in wheels, tire wear and tires marking floors were major issues for focus group users. Tweel™ casters and drive wheels did not mark floors. Most users reported foreign matter getting caught in drive wheels but not in casters. Tweel™ technology performed very well on most surfaces with only limited problems noted. Tire wear was identified as a major problem in the focus groups. Drive wheel subjects did not note wear, but visual inspection after the field trial identified loss of tread. Caster users began reporting wear after one or two weeks of use. Given the short duration of the field trial, this result is significant. Another aspect of the project measured force loss over the field trial and its results corroborated user perception that durability is a significant concern. The overall satisfaction was high for both caster and drive wheel. Despite the issues reported by users, the Tweel™ casters and drive wheels seem to provide certain improvements over those currently used by users in this field trial.

Purpose

Caster and drive wheel performance are critical to effective wheelchair performance and mobility. Casters and drive wheels must perform effectively, be reliable and safe, durable and acceptable to wheelchair users. This report covers the subjective findings based upon the experiences and perceptions of stakeholders (power wheelchair users, manual wheelchair users, clinicians and vendors). The study included surveys, focus groups and field trials. Stakeholder experiences and perceptions were collected on 1) current caster and drive wheel products, 2) product requirements for new and ideal casters and drive wheels, 3) initial perceptions of the Tweel™ prototypes, and 4) the performance of Tweel™ prototypes affixed to power wheelchairs.

Based on the submitted proposal to Michelin and Statement of Work this document will cover objective 4 from the original document, **Usability Studies**. Per agreement, information was collected on three products: manual wheelchair casters and power wheelchair casters and drive wheels.

Methodology- Focus Groups

Collection of stakeholder viewpoints and experiences involved a sequential, three phase study. Phase I-Literature Review, Phase II-Stakeholder Survey and Focus Groups and Phase III-User Field Trials. The literature review has been sent to the sponsor as a separate report. Because little research has been conducted to identify product customers' experiences and problems with current wheels and casters, descriptive and exploratory methods were used in this study. Surveys, focus groups and field trials allowed for in-depth data collection. Data analysis has been used to describe and explore interrelationships between users, their current products, their activities and environments of use. Product requirements generated as a result of this study are grounded in the perception and experience of study participants.

Focus group and survey methods followed the techniques described in Bourque and Fielder (Bourque, L., and Fielder, E., *The survey kit 3: How to conduct self-administered and mail surveys,* 1995 Sage Publications), Greenbaum (Greenbaum, T., 1999, *Moderating focus groups; A practical guide for group facilitation,* Sage Publications) and Krueger and Morgan (Krueger, R., and Morgan, D. 1997, *The focus group kit, volumes 1-6*, Sage Publications).

Procedures

Focus groups were used to collect data from four different stakeholder groups: 1) power wheelchair users, 2) manual wheelchair users, 3) clinicians, and 4) vendors/ suppliers.

Surveys were developed to collect information from wheelchair users on demographics, current wheel and caster use and satisfaction with these products,

problems with wheels and casters, experiences while traversing different surfaces, the process of selection of wheels and casters, and replacement.

An on-line survey was posted on the MobilityRERC website that wheelchair users accessed independently. Participants in the power and manual focus groups were given a similar survey at the beginning of the focus group session. The survey helped to establish points for discussion and provided quantifiable data. The results of the on-line and pre-focus group surveys have been combined for this report.

Phase III consisted of a field trial and used an on-line survey to collect experiences of the subjects. Participants either used the Tweel™ casters, Tweel™ drive wheels, or both, depending on the power wheelchair model. Participants were asked to fill out the survey weekly. During field trial, participants rated the performance of the prototypes over various surfaces and overall performance as compared to their current wheels.

The **Appendix** includes the **Pre-Focus Group Surveys for Power and Manual Wheelchair Users, online Power and Manual Wheelchair User Surveys,** the **Focus Group Questioning Protocol** and the **Field Trail Protocol**.

Recruiting, Participation and Demographics

The on-line survey was posted and was advertised through various bulletin boards and discussion groups to elicit feedback from a larger group of users. Online surveys were received from 27 manual wheelchair users and 20 power wheelchair users.

Focus group participants were recruited from disABILITY Link, a Center for Independent Living, located in Decatur, Georgia, and from Shepherd Center in Atlanta, an acute rehabilitation hospital .

Six focus groups (n=49) were empanelled:

- Power wheelchair users, 2 focus groups, (n=17)
- Manual wheelchair users, 2 focus groups, (n=14)
- Clinicians and vendors, mixed, 2 groups (n=18).

Focus group participants were almost equally divided between men and women, but a clear majority of on-line survey respondents were male (**Table 1**). The majority of focus group participants were White/Caucasian with Black/African American representing 14% and 47% of the manual and powered wheelchair groups, respectively. On-line survey respondents were over 85% White/Caucasian. **Table 2** lists participants' race/ethnicity.

Most users reported living in urban or suburban environment with rural and small town environments also being represented (**Table 3**). Approximately 50% or more of users in each group described themselves as active or very active with the ratios in each group varying quite a bit. Overall, participants in the various surveys

represented a good mix of different activity levels, from very low to very high. A complete reporting of participant demographics is found in the **Appendix**.

Table 1. Gender of Focus Group Participants and On-line Survey Respondents

	Male	Female
Manual Wheelchair Focus Group	8	6
Power Wheelchair Focus Group	8	9
Manual Wheelchair Survey Only Group	21	6
Power Wheelchair Survey Only Group	13	7
Clinicians and Vendors Focus Group	8	10
Totals	58	38

Table 2. Race/Ethnicity Of Focus Group Participants And On-Line Survey Respondents

	White/ Caucasian	Black/ African American	Latino/ Hispanic	Asian, Asian Indian or Pacific Islander
Manual Wheelchair Focus Group	10	3	0	1
Power Wheelchair Focus Group	9	8	0	0
Manual Wheelchair Survey Only Group	24	0	1	1
Power Wheelchair Survey Only Group	17	1	0	1
Clinicians and Vendors Focus Group	17	1	0	0
Totals	77	13	1	3

Table 3. Self-Reported Home Location

	Urban	Suburban	Small Town	Rural
Manual Wheelchair Focus Group	4	5	1	4
Power Wheelchair Focus Group	9	7	1	0
Manual Wheelchair Survey Only Group	4	10	6	7
Power Wheelchair Survey Only Group	9	7	1	0
Totals	26	29	9	11

Focus Group Discussion Format

To prepare the focus group questioning protocol, we first queried the key members of the cross-functional research team (commercial partner-Michelin, technical partner-rehabilitation engineer, and human factors partner-industrial designer, moderator) and collected input and issues. We also drew upon the personal experience of key informants (experienced power and manual wheelchair users), standards, reports, academic research, interviews with Michelin experts, and other information sources.

Team members provided focus group issues related to current product use and design concepts and approaches. Systematic preparation of probing questions lessens the likelihood that critical product requirements will be overlooked. The

focus group questioning protocol is included in the **Appendix**. The focus group used the following discussion format:

Part 1-Complete Pre-Focus Group Survey
Part 2-Discuss problems with current caster and drive wheel products
Part 3-Discuss IDEAL caster and drive wheel characteristics
Part 4-Tweel™ Demonstration and Evaluation
Part 5-Complete Dot Voting Activity

Findings

Survey Findings

Survey Overview

The Tweel™ surveys were conducted to determine the needs and issues of two user groups, manual and power wheelchair users. The surveys were completed prior to the focus groups by the manual and power wheelchair users (n=31) and by wheelchair users in the on-line survey (n=47). Survey respondents had no awareness of Tweel™ technology prior to the survey. Many of needs and issues encountered by power and manual wheelchair users were found to be similar.

User Satisfaction

Only focus group participants were queried on satisfaction with their current products. Most of the 14 manual wheelchair users were satisfied with their current casters with only 1 participant being dissatisfied. Power wheelchair users seemed to have a stronger opinion. A larger percentage of power wheelchair users (41%) were very satisfied with their casters but 30% were either somewhat or very dissatisfied. Appendix Table A contains complete data.

Most Common Problems

Survey respondents were asked to identify the most common problems they experienced with their current casters. Groups were given a variety of options from which to choose and these options differed slightly in the pre-focus group versus the on-line survey. The most frequent problem identified by manual wheelchair users was foreign matter getting caught in casters (>60%). Other common problems included bearing wear (>25%) and leaving marks on the floor (<20%). Over 40% of the on-line survey respondents identified caster shimmy as a problem.

Power wheelchair users were asked to comment on problems with both casters and drive wheels. Power users also identified foreign matter (>50%) as a common problem and also felt that tires wear out too quickly (>50%), that static electricity can build up and deliver a shock (>25%) and tires leave marks (>25%).

Difficult Surfaces

Survey respondents were asked to rank surfaces by how easy or hard they were to traverse. Both power and manual respondents ranked surfaces in almost exactly the same order of difficulty and identified gravel/loose dirt, ice, and grass as the most difficult. The only notable difference was that carpets were more difficult for manual than for power wheelchair users. Respondents were asked to indicate the surfaces that cause the most damage to casters and drive wheels. Both groups indicated that gravel/loose dirt caused the most damage. Asphalt and concrete surfaces were also indicated as damaging, even though they were rated as easy to roll over.

Caster Replacement

Differences were evident between power and manual respondents in how often casters were typically replaced. About 30% of the manual wheelchair respondents reported replacing casters within 3 years but 85% of power wheelchair users replaced casters in under 3 years. There were also some differences in who participated in selecting replacements. Almost 80% of manual wheelchair users reported that they selected replacement casters themselves, with only about 20% getting help from vendors or clinicians while most power wheelchair users selected replacement casters with the assistance of clinicians and/or vendors.

Caster Selection

Both power and manual survey respondents were influenced by the same factors in caster selection. In general, replacement casters were chosen based on their functionality. More than half of respondents in the online survey indicated that function influenced their selection. From the focus group surveys, respondents identified low maintenance, performance, and ride/comfort. The primary difference between the groups was that durability was the most common factor considered by power wheelchair users (>50%) whereas durability was an important factor for only 1 manual wheelchair user (<10%).

Procurement of Casters

There were some differences between the groups in how replacement casters were purchased. About half of manual wheelchair respondents reported that they used personal funds when paying for replacements, the rest used some form of insurance. Less than half power wheelchair respondents used personal funds, so they were more likely to use insurance to purchase casters.

Focus Group Findings

A transcript of all focus group discussions were prepared and analyzed for content. Each focus group content was analyzed independently and all focus groups were analyzed together to find common themes. Many themes were identified across all groups. Synthesis and interpretation of focus group data follows.

Rough Rides, Outdoor Surfaces and Barriers

Outdoor surfaces and barriers tended to present participants with the most challenging problems. Casters and power drive wheels must work well outdoors because users want to get outside and engage in activities with family and friends. Participants (power and manual wheelchair users, clinicians and vendors) discussed a variety of problems with both hard and soft outdoor surfaces and outdoor barriers. Brick surfaces like cobblestones were considered by most participants to be the most difficult hard surface to roll across. Casters didn't absorb the shock produced rolling across brick surfaces and gaps between bricks were wide enough to allow casters to get stuck.

Barriers of ¼" to ½" could halt a manual caster. Casters didn't absorb shock from these barriers and consequently users lost their balance and sometimes slide forward out of the chair, and in some cases experiencing injury. Power wheelchair users complained about barriers of 1" to 2". Broken and cracked sidewalks could sometimes break a caster. Caster tire roll-off occurred when casters hit bumps in sidewalks and asphalt. Drive wheel tire roll-off occurred when power wheelchairs were climbing curbs. Hot asphalt could shred solid, "hard roll" casters.

Both power and manual users mentioned that casters could be halted by striking a barrier at an angle. Striking a barrier at an angle (not head on) caused the caster to rotate laterally and get lodged against the barrier. Power wheelchair users mentioned problems getting casters caught in 1" to 2" gaps. They had been stuck in gaps between MARTA (Atlanta's regional transit system) train doors and train platforms. Gaps were often uneven, that is, the level of the train was either above or below the level of the platform, creating a height differential. Participants noted problems getting across elevator door gaps and crossing drainage grates. Train and elevator doors closed on wheelchair users and grates had broken casters.

Loss of traction on slopes, ramps and driveways was a significant problem. When casters and drive wheels lost traction, wheelchairs tended to slide or skid sideways, riders lost balance and the chair sometimes tipped over or got lodged sideways on the ramp. Traction across soft surfaces like sand, loose dirt and grass was also a significant problem. Casters dug and drive wheels sank into soft surfaces. Besides the problem of getting stuck, users complained about the cleanup required to remove mud and/or sand and soil from casters and bearings. Gravel created similar traction problems. Manual users discussed getting "bogged down" in gravel. Gravel also caused damage. Gravel, rocks and other debris shreded caster materials and/or caused "chunks of rubber" to go missing from tires.

Participants reported that debris like twigs, small branches, clipings from bushes, and wire often got caught between casters and forks and increased rolling resistance or halted casters completely. Smaller debris, like hair, string, and carpet fibers got caught and wrapped around caster and drive wheel axles, increasing rolling resistance. While all participants were from the Atlanta area, several had experienced loss of traction on ice, ice melt/slush and snow. Ice melt or slush got compacted around front caters, caster axles and bearings, causing excessive rolling resistance. This "debris" had to be removed after very short distances of 4 or 5 feet. Ice melt caused caster bearings, caster axles and fork stem bearings to rust. Rusted caster and power drive wheel bearings contributed to increased rolling resistance.

Indoor Surfaces and Barriers

Thick pile carpet was generally considered the most difficult indoor surface to roll or push across. Both manual and power wheelers experienced difficulty turning on thick to medium pile carpet and manual wheelers experienced difficulty tracking across carpet that was not laid straight or laid over flooring that was not level. Casters "pushed" area rugs and throw rugs and bunched them up. Power drive wheels twisted rugs around the wheel, halting the wheel completely.

Indoors, wheelers moved at slower speeds, so smaller barriers created significant problems. Metal sliding door thresholds seemed to present the most difficulty. Casters reportedly would strike the metal sliding door threshold, rotate laterally and get lodged against the threshold, halting the caster. Both manual and power users described significant problems rolling over rubber mats and rubberized surfaces. Casters sank into the material and became stuck. Power drive wheels lost traction on rubber brush mats.

Wear, Flats and Replacement

Participants told us that striking environmental obstacles seemed to wear both casters and bearings. Participants reported that casters sometimes got out of optimal alignment. The caster fork stem shifted from perpendicular to the ground, causing uneven caster wear and shimmy. Poor positioning in the wheelchair contributed to caster wear. More body weight in front of the rear axle contributed to more weight and stress on the front casters and more wear. Engaging in outdoor sports and recreational activities contributed to caster and power drive wheel wear. Casters were used to steer the power wheelchair and turning contributed to caster wear. Casters got extra wear from rubbing on shoes and footrests. Surprisingly, participants reported that casters took abuse from MARTA bus operators. Power drive wheels were worn down from hitting the edges of bus ramps and lifts and operators had broken casters while loading and unloading wheelchairs.

Caster wear depended on other factors including activity level and type of caster. Active manual wheelers replaced casters more frequently, especially if they

engaged in outdoor sports activities. Less active manual wheelers replaced casters less frequently. The type of caster used (pneumatic, solid, flat-free solid) impacted wear. Due to problems with proper inflation and flats, pneumatics tires were replaced most frequently and were not recommended. Flat-free solid or "soft roll" casters were reported to wear out quicker than solid or "hard roll" casters and were usually replaced more frequently. Replacement rates varied widely. Participants usually replaced a pair of casters. A pair of drive wheels was usually replaced to prevent uneven wear and poor tracking. Often, vendors replaced both casters and power drive wheels at the same time, as preventive maintenance.

Caster bearings were replaced more frequently than caster wheels. As bearings wore, they made noise. Bearing wear was related to weather, activity, environments of use, cleaning and lubrication practices. While bearings were not costly parts, bearing replacement usually involved a service call and labor charges.

Cleaning and Adjustment

Maintenance and repair problems contributed to reduced activity and participation. Participants voiced concerns about problems with proper penumatic tire inflation and flat tire repair. If pressure in one tire became low, wheelchair tracking was affected and the chair pulled to one side. Flats often stranded powerchair users for hours. When flats occurred after business hours or on weekends, vendors were not always able to respond. Generally, pneumatic casters and power drive tires don't hold up well. Vendors lost money on service calls and labor, because reimbursement doesn't cover costs. For these reasons, therapists and vendors didn't recommend pneumatic tires or casters for powerchairs and they didn't recommend pneumatic casters for manual chairs. Non-pneumatics were chosen as standard, even though the smooth ride and shock absorption or "give" of penumatic casters and power drive wheels were preferred.

Participants discussed problems with tire roll-off. Manual users experienced caster tire roll-off when they hit barriers like cracks or bumps in sidewalks or asphalt. When powerchairs made sharp turns, tires would sometimes roll off rims. Rolling on rims destroyed both the tire and the rim.

Participants reported spending a significant amount of time removing debris, like hair, string, and carpet fibers from around casters and drive wheel axles. If the "hair washer," as participants referred to it, was not cleared every several months, participants noticed that it contributed to increased rolling resistance. If participants owned pets, they dealt with this issue more frequently. Vendors reported that hair could become so tightly wrapped around the axle, that it could freeze bearings and hault the wheel. Cleaning mud, sand and other debris from casters and power drive wheels presented problems. Water was used to clean mud, sand, dirt and saltwater. Other method of cleaning included the use of fingers, a screwdriver, a toothbrush and towels. Some wheelers reported using WD 40 on axles, bearings and bolts as a lubricant.

Caster shimmy and vibration resulted from stem and axle bolts that loosened up and become misaligned. The perpendicular alignment of the caster stem requried adjustment. Bent caster forks contributed to caster shimmy and vibration and problems with wheel tracking. Powerchair users seemed to experience more difficulty with caster shimmy and vibration than did manual wheelers.

Caster Selection Criteria and Trade-offs

Clinicians and vendors indicated that the caster and power drive wheel selection criteria varied by the experience of the user. New wheelers needed direction whereas more experienced users were engaged in the selection process. They were asked about goals, activities, environments of use and problems they were experiencing. Age and weight were important. Casters had to be sized so that they didn't interfere with the operation of leg rests and foot plates. Heavy individuals required more durable products and large loads were undesirable on small diameter casters. Casters needed to be compatible with wheelchair frames and forks. A range of caster and power drive wheel diameters and widths were needed to fit the wheelchair to the needs of each user.

Diagnosis, level of injury, functioning, history and skill level using a manual wheelchair were important. Reduced strength and balance affected the ability to control the chair, traverse surfaces and negotiate barriers. Marginal manual propellers required larger casters to overcome barriers and thresholds. Small diameter casters had higher rolling resistance and casters with diameters less than 4 inches were not selected for or recommended to users who could not perform a wheelie.

Participants were frustrated with tradeoffs they had to make in caster selection. Typically, the selection of a particular caster meant giving up functions not inherent to that type of caster and, by extension, giving up some of the goals and activities that users desired. For example, urban wheelers reported the need for large, wide casters in order to get up curbs and across gaps. Rural and suburban users reported that outdoor activities required the use of large, wide casters to roll over gravel, rough, uneven or soft surfaces. To achieve successful outdoor activities using large, wide casters, users had to give up maneuverability in tight spaces, associated with the use of small and narrow casters. The perception was that wider casters of 2 inches or more didn't turn easily and didn't maneuver well in tight places.

Small, narrow casters were prized for their turning and maneuverability. To have this type of performance, higher functioning manual users reported giving up on smooth rides over rough, outdoor surfaces. Suspension systems were used to smooth out rough rides and absorb the shock of hitting barriers. Wheelies were used effectively by some manual chair users to overcome obstacles.

Pneumatic casters and tires were prized for smooth ride and shock absorption characteristics, but were difficult to maintain and repair. "Hard-roll" or solid casters and power drive wheels were relatively low maintenance, but users reported rough

rides, feeling "every bump" they rolled over. "Soft-roll" or flat-free solid casters provided better shock absorption, but didn't wear well.

Clinicians and vendors reported making caster and power drive wheel selections in an effort to improve the function, independence and safety of wheelchair users. They tried to select casters that produced a comfortable, smooth ride, while not requiring maintenance. Safety during transfers was important. Clinicians tried to train manual users to position their casters in forward trail to increase the wheelbase, thereby improving chair stability as the user moved forward in chair to make the transfer. Caster movement during transfers continues to be a significant safety problem for manual users.

Need for Innovation

According to participants, current caster and power drive wheel products had not changed in the last 20 years. Participants expressed frustration with the problems they experienced and with the tradeoffs that current products required. While several types of casters existed, each type had limitations. Because these components were essential to the operation of the wheelchair, problems with casters and power drive wheels were significant. When these components failed or failed to operate correctly, user's quality of life was dramatically impacted. According to vendors, only three power drive wheel choices existed. Lack of competition in the market kept prices artificially inflated. Most current products were manufactured by one or two companies and while prices kept going up, quality hadn't improved. Improvements would improve users' quality of life.

Focus group comments appeared to be in contrast to the satisfaction expressed by pre-focus group survey respondents. While respondents expressed general satisfaction with their current caster and power drive wheel products, they may have done so because they believed they had selected the best option that was currently available. Often users have been told that a given product is the best available, even with its limitations. Many wheelers have developed low expectations for their casters and power drive wheels and high tolerances for problems. Focus group discussions are ideal for probing 'why' respondents answered a survey question in a specific manner.

Product Requirements for Ideal Caster and Power Drive Wheel

After discussing their experiences and problems with current products, participants were asked to discuss characteristics of their 'ideal' caster and drive wheel. These "Product Requirements" were the characteristics, functions and features that Tweel™ technology should have in order to satisfy customers and gain competitive advantage.

Participants told us that the IDEAL caster...

Gives a smooth, level ride and absorbs shock- Participants wanted the smooth ride of a pneumatic caster without the problems of inflation and flat repair. They wanted casters that would absorb the shock of hitting barriers and not shift laterally and get stuck against a barrier. Casters should reduce vibration when traveling over rough, uneven surfaces. Casters should glide across soft surfaces without sinking in. Casters should keep users level when rolling over obstacles, adjust to differences in terrain and compensate for cross-slopes (side slopes).

Is self-cleaning, requires no maintenance or adjustment- Participants wanted casters that did not catch debris. They wanted materials that repelled dirt and mud and disintegrated foreign matter. They wanted durable, sealed bearings that debris couldn't penetrate and axle bolts and nuts that wouldn't become loose and require tightening.

Is durable- Participants wanted casters that lasted between 3 and 5 years with daily outdoor use and lasted 7 to 8 years if used mainly on indoor surfaces. Participants wanted to roll or push over gravel without causing damage to caster materials.

Grips wet and icy surfaces (tread)- Participants wanted casters that gripped hard wet surfaces like concrete sidewalks, ramps and asphalt. They wanted tread on casters, but not so much that turning and maneuverability was adversely affected. They didn't want tread that would damage carpet. They wanted tread material and patterns that would not collect dirt, mud and other debris. They didn't want casters to push throw rugs and bunch them up.

Turns/ maneuvers well in tight spaces- Participants wanted casters that would turn easily in tight spaces like bathrooms and turn easily on soft indoor surfaces like rugs and carpet and soft outdoor surfaces like grass.

Is convertible, users can vary the caster shock absorption characteristics- Participants wanted to be able to adjust the shock absorption or flex characterizes of casters so that they could be "tuned" (would absorb more or less shock) and customized to unique user characteristics, environments (outdoor or indoor, rural or urban) and activities.

Is one piece construction with a quick-release mechanism- Participants wanted caster hubs and tires to be constructed in one piece, which could not become separated (as in tire roll-off). They wanted only one part to change when they replaced casters. They wanted a caster quick-release mechanism similar to ones found on bicycle wheels, but durable enough for wheelchair use.

Is available in multiple diameters- Participants wanted a range of caster diameters from which to choose. They wanted to be able to select and change casters for different activities, different environments of use and different personal preferences. Ideally, they wanted a range of manual chair caster diameters from 3 to 8 inches, in ½" increments and a range of power chair casters diameters from 4 to 9 inches; in ½" increments. They wanted interchangeable casters that could be used on either manual or power wheelchairs.

Is available in multiple widths- Participants wanted a range of caster widths. They wanted to be able to select and change caster widths for different activities, different environments of use and different personal preferences. Ideally, they wanted a range of manual caster widths from 1 to 2 inches, in ¼" increments and a range of power caster widths from 2 to 5 inches, in ½" increments.

Is lightweight- Participants wanted casters to weigh between 8 oz and 1 lb. Manual wheelers wanted a pair of casters to be easy to carry around in a carry case.

Is available in multiple colors that will not mark flooring- Participants wanted to choose among a variety of colors. Dark colors were preferred because they didn't show dirt. Participants wanted

reflective paint that would reflect car lights, for safety after dark. Participants didn't want colors that would leave marks on flooring.

Is stylish with effects- Participants wanted casters that looked sporty, they wanted hubs to stand out and be a different color than caster tires. Just like decorative auto wheels, participants wanted options including, spinning rims, lighted wheels (a feature that can be turned on/off by user), decorative lug nuts and hub caps or covers that would keep out debris.

Doesn't make noise when rolling across floors- Participants didn't want casters to announce their presence. They wanted casters to operate quietly, not squeak on cleaned, waxed flooring.

The IDEAL power drive wheel...

Gives a smooth ride and absorbs shock- Participants wanted power drive wheels to give a smooth ride over rough, uneven surfaces and absorb the shock of hitting barriers. They wanted tires to perform like pneumatics without being pneumatic. They didn't want power drive wheels to fail catastrophically. They didn't want tires to roll off rims.

Grips wet and dry indoor and outdoor surfaces (tread)- Participants wanted enough tread on power drive wheels to provide traction on wet and dry outdoor and indoor surfaces, but not so much tread that turning and maneuverability were adversely affected. They wanted optional deeper tread available for farmers and others who worked outdoors. They wanted tread that provided traction on snow, ice and slush. Participants didn't want drive wheels to pick up and wrap area rugs. They wanted the tread to roll over flooring without making squeaking noise.

Is durable- Participants wanted power drive wheels to last between 3 and 5 years with daily outdoor use. They wanted to roll over gravel without causing damage to power drive wheel materials.

Is self-cleaning / low maintenance- Participants wanted power drive wheels that repelled dirt and debris and didn't get dirt and debris stuck in tread.

Is available in multiple diameters and widths- Participants wanted a range of power drive wheel diameters and widths to accommodate a range of power wheelchair configurations.

Is available in multiple colors that will not mark flooring- Participants wanted power drive wheels to be available in a variety of colors. Participants wanted reflective paint that would reflect car lights, for safety after dark. Participants didn't want colors that would leave marks on flooring.

Looks sporty- Participants wanted power drive wheels that looked sporty. They wanted lighted wheels (a feature that can be turned on/off by user), decorative lug nuts and hub caps or covers that would keep out debris out of drive wheels.

Is lightweight- Participants wanted power drive wheels that weighed around 1 lb.

Tweel™ Evaluation

After reviewing a demonstration of the Tweel™ caster and drive wheel, participants were asked to offer an initial impression of the Tweel™ technology and evaluate it against the ideal product requirements. While initial reaction to the Tweel™ was mixed, participants appeared to be impressed with the air-less feature coupled with the appearance of shock absorption. The Tweel™ technology appeared to give pneumatic performance without the constant maintenance problems of inflation or the catastrophic failure of flats. The Tweel™ was considered to be an improvement over current power caster and power drive wheel products. While manual wheelers

were excited about the potential the Tweel™, they offered a number of suggestions for further development.

Tweel™ Ride and Shock Absorption

Participants appeared to be impressed with the rugged performance of the Tweel™. They felt that the Tweel™ would be great on rough terrain and gravel and would roll over curbs and thresholds. The "give" of the caster and drive wheel appeared to be adequate for most power wheelchairs, but participants were concerned that the fins would wear quickly and would loose their 'resiliency.'

On the other hand, the Tweel™ caster prototype appeared to be too stiff for manual wheelchair use. Similar to soft-roll (flat-free solid) casters, the Tweel™ caster needed more 'give' to absorb the shock of hitting pot holes and sidewalk cracks. Manual users wanted to reduce the number and thickness of the caster fins. They suggested that the fins could be thicker or thinner depending on the needs of the user and the application (environments and tasks).

Tweel™ Construction, Cleaning and Durability

Participants liked the single piece construction of the prototypes. The Tweel™ eliminated many of the parts of the typical caster and power drive wheel. Tire roll-off was eliminated. Participants reasoned that even if one or two fins got cut, the "ride" would not be affected, the caster and wheel wouldn't stop working. This greatly improved user safety.

Participants were concerned that debris and foreign matter would collect in the fins and bearing areas. The fins would collect dust, dirt, mud and other debris in outdoor environments. The prototypes were compared to mag wheels and participants commented on the effort required to clean mag wheels. They suggested that some type of cover be used to enclose the fins, preventing foreign matter from getting into the fins and bearing areas.

Caster bearings didn't appear to be seated well in caster hubs. Participants were concerned that bearings might loosen up and contribute to caster wobble and shimmy. If bearings worked loose, participants were concerned that the entire caster would need to be replaced.

The prototypes looked like they would last between 3 and 5 years, but participants told us it would be hard to know without trying them out. They were concerned that fins would become brittle and cracked with wear and loose their resiliency.

Tweel™ Maneuverability, Traction and Tread

The wide, flat caster design was considered to provide better traction on wet surfaces, but participants wanted a small amount of tread on the caster to improve traction. There was also concern that the wide, flat caster, when compressed, would make turns more difficult. Participants wanted slightly more arc or "crown"

on the caster to improve maneuverability and turning. With more arc or crown, the caster would overcome barriers that were struck at an angle. Participants believed that striking a barrier at an angle (like the metal threshold of a glass sliding door or the edge of a sidewalk), would cause the flat edge of the Tweel™ caster to shift laterally and get stuck on the barrier, halting the chair.

Tweel™ Dimensions

The lightweight Tweel™ prototypes surprised and impressed participants. The Tweel™ caster and power drive wheel were acceptable to participants for use on power wheelchairs, but other sizes would be needed.

As a manual caster, the Tweel™ was considered to be too wide. It looked like it would be difficult to turn. Fork compatibility was considered problematic. It was interesting to note that manual users expected to lose some of the shock absorption of the current caster prototype, if the width of the caster was reduced. Participants remarked that several diameters and widths were needed to accommodate the majority of manual wheelchair configurations. These include 4", 5" and 6" diameters and 1, 1¼, 1½ and 1¾ inch widths. Vendors affirmed that 1¾ inch widths were used on manual chairs and this width was useful for some configurations.

Tweel™ Aesthetics

Generally, participants were excited by the look of the Tweel™. It looked sporty, like a high performance auto tire. While the green Tweel™ caster was considered to be "a color that kids would love," participants stated that gray was the norm and didn't mark flooring. To meet current conventions, they suggested a two color scheme. The hub area or center of the caster and wheel should be a different color from the surrounding rim, tread and fins. For example, a black/anodized or silver colored 'hub' would be easy to distinguish from the black or grey 'tire' and would fit current conventions. Power wheelchair users reported that they wanted more color choices. Participants agreed that reflective colors, lighted effects and glow-in-the-dark materials could play an important role in improving user safety.

Medical Justification and Procurement

According to vendors and clinicians, Tweel™ technology must improve patient/client outcomes in indoor activities, on indoor surfaces. They must be durable, require no maintenance, stay clean and must be shown to improve the independent mobility of users. Improved mobility over indoor surfaces and thresholds, no tire roll-off and no flats, were all mentioned as important factors necessary to support the claim of 'improved independent mobility.' If Tweel™ technology was justified solely for outdoor activities and surfaces, reimbursement would likely be rejected by Medicare and Medicaid and most private insurance policies were consistent with Medicare and Medicaid.

Tweel™ casters and power drive wheels must come as standard parts of the wheelchair from the original equipment manufacturer (OEM), not as options. The products must be easy to order on the OEM's order form.

Product testing was considered to be an important strategy in obtaining insurance coverage. Clinicians reviewed research studies published in journals and discussed findings of product testing with researchers at conferences. Clinicians and vendors wanted evidence-based research that substantiated the product manufacturers' claims. They expected this to be independent research such as testing sponsored by the National Institute on Disability Rehabilitation Research (NIDRR), rather than performed by the product manufacturer. With the occasional exception, clinicians and vendors didn't find marketing materials from manufacturers particularly helpful. Clinicians and vendors both relied on reports from users who had tried products, and on discussions with their colleagues.

Awareness

At the conclusion of each focus group, participants were asked to indicate by show of hands if they knew of Michelin. Almost all participants indicated that they had knowledge of Michelin products. All participants indicated that they believed that Michelin made quality products. Participants were mixed as to whether the Michelin brand would influence their decision to purchase casters and drive wheels made by Michelin. Clinicians and vendors pointed out that Michelin didn't have a history in wheelchair products. Clinicians and vendors had a 'wait and see' attitude. They acknowledged that the Tweel™ prototypes were on the right track, but needed the improvements discussed.

Field Trial

Field Trial Abstract

Phase III of the study involved nine power wheelchair users participating in a field trial during which Tweel™ technology casters and/or drive wheels were used during everyday mobility. Subjects were instructed to participate in their daily activities as normal, paying special attention to how their wheelchair felt when going over various surfaces. Subjects were asked to provide weekly feedback on performance during the 4 week trial.

Subjects felt that both provided good shock absorption and did not leave marks on floors. The maneuverability provided by the casters was consistently noted by all users. Five of the six caster users reported signs of wear and shimmy or vibration was noted on one-third of the surveys. Drive wheel users did not note wear, but three of the 4 noted debris getting caught in the wheels. Perceptions of performance over different surfaces was fairly consistent across caster and drive wheel users with most surfaces receiving high ratings. Only two surfaces were rated less than 'good'- wet surfaces by drive wheel users and gravel/loose dirt by caster users.

Overall users were very satisfied with the Tweel™ casters and drive wheels. The overall rating given to the Tweel™ technology was very high: 3.54 out of 4 by casters users and 3.29 out of 4 by drive wheel users. Such high ratings would not be expected if the benefits provided over current casters and drive wheels were not noticeable or important to the users.

Subjects

Only power wheelchair users were recruited for the field trial because the available Tweel™ casters and drive wheels were sized for power chairs and not manual wheelchairs. Subjects were recruited from the focus group participants and from Shepherd Center and disABILITY Link.

To be considered for the field trial, wheelchair users had to have used a power wheelchair for at least two years and be between 18 and 55 years of age. They had to be able to independently control the wheelchair with a joystick and typically leave their residences at least once a day. Only users with drive wheels between 12 and 14 inches and casters that were either 6x2 or 6x1 1/2 inches were recruited to ensure compatibility with the Tweel™ technology. Power wheelchairs fit with an Easy Lock tie down system were excluded due to the potential for altering frame height that results in tie-down interface problems. Chairs with two-sided forks were required for users fitted with Tweel™ casters, except for certain Invacare wheelchairs which had one sided forks. These were replaced with two sided forks for the field trial. Nine subjects participated in the field trial. Seven of the subjects

were male and two were female. Six of the participants participated in the focus group phase.

A variety of different wheelchairs were used by field trial participants. Invacare chairs were used by six subjects, three TDX3 models, one Storm TDX5, one Torque and one Action X Ranger 1. Two subjects used Quickie wheelchairs, a V-121 and P222 SE. One subjects used a Jazzy 1122.

Data Collection

The field trial survey consisted of a set of questions asking impressions about various aspects of the performance of the Tweel™ casters and drive wheels. A list of problems (**Table 4**) and benefits (**Table 5**) were provided and subjects had the option of entering specific comments to add specificity. [See Appendix A for a copy of the survey].

Table 4. List of problems with casters and drive wheels

Rough ride over uneven or bumpy surfaces	Casters roll up or push carpets or mats
Stick in cracks gaps or obstacles	Casters mark floors
Dig into or get stuck in soft surfaces	Noticeable wear
Loss of traction or slippage	Foreign matter or debris gets caught in casters
Shimmy or vibration	Tracks mud
Casters shed, peel, or crack	

Table 5. List of benefits of casters and drive wheels

Smooth ride over bumpy or uneven surfaces	Casters turn and maneuver well
Absorb shock from obstacles or barriers	Roll over soft objects well (rugs)
Go over cracks or gaps well	No noticeable wear
Roll over soft surfaces well	Do not mark floors
Give good traction	Automatically removes foreign matter or debris
No shimmy or vibration	

Impressions were recorded each time the subjects took the survey. If a subject experienced a benefit or problem for the week it was selected in the form, otherwise it was left blank. Each benefit or problem could be selected once each time the survey was filled out.

The next set of questions asked users to rate the performance of the Tweel™ caster or drive wheel on various surfaces that they had rolled over in the last week. The surfaces that could be rated were:

gravel/loose dirt
wet surfaces
soft outdoor surfaces, grass, or sand
rubber flooring or mats
carpet or throw rugs
asphalt or uneven surfaces
concrete sidewalks or cracks
curbs or curb cuts
hardwood or vinyl floors
ramps or slopes

A numeric score was assigned to the answer given by each user when they selected a rating for the performance for each surface. The scores were assigned to the ratings in the following way:

4 = very well
3 = good
2 = poorly
1 = very poorly

Results

During the field trial, 5 subjects had only casters installed, 3 only used drive wheels, and one subject had both caster and drive wheel installed. In total, 6 subjects tested casters, and 4 tested drive wheels only installed.

Subjects used Tweel™ technology tires for slightly different periods of time and filled out a different number of surveys (**Table 6**). The duration of the field trial listed in Table 3 reflects the number of days from when the Tweel™ was installed to the last survey submitted by the subject.

Table 6. Description of filed trial length and surveys completed.

	Subject number	Duration of field trial (days)	# of surveys completed
Caster only group	2	28	5
	3	22	4
	9	20	2
	11	25	4
	13	19	4
Drive wheel only group	4	30	5
	5	21	4
	8	30	5
Caster and Drive wheel	15	26	4

Data on problems and benefits are reported in two manners: the percentage of time that a problem or benefit was reported in a survey and the number of subjects that mentioned a specific problem or benefit. These results can be seen in **Tables 7-10**.

Caster user perceptions. Good turning and maneuverability was mentioned by all 6 subjects and on 100% of the returned surveys. This would represent the most significant benefit of Tweel™ Technology. Subjects also felt that Tweel™ casters absorbed shock from obstacles- being mentioned by all subjects and on >75% of returned surveys. Most subjects also felt the casters rolled well over cracks/gaps and soft surfaces and obstacles. Noticeable wear was mentioned by 5 of the 6 caster users with this response being more frequent as the trial progressed. Over 1/3 of the surveys and 4 or 6 subjects listed shimmy or vibration as a noticeable problem.

Table 7. Caster user question: *Which of the following problems did you experience in the last week?*

	% of surveys mentioning problem	# of subject mentioning problem (out of 6)
Rough ride over uneven or bumpy surfaces	26.1%	2
Stick in cracks gaps or obstacles	0.0%	0
Dig into or get stuck in soft surfaces	17.4%	2
Loss of traction or slippage	17.4%	1
Shimmy or vibration	34.8%	4
Casters shed, peel, or crack	4.3%	1
Casters roll up or push carpets or mats	17.4%	2
Casters mark floors	4.3%	1
Noticeable wear	43.5%	5
Foreign matter or debris gets caught in casters	17.4%	1
Tracks mud	21.7%	2

Table 8. Caster user question: *Which of the following benefits did you experience in the last week?*

	% of surveys mentioning benefit	# of subject mentioning benefit (out of 6)
Smooth ride over bumpy/ uneven surfaces	39.1%	4
Absorb shock from obstacles/ barriers	78.3%	6
Go over cracks/ gaps well	52.2%	5
Roll over soft surfaces well	43.5%	5
Give good traction	34.8%	3
No shimmy or vibration	47.8%	5
Casters turn and maneuver well	100.0%	6
Roll over soft objects well	52.2%	5
No noticeable wear	39.1%	4
Do not mark floors	69.6%	5
Automatically remove debris	34.8%	3

Drive Wheel user perceptions. Drive wheel users noted fewer problems than caster users. As indicated in Table 6, no reports of wear or the marking of floor were recorded. Foreign matter being caught in the drive wheel was noted in over 40% or returned surveys and by 3 of the 4 drive wheel users. Loss of traction was also noted in close to 40% of the returned surveys. Many benefits to the drive wheels were recorded, with all subjects reporting a smooth ride and the ability to absorb shocks.

Table 9. Drive wheel user question: *Which of the following problems did you experience in the last week?*

	% of surveys mentioning problem	# of subject mentioning problem (out of 4)
Rough ride on uneven or bumpy surfaces	22.2%	2
Dig in/ get stuck in soft surfaces	27.8%	2
Lose traction/slip	38.9%	3
Shimmy/ vibration	0.0%	0
Wheels shred/ peel/ crack	0.0%	0
Roll up rugs/ mats	22.2%	3
Mark floors	0.0%	0
Noticeable signs of wear	0.0%	0
Foreign matter caught in wheel	44.4%	3
Track mud inside	22.2%	1

Table 10. Drive wheel user's answers to: *Which of the following benefits did you experience in the last week?*

	% of surveys mentioning benefit	# of subject mentioning benefit (out of 4)
Smooth ride over bumpy/ uneven surfaces	72.2%	4
Absorb shock from obstacles/ barriers	77.8%	4
Go over cracks/ gaps well	66.7%	3
Roll over soft surfaces well	50.0%	3
Give good traction	66.7%	3
No shimmy or vibration	72.2%	3
Roll over soft objects well	33.3%	3
No noticeable signs of wear	72.2%	3
Doesn't mark floors	77.8%	4
Automatically remove debris	11.1%	1

Performance on different surfaces. Subject's perceptions of Tweel™ performance on 10 different surfaces are reported as overall averages. Scores were first analyzed individually- averaging the ratings over the number of surveys returned. Then an overall rating was calculated by averaging these individual ratings (**Figures 1 and 2**). Subjects who did not offer feedback on a particular surface did not contribute to the overall average.

As indicated in the graphs, Tweel™ technology performed well on most surfaces. Only two surfaces were rated below the 'good' level- wet surfaces by drive wheel users and gravel/loose dirt by caster users.

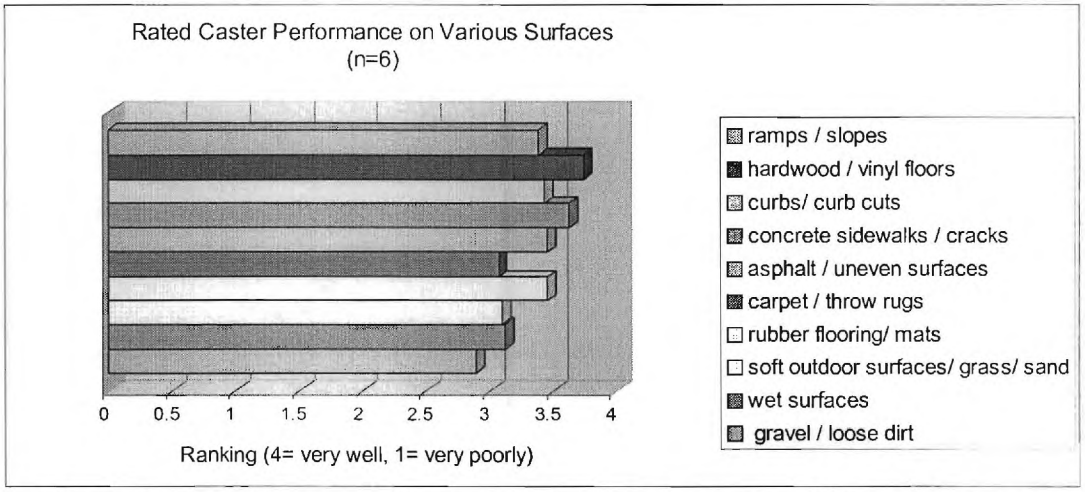


Figure 1. Overall user rankings of caster performance on different surfaces.

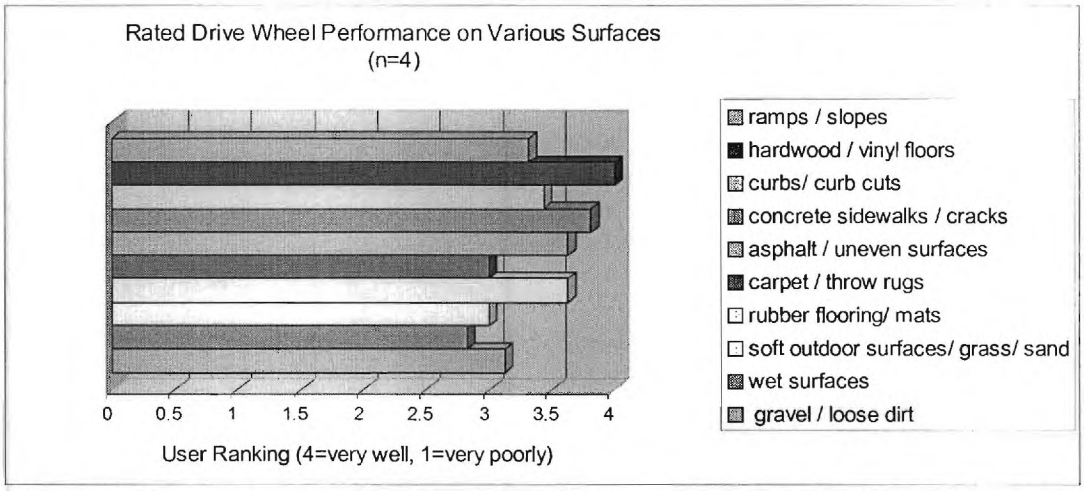


Figure 2. Overall user rankings of drive wheel performance on different surfaces

Overall performance rating. Each survey requested an overall rating of Tweel™ performance on a 4-point scale:

4 = Very Satisfied
3 = Somewhat Satisfied
2 = Somewhat Dissatisfied
1 = Very Dissatisfied

Overall, users were satisfied with both casters and drive wheels. The average ranking for Tweel™ casters was 3.54 and 3.29 for Tweel™ drive wheels.

Conclusion

Several of the needs identified in the focus groups were corroborated or explained by experiences during the field trials. Gravel and loose dirt surfaces, foreign matter caught in wheels, tire wear and tires marking floors were major issues for focus group users. Tweel™ casters and drive wheels did not mark floors. Most users reported foreign matter getting caught in drive wheels but not by caster users. Tweel™ technology performed very well on most surfaces with only limited problems noted. Tire wear was identified as a major problem in the focus groups. No drive wheel subjects noted wear but caster users began reporting wear after one or two weeks of use. Given the short duration of the field trial, this result is significant. Another aspect of the project measured force loss over the field trial and its results corroborated user perception. The overall satisfaction was high for both caster and drive wheel. Despite the issues reported by users, the Tweel™ casters and drive wheels seem to provide certain improvements over those currently used by users in this field trial.

Summary of Findings

Tweel™ Power wheelchair Casters

While the Tweel™ caster was acceptable to a majority of participants, some initial impressions of the Tweel™ casters were mixed as were the results of field trials. Participants were impressed with the airless features, shock absorption characteristics, turning and maneuverability. While study participants were pleased and satisfied with these features, they noted these same features were found in current power caster products.

During focus groups, participants voiced concern about the durability of the Tweel™ technology. This concern was validated by the noticeable wear during field trials. Participants expect Tweel™ casters should last a minimum of three to five years with daily outdoor use. Michelin should address the issue of caster wear.

During focus groups, participants wanted to add more tread to the caster to improve traction. During field trials, users didn't report loss of caster traction on wet surfaces. Focus group participants felt that more crown on the caster would improve performance, but during field trials, users reported high levels of satisfaction with the turning and maneuverability of the current prototype.

Caster bearing wear, maintenance and replacement were also concerns for focus group participants. Bearings are replaced more frequently and had more maintenance issues than caster wheels. Michelin should attend to caster bearings in

terms of durability and usability. A caster bearing that can be easily removed for cleaning would be a competitive advantage.

Aesthetic suggestions included offering a two-color scheme and alternative colors. This is a common practice in current technology. On a related note, a concern was raised about the collection of debris within the spokes of the caster wheel. Foreign matter being caught in the wheels was not mentioned frequently during the field trial, but this issue should be monitored during longer trials.

Tweel™ Power wheelchair Drive Wheels

Focus group participants had a favorable opinion of the Tweel drive wheels. The perception that they would provide shock absorption and a smooth ride was corroborated by the field trial subjects. The drive wheels were thought to be rugged and durable by focus group participants, but noticeable wear was reported during field trials. During focus groups, participants reported the expectation that power drive wheels should last at least three to five years with daily outdoor use. Based upon the field trial results and force loss tests (submitted as a separate report), Michelin should investigate the durability of the drive wheel tire materials.

Focus group participants seemed pleased with the tire tread and tread pattern on the drive wheel prototypes. They believed that the tread would provide good traction on all types of surfaces. However, field trial subjects rated the performance on wet surfaces between 'poor' and 'good'. Focus group participants suggested optional deeper tread be made available for farmers and others who worked (and played) outdoors.

To improve competitive advantage, certain aesthetic suggestions were made, including the availability of a two-color schema and a variety of color options.

Tweel™ Manual Casters

No field trials were done with manual wheelchair users using the Tweel™ caster so all feedback is limited to focus group results. They iterated a need for a range of tire diameters and widths consistent with current caster designs. Participant thought the prototype was too stiff to be used as a manual caster. Manual wheelers reported the same problems with wear, cleaning and replacement of caster bearing as did power wheelchair users.

Participants generally seemed to want the Tweel™ manual caster to have slightly more crown to improve turning and angle compression of the caster, making it less prone to damage from hitting obstacles at an angle. Aesthetic suggestions included the availability of a two-color schema and a variety of color options. Participants also discussed the possibility of reducing the number of caster fins to make the wheel look more conventional. They did acknowledge that any such change should not impact performance.

As in the case of power wheelchair casters, participants expressed concern about debris being caught in the fins. Of note is that field trial subjects did not report this as a significant problem. They also wanted a quick-release mechanism, to facilitate maintenance, cleaning and replacement. To improve safety during transfers, a caster locking mechanism should be considered.

One notable discussion centered on the concept of selectable stiffness that could be adjusted by the user, depending on the environment. While this idea was not probed in-depth, it seemed to address a major design tradeoff in which casters are not well designed for different surfaces and environments.

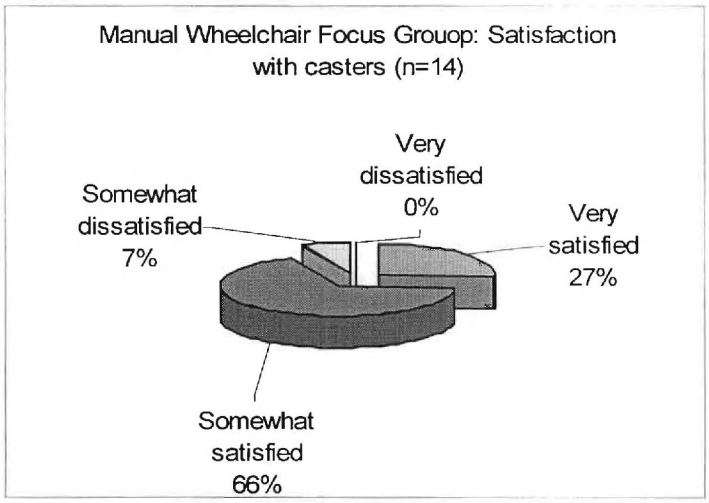
Appendix

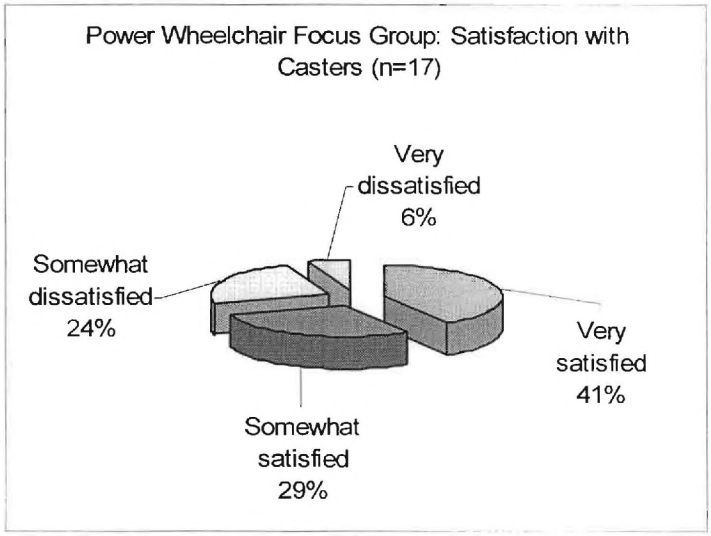
The **Appendix** includes the pre-focus group survey, the focus group discussion script, Field Trial Protocol and the Field Trial On-line Survey.

Survey Results – Pre Focus Group and On-Line Survey

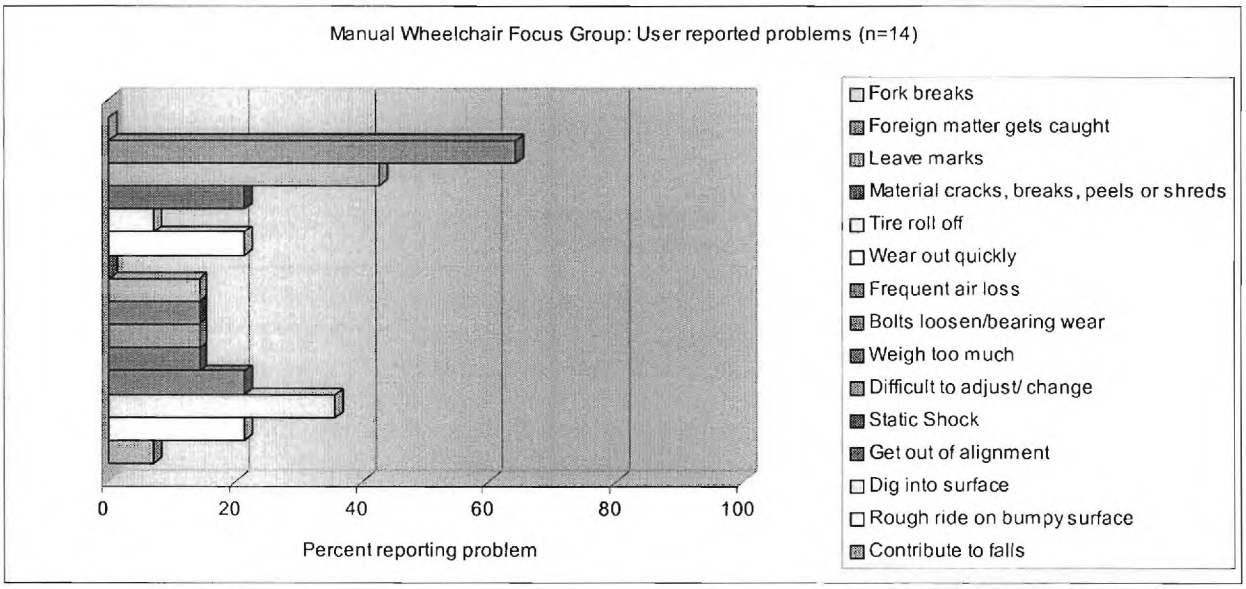
Survey data from the online and focus group surveys for manual and power wheelchair users is presented below. The survey questions are presented after the data.

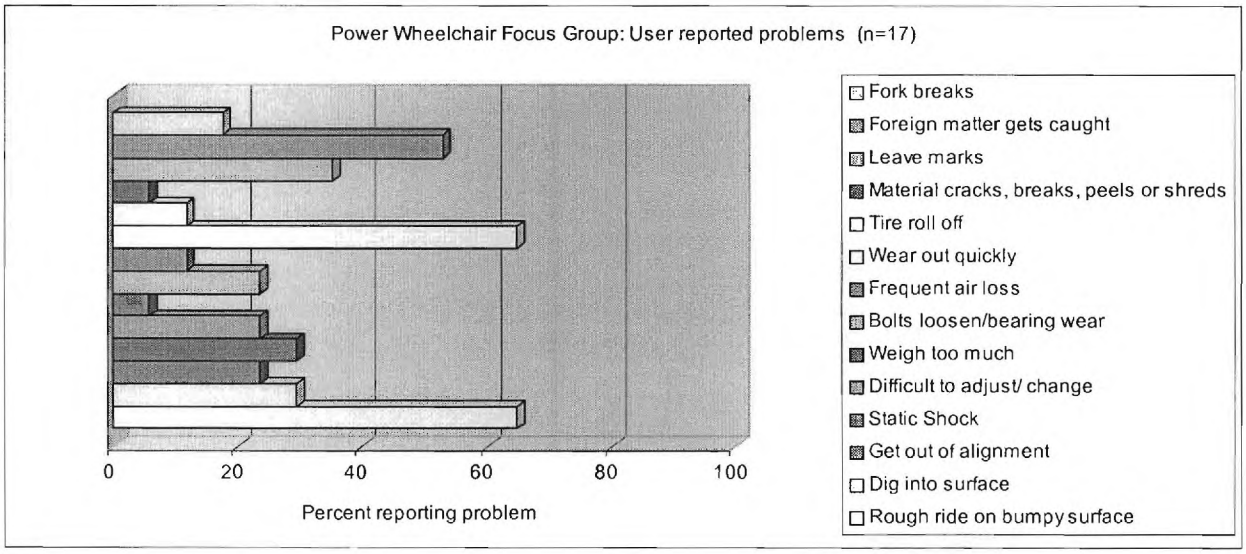
Survey question asked in focus groups:
How satisfied are you with the performance of your caster wheels?

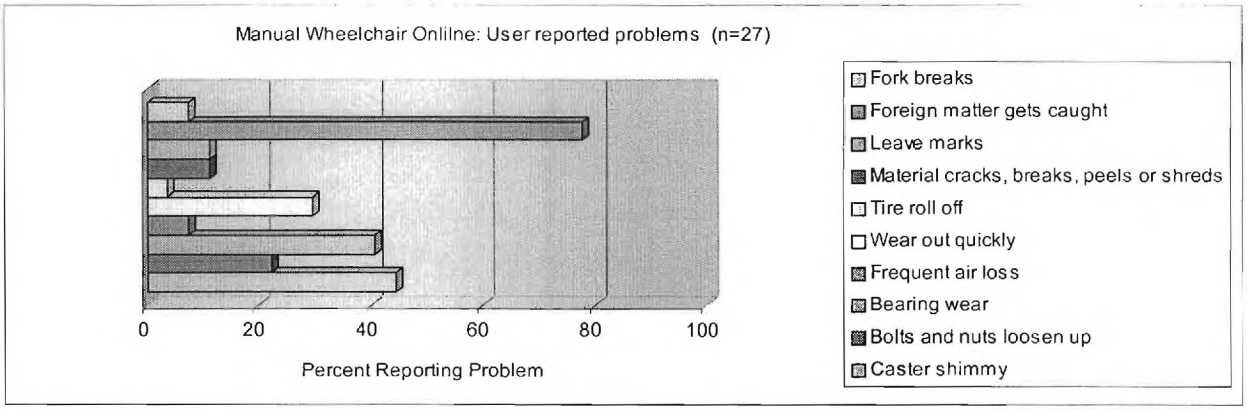


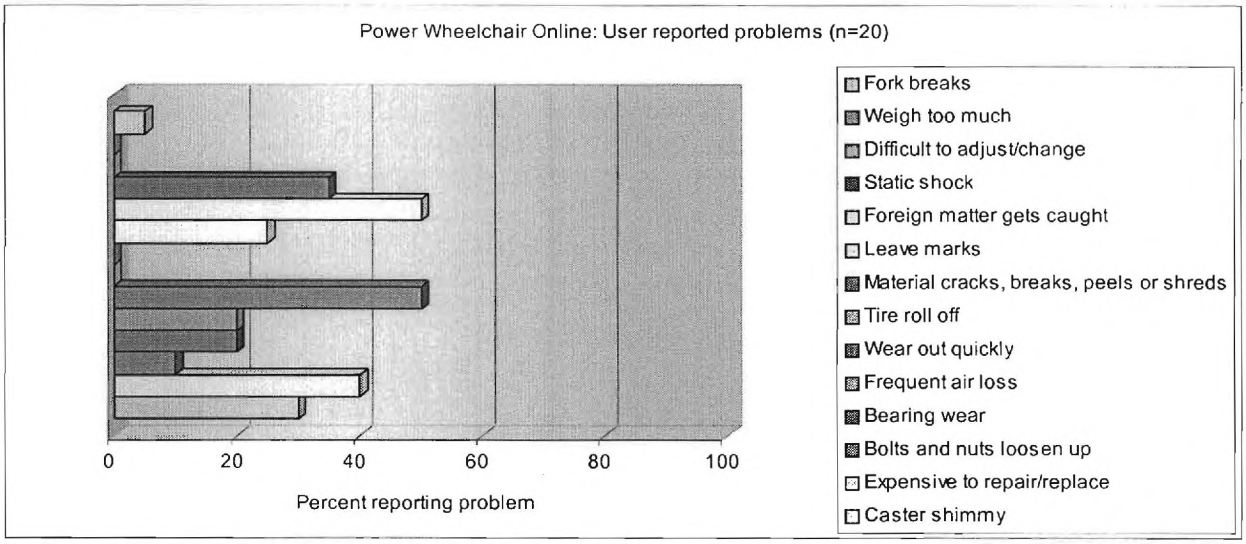


Survey question asked in focus groups:
What caster related problems have you experienced?

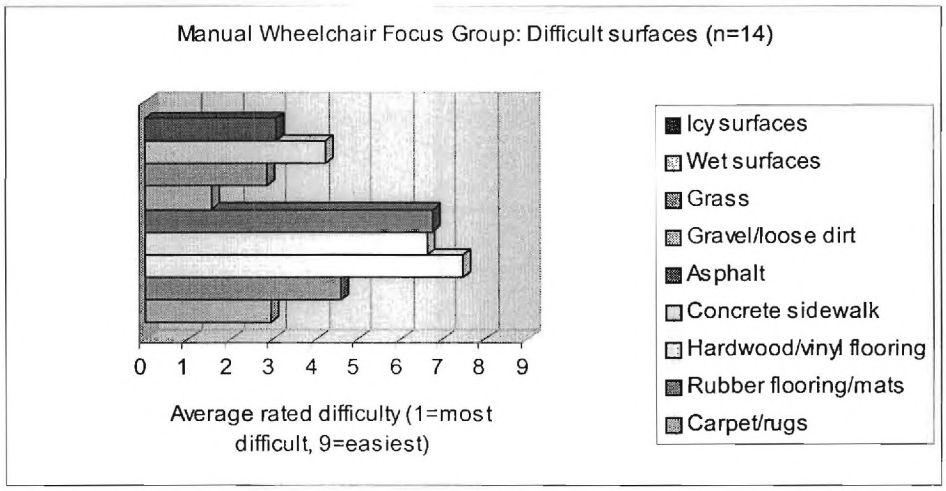


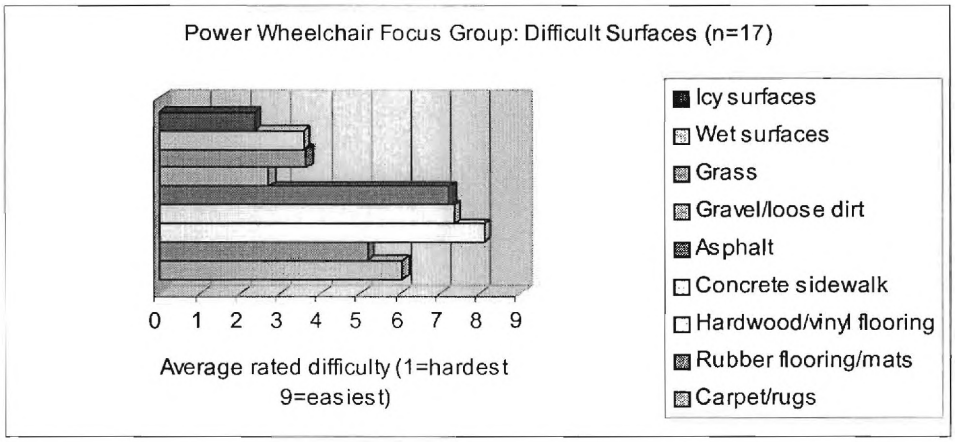


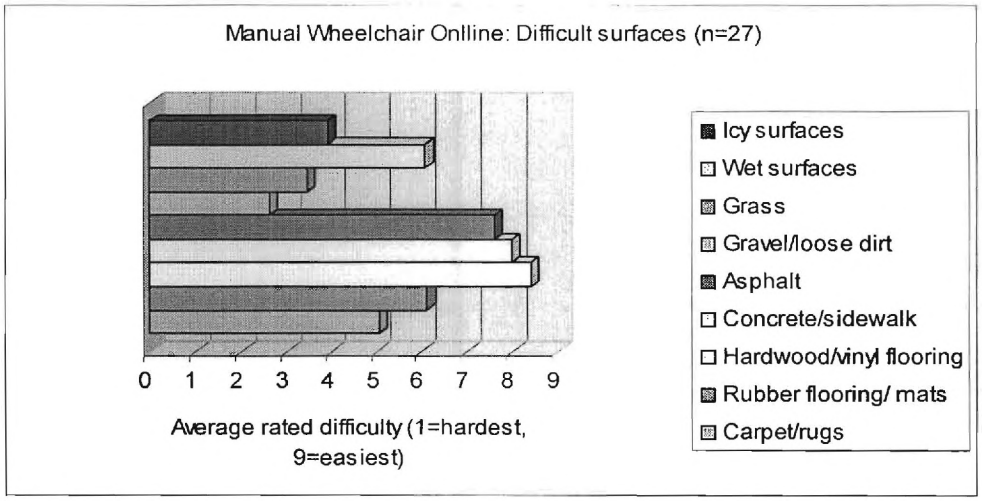

Manual Wheelchair Onlilne: User reported problems (n=27)
0
20
40
60
80
100
Percent Reporting Problem
Fork breaks
Foreign matter gets caught
Leave marks
Material cracks, breaks, peels or shreds
Tire roll off
Wear out quickly
Frequent air loss
Bearing wear
Bolts and nuts loosen up
Caster shimmy

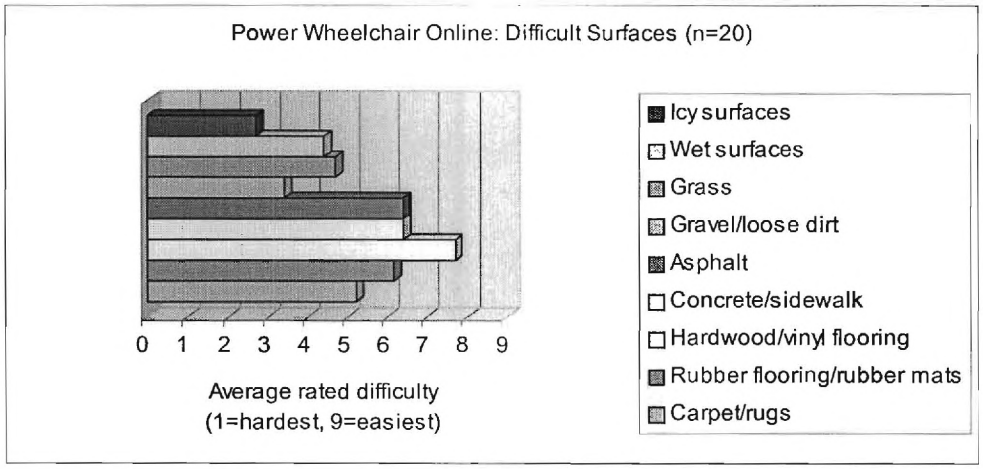

Power Wheelchair Online: User reported problems (n=20)
0
20
40
60
80
100
Percent reporting problem
Fork breaks
Weigh too much
Difficult to adjust/change
Static shock
Foreign matter gets caught
Leave marks
Material cracks, breaks, peels or shreds
Tire roll off
Wear out quickly
Frequent air loss
Bearing wear
Bolts and nuts loosen up
Expensive to repair/replace
Caster shimmy

Survey question asked in focus groups:
Order the following surfaces according to the difficulty you experience when pushing/rolling over them ---1 is most difficult, 9 is the easiest.

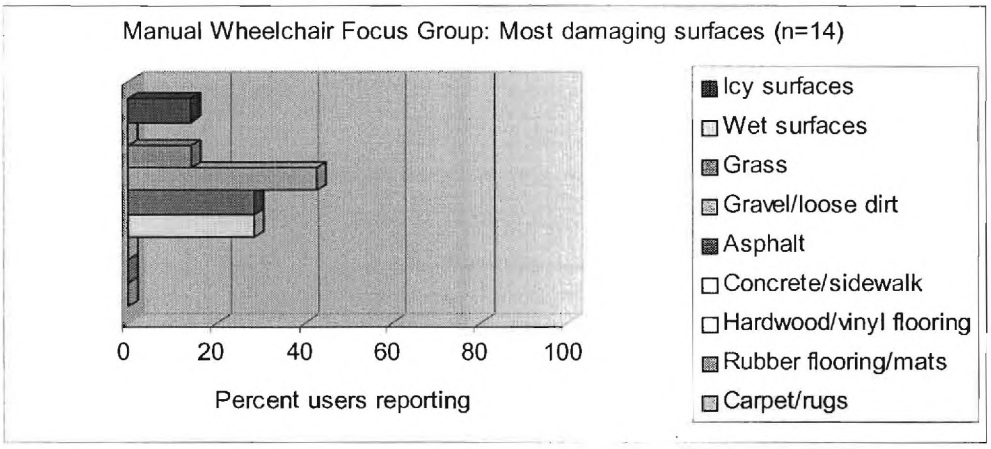


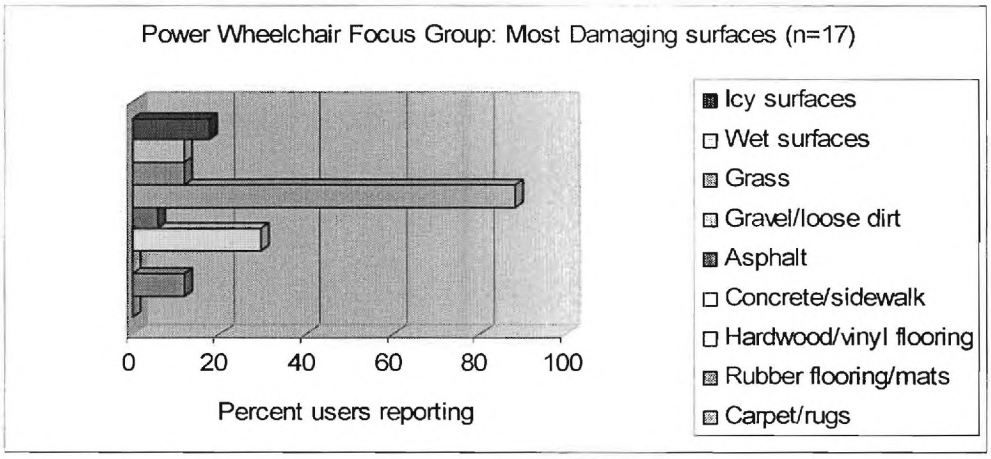


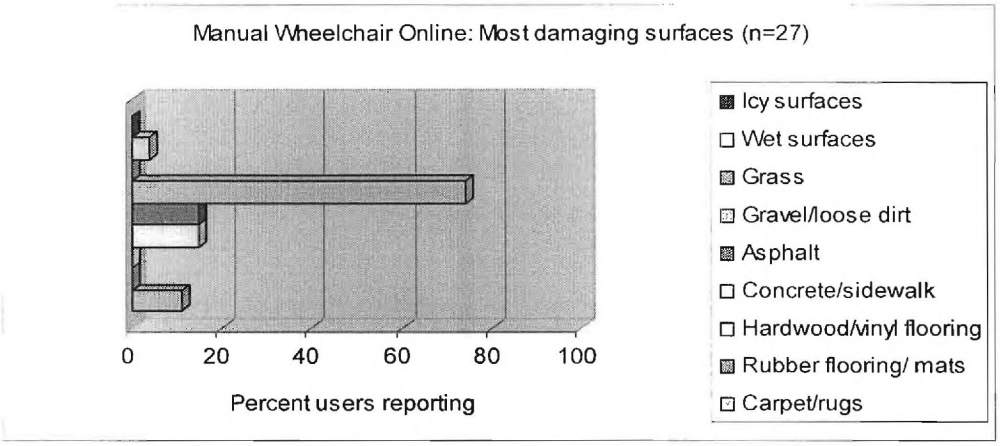

Manual Wheelchair Onlline: Difficult surfaces (n=27)
0 1 2 3 4 5 6 7 8 9
Average rated difficulty (1=hardest, 9=easiest)
Icy surfaces
Wet surfaces
Grass
Gravel/loose dirt
Asphalt
Concrete/sidewalk
Hardwood/vinyl flooring
Rubber flooring/ mats
Carpet/rugs

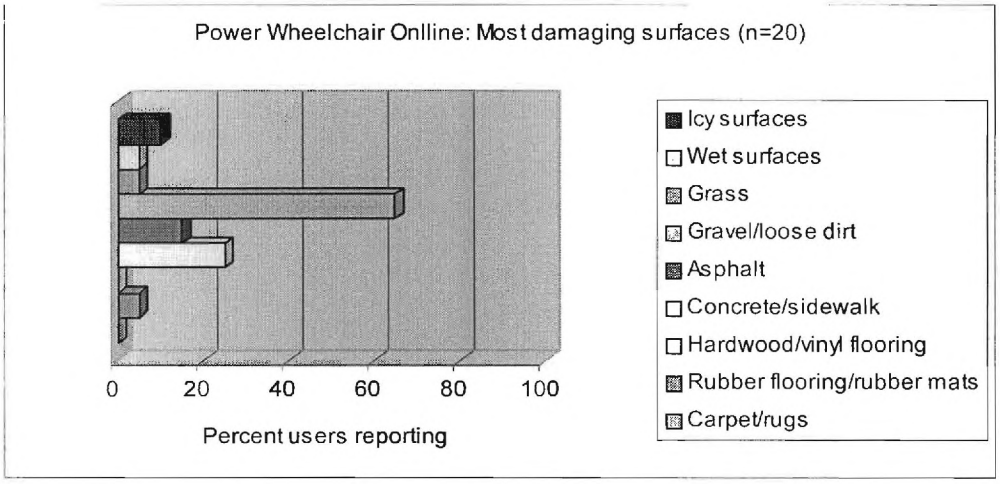

Power Wheelchair Online: Difficult Surfaces (n=20)
0 1 2 3 4 5 6 7 8 9
Average rated difficulty (1=hardest, 9=easiest)
Icy surfaces
Wet surfaces
Grass
Gravel/loose dirt
Asphalt
Concrete/sidewalk
Hardwood/vinyl flooring
Rubber flooring/rubber mats
Carpet/rugs

Survey question asked in focus groups:
Which surfaces cause the most damage to your casters?

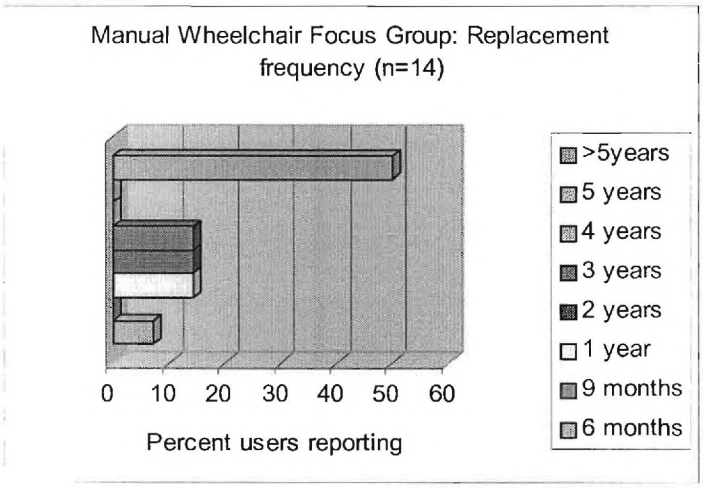


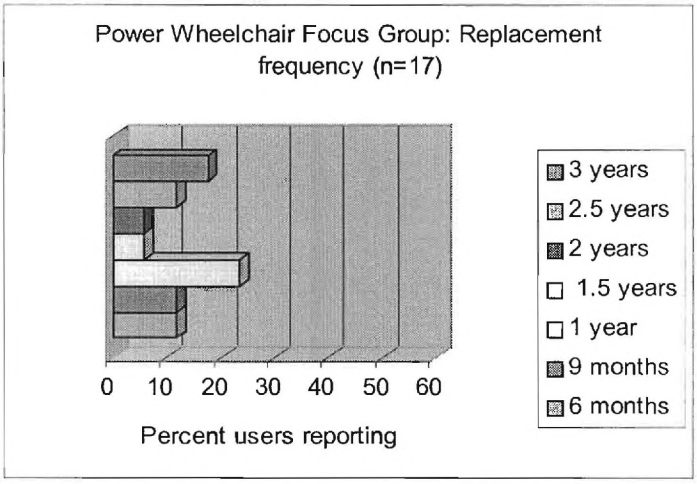


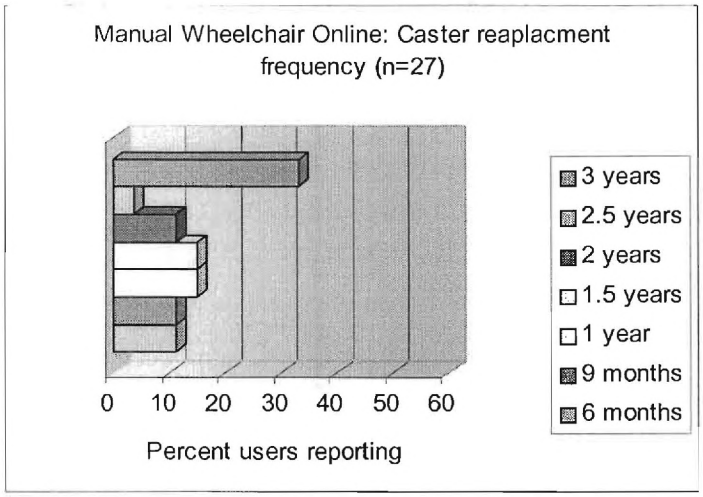

Manual Wheelchair Online: Most damaging surfaces (n=27)
0
20
40
60
80
100
Percent users reporting
Icy surfaces
Wet surfaces
Grass
Gravel/loose dirt
Asphalt
Concrete/sidewalk
Hardwood/vinyl flooring
Rubber flooring/ mats
Carpet/rugs

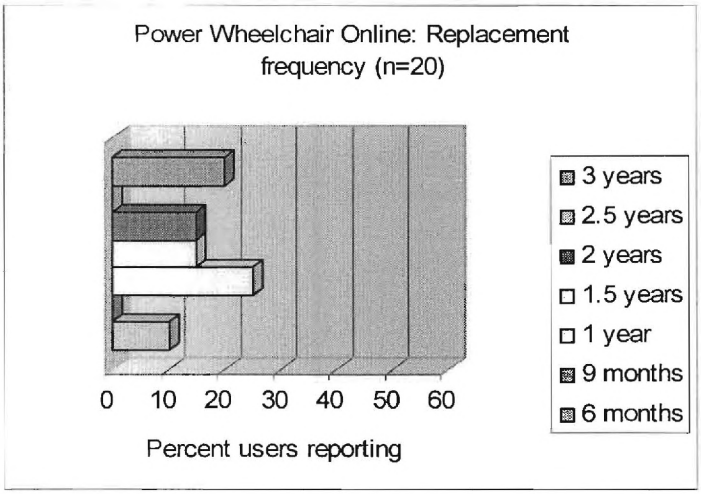

Power Wheelchair Onlline: Most damaging surfaces (n=20)
0
20
40
60
80
100
Percent users reporting
Icy surfaces
Wet surfaces
Grass
Gravel/loose dirt
Asphalt
Concrete/sidewalk
Hardwood/vinyl flooring
Rubber flooring/rubber mats
Carpet/rugs

Survey question asked in focus groups:
How often are the casters on your wheelchair replaced?

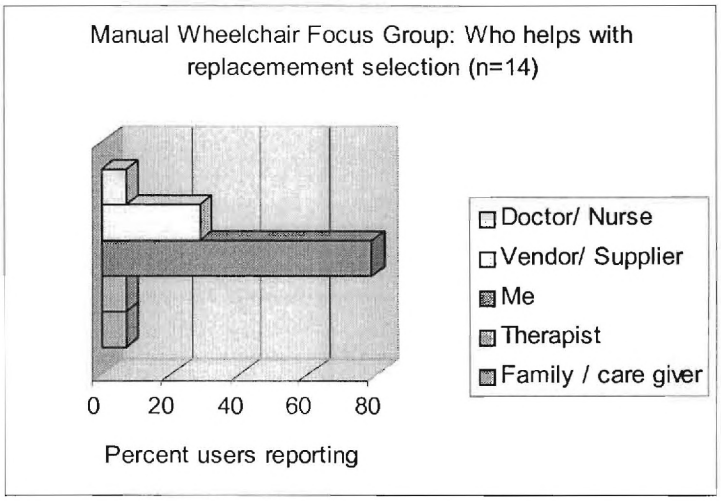


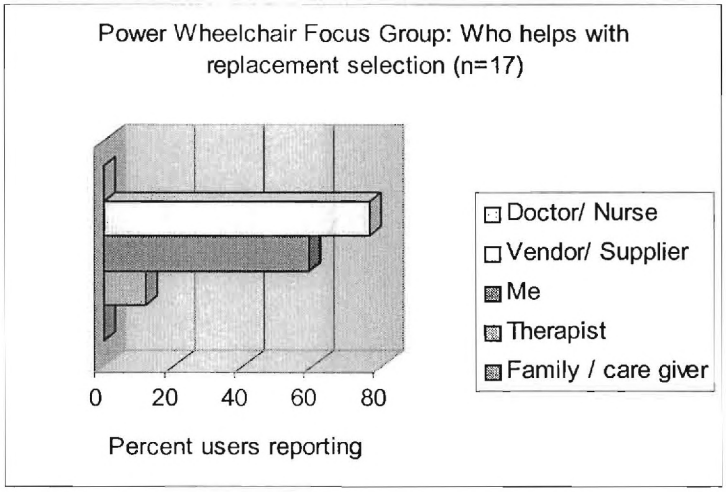


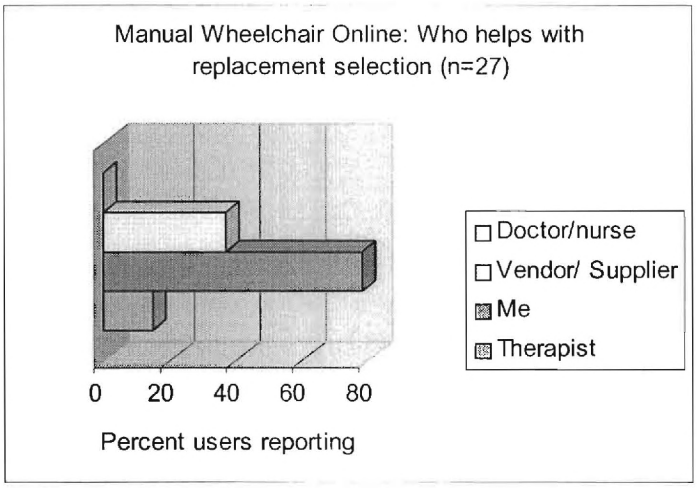

Manual Wheelchair Online: Caster reaplacment frequency (n=27)
0
10
20
30
40
50
60
Percent users reporting
3 years
2.5 years
2 years
1.5 years
1 year
9 months
6 months

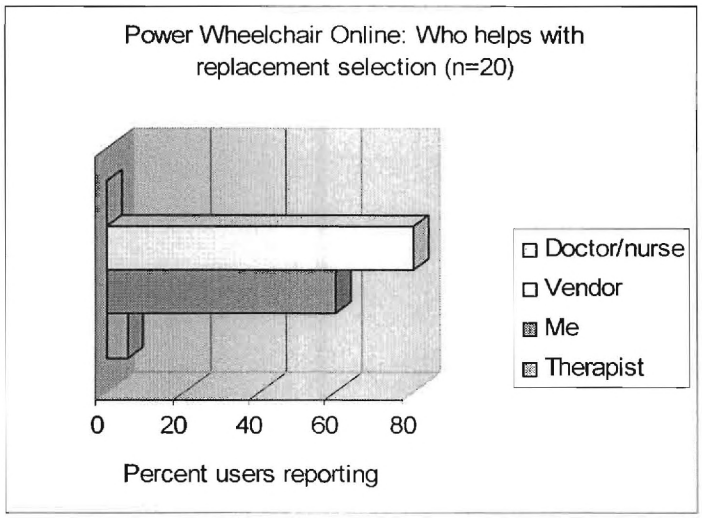

Power Wheelchair Online: Replacement frequency (n=20)
0
10
20
30
40
50
60
Percent users reporting
3 years
2.5 years
2 years
1.5 years
1 year
9 months
6 months

Survey question asked in focus groups:
Who participates in the selection of casters for your wheelchair?

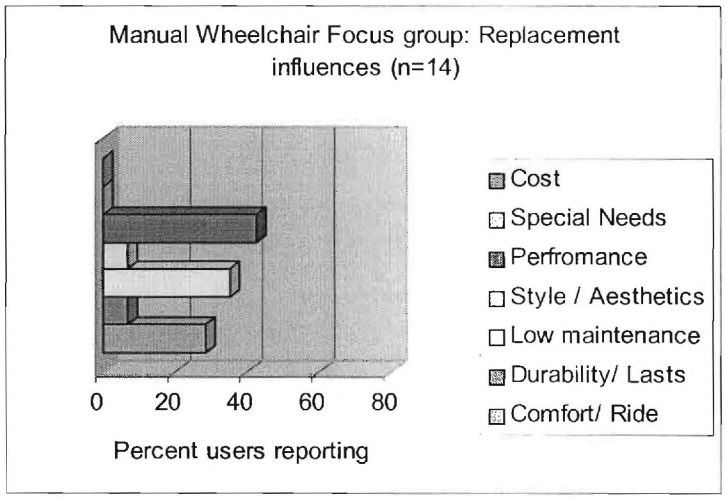


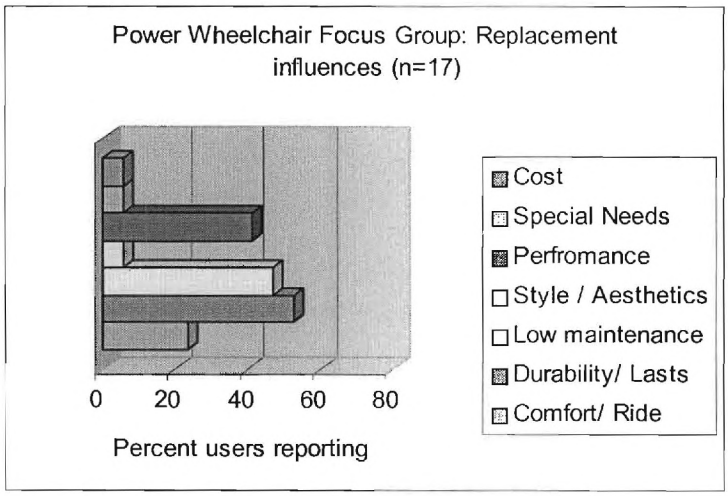


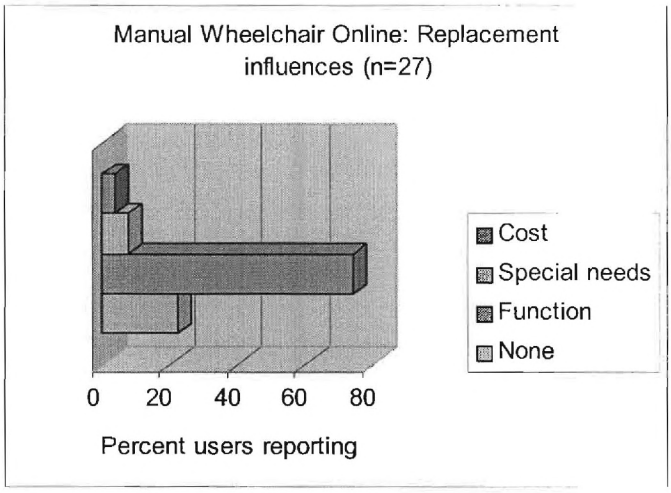

Manual Wheelchair Online: Who helps with replacement selection (n=27)
0
20
40
60
80
Percent users reporting
Doctor/nurse
Vendor/ Supplier
Me
Therapist

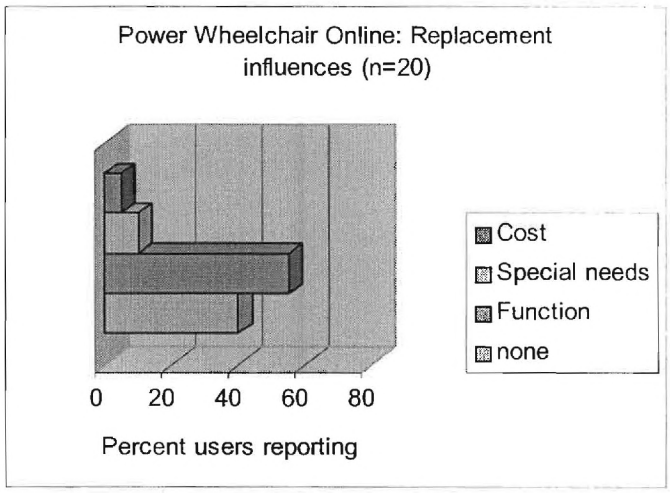

Power Wheelchair Online: Who helps with replacement selection (n=20)
0
20
40
60
80
Percent users reporting
Doctor/nurse
Vendor
Me
Therapist

Survey question asked in focus groups:
Which of the following <u>most</u> influences your selection of casters?

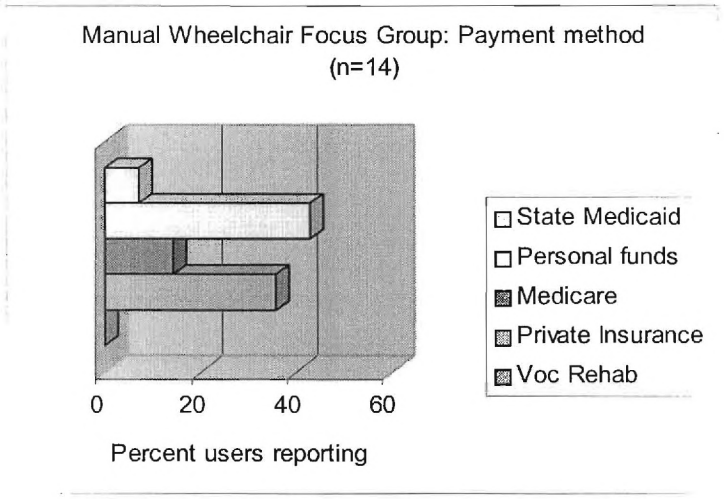


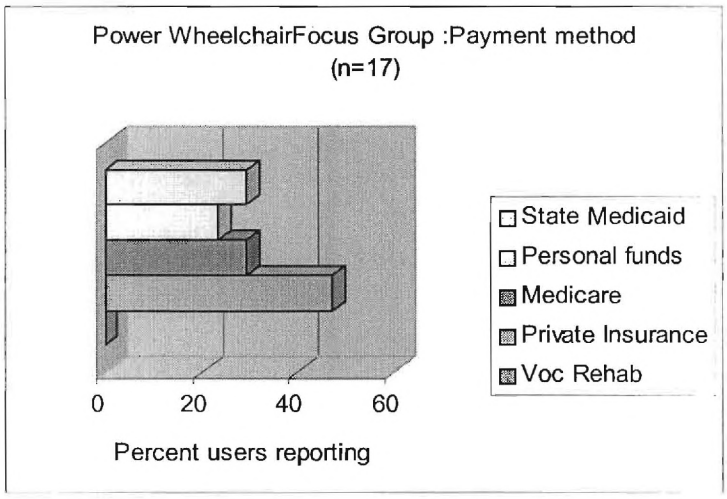


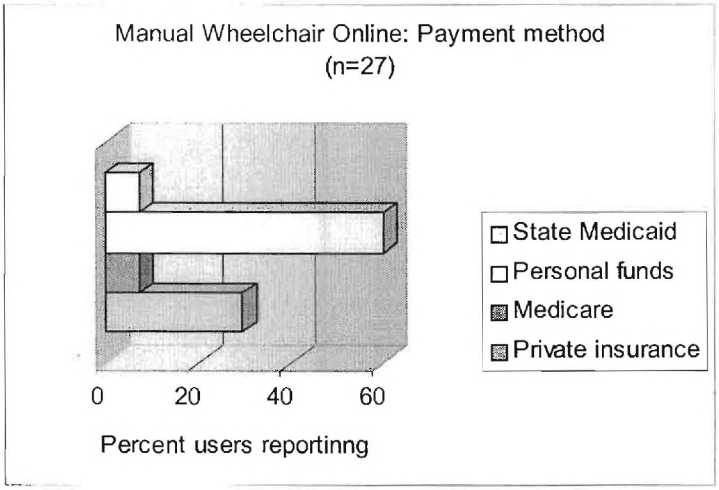

Manual Wheelchair Online: Replacement influences (n=27)
0
20
40
60
80
Percent users reporting
Cost
Special needs
Function
None

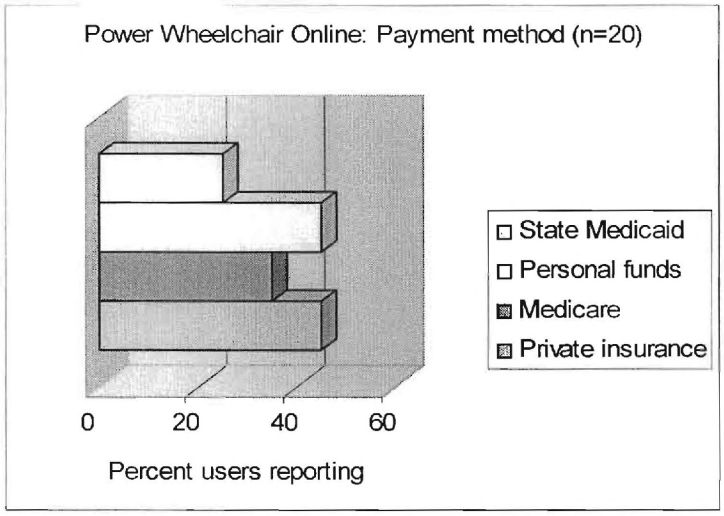

Power Wheelchair Online: Replacement influences (n=20)
0
20
40
60
80
Percent users reporting
Cost
Special needs
Function
none

Survey question asked in focus groups:
How are replacement casters on your wheelchair usually paid for?

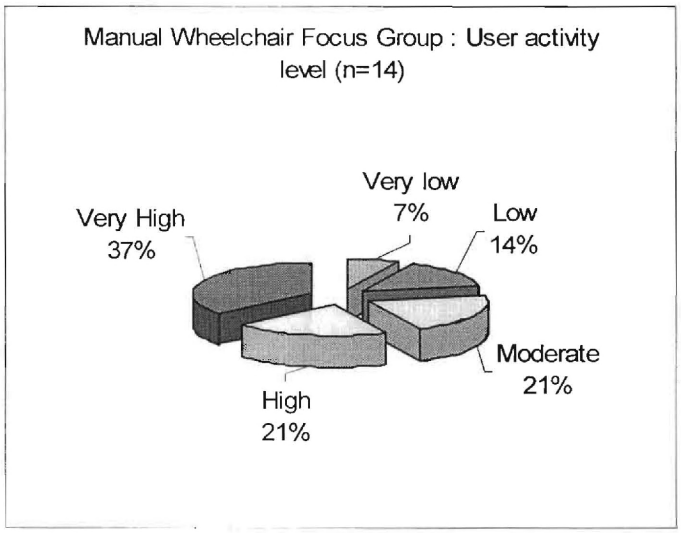


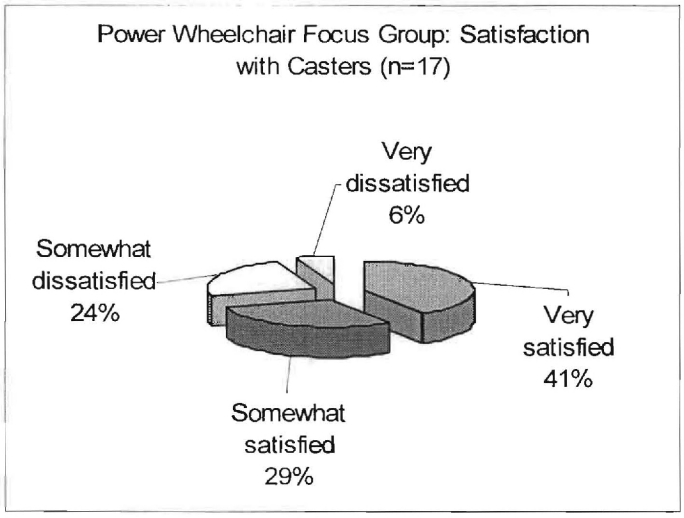


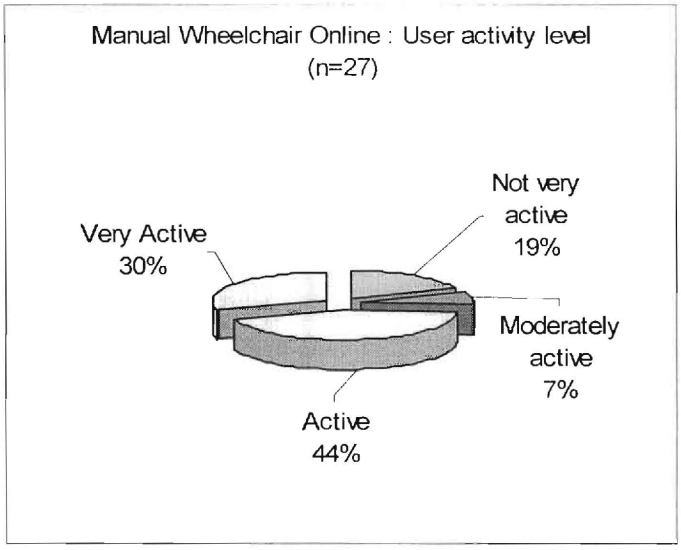

Manual Wheelchair Online: Payment method
(n=27)
State Medicaid
Personal funds
Medicare
Private insurance
0
20
40
60
Percent users reportinng

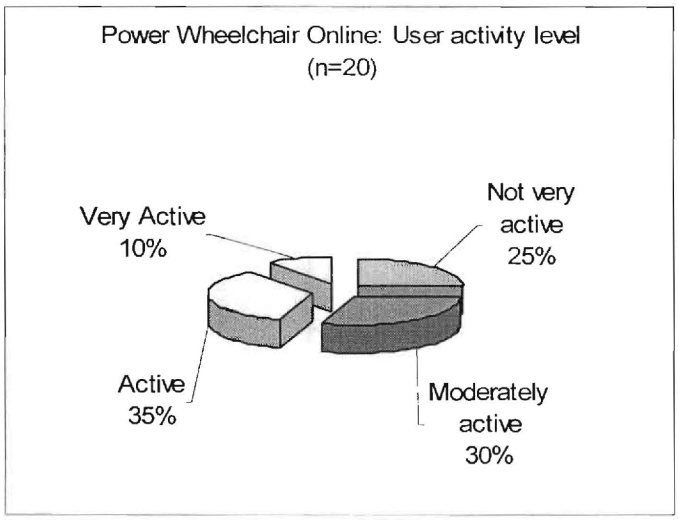

Power Wheelchair Online: Payment method (n=20)
State Medicaid
Personal funds
Medicare
Private insurance
0
20
40
60
Percent users reporting

Survey question asked in focus groups:
How do you rate your weekly activity level?






Manual Wheelchair Online : User activity level
(n=27)
Not very active 19%
Very Active 30%
Moderately active 7%
Active 44%


Power Wheelchair Online: User activity level
(n=20)
Not very active 25%
Very Active 10%
Active 35%
Moderately active 30%

Pre-Focus Group Power Wheelchair User Survey

This short survey is related to power wheelchair caster and drive wheel use. There are two parts to the survey. The survey will take about 10 minutes to complete. **Part I** asks about your current equipment, your satisfaction with this equipment, problems you experience using casters and power drive wheels and how often you replace these parts. **Part II** asks for some basic information about your situation.

Part I-Your Current Equipment, Problems & Replacement

For each question below, place an "X" in the box that best describes your situation. *Your answers will be confidential.*

What is the make (manufacturer) and model of your current wheelchair?

Make _____

Model _____

What size caster wheels are on your power wheelchair?

- ☐ 4 x 2 Casters
- ☐ 5 x 2 Casters
- ☐ 6 x 1 ¼ Casters
- ☐ 6 x 2 Casters
- ☐ 8 x 1 ¾ Casters
- ☐ 8 x 2 Casters
- ☐ 8 x 2 ¼ Casters
- ☐ 9 x 2 Casters

What type of caster wheels are they? Are these casters...

- ☐ Air up (pneumatic)
- ☐ Hard Roll (non-pneumatic)

How satisfied are you with the performance of these caster wheels?

☐ very satisfied ☐ somewhat satisfied ☐ somewhat dissatisfied ☐ very dissatisfied

What size of power drive wheels are on your power wheelchair?

- ☐ 10 x 3
- ☐ 10 ½ x 3 ½
- ☐ Other size _____
- ☐ 12 ½ x 2 ¼
- ☐ 14 x 3

What type of power drive wheels are they? Are these power drive wheels...

- ☐ Air up (pneumatic)
- ☐ Hard Roll (non-pneumatic)

How satisfied are you with the performance of these power drive wheels?

☐ very satisfied ☐ somewhat satisfied ☐ somewhat dissatisfied ☐ very dissatisfied

What types of caster and/or power drive wheel related problems have you experienced (Check all that apply)?

- ☐ Rough ride on bumpy surfaces sometimes jars me or makes my back/butt hurt
- ☐ Dig into surfaces making it difficult to roll over the surface
- ☐ Frequent air loss and/or flats on pneumatic (air up) tires
- ☐ Wear out to quickly
- ☐ Tire roll-off (i.e. tire rolls off the caster)
- ☐ Get out of alignment, shimmy or wiggle and vibrate
- ☐ Fail suddenly and/or material cracks, breaks, peels apart or shreds
- ☐ Leave marks on carpet or other types of flooring
- ☐ Foreign matter (i.e. hair, thread, dirt, etc.) gets caught in casters
- ☐ Buildup static electricity and shock me
- ☐ Are difficult to adjust and change out
- ☐ Weigh too much
- ☐ Caster bolts and nuts loosen up and/or bearings wear out or freeze-up
- ☐ Caster fork breaks

Order the following surfaces according to the difficulty you experience when rolling over them--1 is most difficult, 9 is the easiest.

_____ Carpet or rugs	_____ Gravel or loose dirt
_____ Rubber flooring or rubber mats	_____ Grass
_____ Hardwood or vinyl flooring	_____ Wet surfaces
_____ Concrete sidewalk	_____ Icy surfaces
_____ Asphalt	_____ Other _____

Which surface causes the most damage to your casters or drive wheels (Choose one)?

☐ Carpet or rugs	☐ Gravel or loose dirt
☐ Rubber flooring or rubber mats	☐ Grass
☐ Hardwood or vinyl flooring	☐ Wet surfaces
☐ Concrete sidewalk	☐ Icy surfaces
☐ Asphalt	_____ Other _____

Which of the following most influences your selection of casters and power drive wheel tires?

☐ Comfort/ride	☐ Cost
☐ Performance	☐ Style/ Aesthetics
☐ Durability/ Lasts long time	☐ Special needs
☐ Low maintenance	☐ Other _____

How are replacement casters and power drive wheel tires on your wheelchair usually paid for?

- ☐ Private Insurance
- ☐ Out-of-pocket/ personal funds
- ☐ Vocational Rehab
- ☐ Medicare
- ☐ State Medicaid
- ☐ Other _____

Who participates in the selection of casters and power drive wheel tires for your wheelchair (Check all that apply)?

- ☐ Me
- ☐ Vendor/Supplier
- ☐ Doctor/Nurse
- ☐ My family/care giver/attendant
- ☐ Therapist
- ☐ Other _____

How often are the casters on your wheelchair replaced?

- ☐ Every 6 months
- ☐ Every 9 months
- ☐ Every year
- ☐ Every year and a half
- ☐ Every two years
- ☐ Every two and a half years
- ☐ Every three years
- ☐ Other _____

How often are the drive wheel tires on your wheelchair replaced?

- ☐ Every 6 months
- ☐ Every 9 months
- ☐ Every year
- ☐ Every year and a half
- ☐ Every two years
- ☐ Every two and a half years
- ☐ Every three years
- ☐ Other _____

How many casters do you typically obtain/replace at one time?

- ☐ one
- ☐ three
- ☐ more than four
- ☐ two
- ☐ four
- ☐ Don't' know/other _____

How much do you spend out-of-pocket (using personal funds) on the caster(s) during the period you checked above?

Dollar amount $_____ per (time frame) _____

How many drive wheel tires do you typically obtain/replace at one time?

- ☐ one
- ☐ three
- ☐ more than four
- ☐ two
- ☐ four
- ☐ Don't know/other _____

How much do you spend out-of-pocket (using personal funds) on the drive wheel tire(s) during the period you checked above?

Dollar amount $_____ per (time frame) _____

From where are your casters and drive wheel tires obtained or purchased?

- ☐ Local DME vendor supplier
- ☐ Bike/Skate Boarding shop
- ☐ Other _____
- ☐ Catalog sales _____
- ☐ Internet site _____
- ☐ Do not know

Rank the following caster and drive wheel tire colors from 1 (most desirable) to 7 (least desirable)

- _____ Black
- _____ Green
- _____ Grey
- _____ Yellow
- _____ Blue
- _____ Orange
- _____ Red
- _____ Other color _____

Select the following caster effects that you prefer?

☐ Clear ☐ Lighted ☐ None ☐ Other _____

What front suspension system do you have on your wheelchair?

- ☐ Frog Legs
- ☐ Bull Frogs
- ☐ Frog Legs Uni-Tine Forks
- ☐ Do not know
- ☐ None
- ☐ Other _____

How satisfied are you with this suspension system?

☐ very satisfied ☐ somewhat satisfied ☐ somewhat dissatisfied ☐ very dissatisfied

Part II-Please tell us a little about you...

What is your year of birth? 19 ___ ___

What is your gender? ☐ **Male** ☐ **Female**

What is your ethnicity?

- ☐ Asian or Pacific Islander
- ☐ African-American
- ☐ Native American or Alaskan Native
- ☐ Other _____
- ☐ Asian Indian or Middle Easterner
- ☐ Hispanic or Latino
- ☐ White/Caucasian

Where is your home located?

- ☐ Rural community/in the country
- ☐ Small to mid-sized town
- ☐ Suburban neighborhood
- ☐ Urban neighborhood/inner city

What is your current level of employment? (Check all that apply)

- ☐ Employed full-time
- ☐ Employed part-time
- ☐ Parenting/Homemaker
- ☐ Full-time student
- ☐ Part-time student
- ☐ Unemployed
- ☐ Unable to work
- ☐ Other _____

How do you rate your weekly activity level?

- ☐ **very low** (unemployed, only leave home about once or twice weekly)
- ☐ **low** (unemployed, leave home about once per day, move around inside home)
- ☐ **moderate** (at least a part-time employee or student, leave home more than once per day and move outside home, access community services outside home)
- ☐ **high** (full-time employee or student, leave home more than once per day, more around outside the home, access community services)
- ☐ **very high** (in addition to "active," play a sport like wheelchair basketball or tennis at least once per week)

What is your total average monthly household income? (Optional)

- ☐ Less than $600
- ☐ $600-$1199
- ☐ $1200-$1999
- ☐ $2000-$2999
- ☐ $3000-$4999
- ☐ $5000 or more

Pre-Focus Group Manual Wheelchair User Survey

This short survey is related to manual wheelchair caster use. There are two parts to the survey. The survey will take about ten minutes to complete. **Part I** asks about your current equipment, your satisfaction with this equipment, problems you experience using manual casters and how often you replace these parts. **Part II** asks for some basic information about your situation.

Part I-Your Current Equipment, Problems & Replacement

For each question below, place an "X" in the box that best describes your situation. Your answers will be confidential.

What is the make (manufacturer) and model of your current wheelchair?
Make _____
Model _____

What casters are on your manual wheelchair?
☐ 3 x 1 Roller Blade Casters
☐ 4 x 1 Roller Blade Casters
☐ 4 x 1 Soft Roll Casters
☐ 4 x 1 Frog Legs Soft Roll Casters
☐ 4 x 1 Aluminum Micro Casters
☐ 4 x 1 ½ Machined Aluminum Casters
☐ 5 x 1 Poly Casters
☐ 5 x 1 Soft Roll Casters
☐ 5 x 1 Frog Legs Soft Roll Casters
☐ 5 x 1 Machined Aluminum Casters
☐ 5 x 1½ Poly Casters
☐ 5 x 1½ Machined Aluminum Casters
☐ 6 x 1¼ Soft Roll Casters
☐ 6 x 1¼ Pneumatic (air up) Casters
☐ 6 x 1½ Poly Casters
☐ 6 x 1½ Machined Aluminum Casters
☐ 8 x 1 Poly Casters
☐ 8 x 1¼ Soft Roll Casters
☐ 8 x 1¼ Pneumatic (air up) Casters

How satisfied are you with the performance of these caster wheels?
☐ very satisfied ☐ somewhat satisfied ☐ somewhat dissatisfied ☐ very dissatisfied

What caster related problems have you experienced (Check all that apply)?

- ☐ Rough ride on bumpy surfaces sometimes jars me or makes my back/butt hurt
- ☐ Dig into surfaces making it difficult to roll over the surface
- ☐ Frequent air loss and/or flats on pneumatic (air up) tires
- ☐ Wear out to quickly
- ☐ Tire roll-off (i.e. tire rolls off the caster)
- ☐ Get out of alignment, shimmy or wiggle and vibrate
- ☐ Fail suddenly and/or material cracks, breaks, peels apart or shreds
- ☐ Leave marks on carpet or other types of flooring
- ☐ Foreign matter (i.e. hair, thread, dirt, etc.) gets caught in casters
- ☐ Buildup static electricity and shock me
- ☐ Are difficult to adjust and change out
- ☐ Weigh too much
- ☐ Caster bolts and nuts loosen up and/or bearings wear out or freeze-up
- ☐ Caster fork breaks

Order the following surfaces according to the difficulty you experience when pushing/rolling over them---1 is most difficult, 9 is the easiest.

_____ Carpet or rugs
_____ Rubber flooring or rubber mats
_____ Hardwood or vinyl flooring
_____ Concrete sidewalk
_____ Asphalt
_____ Gravel or loose dirt
_____ Grass
_____ Wet surfaces
_____ Icy surfaces
_____ Other _____

Which surface causes the most damage to your casters? (Choose one)

- ☐ Carpet or rugs
- ☐ Rubber flooring or rubber mats
- ☐ Hardwood or vinyl flooring
- ☐ Concrete sidewalk
- ☐ Asphalt
- ☐ Gravel or loose dirt
- ☐ Grass
- ☐ Wet surfaces
- ☐ Icy surfaces
- ☐ Other _____

Which of the following most influences your selection of casters?

- ☐ Comfort/ride
- ☐ Performance
- ☐ Durability/ Lasts long time
- ☐ Low maintenance
- ☐ Cost
- ☐ Style/ Aesthetics
- ☐ Special needs
- ☐ Other _____

How are replacement casters on your wheelchair usually paid for?

- ☐ Private Insurance
- ☐ Out-of-pocket/ personal funds
- ☐ Vocational Rehab
- ☐ Medicare
- ☐ State Medicaid
- ☐ Other _____

Who participates in the selection of casters for your manual wheelchair (Check all that apply)?

- ☐ Me
- ☐ Vendor/Supplier
- ☐ Doctor/Nurse
- ☐ My family/care giver/attendant
- ☐ Therapist
- ☐ Other _____

How often are the casters on your wheelchair replaced?

☐ every 6 months ☐ every nine months
☐ every year ☐ every two years
☐ every three years ☐ every four years
☐ every five years ☐ other _____

How many casters do you typically obtain/replace at one time?

☐ one ☐ two
☐ three ☐ four
☐ more than four ☐ Don't' know/other _____

How much do you spend out-of-pocket (using personal funds) on the caster(s) during the period you checked above?

Dollar amount $_____ per (time frame) _____

From where are your casters obtained or purchased?

☐ Local DME vendor supplier ☐ Catalog sales _____
☐ Bike/Boarding Sports shop ☐ Internet site _____
☐ Other _____ ☐ Do not know

Order the following caster colors from 1 (most desirable) to 7 (least desirable)

_____ Black _____ Blue
_____ Green _____ Orange
_____ Grey _____ Red
_____ Yellow _____ Other color _____

Select the following caster effects that you prefer?

☐ Clear ☐ Lighted ☐ None ☐ Other _____

What front suspension system do you have on your current wheelchair?

☐ Frog Legs ☐ Bull Frogs
☐ Frog Legs Uni-Tine Forks ☐ Do not know
☐ Other _____ ☐ None

How satisfied are you with this suspension system?

☐ very satisfied ☐ somewhat satisfied ☐ somewhat dissatisfied ☐ very dissatisfied

Part II-Please tell us a little about you...

What is your year of birth? 19 ___ ___

What is your gender? ☐ Male ☐ Female

What is your ethnicity?

☐ Asian or Pacific Islander
☐ Asian Indian or Middle Easterner
☐ African-American
☐ Hispanic or Latino
☐ Native American or Alaskan Native
☐ White/Caucasian
☐ Other _____

Where is your home located?

☐ Rural community/in the country
☐ Small to mid-sized town
☐ Suburban neighborhood
☐ Urban neighborhood/inner city

What is your current level of employment? (Check all that apply)

☐ Employed full-time
☐ Employed part-time
☐ Parenting/Homemaker
☐ Full-time student
☐ Part-time student
☐ Unemployed
☐ Unable to work
☐ Other _____

How do you rate your weekly activity level?

☐ very low (unemployed, only leave home about once or twice weekly)
☐ low (unemployed, leave home about once per day, move around inside home)
☐ moderate (at least a part-time employee or student, leave home more than once per day and move outside home, access community services outside home)
☐ high (full-time employee or student, leave home more than once per day, more around outside the home, access community services)
☐ very high (in addition to "active," play a sport like wheelchair basketball or tennis at least once per week)

What is your total average monthly household income? (Optional)

☐ Less than $600
☐ $600-$1199
☐ $1200-$1999
☐ $2000-$2999
☐ $3000-$4999
☐ $5000 or more

Online Power Wheelchair User Survey

What is the make (manufacturer) and model of your current wheelchair?
Make: _____
Model:_____

What casters are on your power wheelchair?
☐ 4 x 2 Casters (☐--Air up—OR—Hard Roll--☐)
☐ 5 x 2 Casters (☐--Air up—OR—Hard Roll--☐)
☐ 6 x 1 ¼ Casters (☐--Air up—OR—Hard Roll--☐)
☐ 6 x 2 Casters (☐--Air up—OR—Hard Roll--☐)
☐ 8 x 1 ¾ Casters (☐--Air up—OR—Hard Roll--☐)
☐ 8 x 2 Casters (☐--Air up—OR—Hard Roll--☐)
☐ 8 x 2 ¼ Casters (☐--Air up—OR—Hard Roll--☐)
☐ 9 x 2 Casters (☐--Air up—OR—Hard Roll--☐)

What power drive wheels are on you power wheelchair?
☐ 10 x 3
☐ 10 ½ x 3 ½
☐ 12 ½ x 2 ¼
☐ 14 x 3

What types of caster and/or power drive wheel related problems have you experienced (Check all that apply)?
☐ Frequent air loss and/or flats on pneumatic (air up) tires
☐ Tires wear out
☐ Tire roll-off (i.e. tire rolls off the caster or tire rolls off the drive wheel)
☐ Caster shimmy (i.e. the casters or drive wheels wiggle when you roll)
☐ Caster material cracks, breaks, peels apart or shreds
☐ Casters or drive wheels leave marks on carpet or other types of flooring
☐ Foreign matter (i.e. hair, thread, dirt, etc.) gets caught in casters
☐ Casters or power drive wheels buildup static electricity and I get shocked
☐ Casters and power drive wheels are difficult to adjust
☐ Casters and power drive wheels weigh too much
☐ Casters and power drive wheels are expensive to repair/replace
☐ Caster bolts and nuts loosen up
☐ Bearings wear out and/or freeze-up
☐ Fork or caster breaks

Number the following surfaces according to the difficulty you experience when pushing/rolling over them
1 is most difficult, 9 is the easiest.

_____ Carpet or rugs
_____ Hardwood or vinyl flooring
_____ Rubber Flooring or rubber mats
_____ Grass
_____ Gravel or loose dirt
_____ Wet surfaces
_____ Concrete sidewalk
_____ Icy surfaces
_____ Asphalt

Which surface causes the most damage to your casters or drive wheels?
☐ Carpet or rugs
☐ Gravel or loose dirt
☐ Rubber flooring or rubber mats
☐ Grass
☐ Hardwood or vinyl flooring
☐ Wet surfaces
☐ Concrete sidewalk
☐ Icy surfaces
☐ Asphalt

How often are the casters on your wheelchair replaced?
☐ Every 6 months
☐ Every 9 months
☐ Every year
☐ Every year and a half
☐ Every two years
☐ Every two and a half years
☐ Every three years

How often are the drive wheels on your power wheelchair replaced?
☐ Every 6 months
☐ Every 9 months
☐ Every year
☐ Every year and a half
☐ Every two years
☐ Every two and a half years
☐ Every three years

Who participated in the selection of the casters and drive wheels for your power wheelchair?

☐ Myself
☐ Therapist
☐ Vendor
☐ Nurse

What factors were used for the selection of the casters and drive wheels?

☐ For function
☐ Special needs
☐ Cost
☐ None

How are replacement casters on your wheelchair paid for?

☐ Private Insurance
☐ Medicare
☐ Out-of-pocket/ personal funds
☐ State Medicaid

How much do you spend out-of-pocket (using personal funds) on casters?

Dollar Amount _____ Time Frame _____

What caster colors do you prefer? 1 is most desirable, 7 is the least.

Black ____
Blue _____
Green _____
Orange _____
Grey _____
Red _____
Yellow _____
Clear _____
Lighted _____

What front suspension system do you have on your current wheelchair?

☐ Frog Legs
☐ Frog Legs Uni-Tine Forks
☐ Bull Frogs
☐ None

What is your gender?

☐ Male
☐ Female

What is your ethnicity?

- ☐ Asian, Asian Indian or Pacific Islander
- ☐ Black or African-American
- ☐ Hispanic or Latino
- ☐ Native American or Alaskan Native
- ☐ White/Caucasian
- ☐ Other

Where is your home located?

- ☐ Rural community/in the country
- ☐ Small to mid-sized town
- ☐ Suburban neighborhood
- ☐ Urban neighborhood/inner city

What is your current level of employment? (Check all that apply)

- ☐ Employed full-time
- ☐ Employed part-time
- ☐ Parenting/Homemaker
- ☐ Full-time student
- ☐ Part-time student
- ☐ Unemployed
- ☐ Unable to work

What is the highest level of education you have completed?

- ☐ No high school
- ☐ Some high school
- ☐ High school diploma or GED
- ☐ Completed 1-3 years of college (i.e. an associate's or technical degree)
- ☐ Completed four-year bachelor's degree
- ☐ Some graduate work
- ☐ Completed master's
- ☐ Completed doctorate
- ☐ Completed professional degree such as MD, JD, RN
- ☐ Other _____

What is your total average monthly household income?

- ☐ Less than $600
- ☐ $600-$1199
- ☐ $1200-$1999
- ☐ $2000-$2999
- ☐ $3000-$4999
- ☐ $5000 or more

How do you rate your weekly activity level? Are you

☐ not very active (unemployed, leave home once per day, move around inside)
☐ moderately active (at least a part-time employee or student, leave home more than once per day and move around outside home, access community services outside home)
☐ active (full-time employee or student, leave home more than once per day, more around outside the home, access community services)
☐ very active (in addition to "active," play a sport like wheelchair basketball or tennis at least once per week)

Additional Comments:

Online Manual Wheelchair User Survey

What is the make (manufacturer) and model of your current wheelchair?

Make: _____
Model: _____

What casters are on your manual wheelchair?

- ☐ 3 x 1 Roller Blade Casters
- ☐ 4 x 1 Roller Blade Casters
- ☐ 4 x 1 Soft Roll Casters
- ☐ 4 x 1 Frog Legs Soft Roll Casters
- ☐ 4 x 1 Aluminum Micro Casters
- ☐ 4 x 1 ½ Machined Aluminum Casters
- ☐ 5 x 1 Poly Casters
- ☐ 5 x 1 Soft Roll Casters
- ☐ 5 x 1 Frog Legs Soft Roll Casters
- ☐ 5 x 1 Machined Aluminum Casters
- ☐ 5 x 1 ½ Poly Casters
- ☐ 5 x 1 ½ Machined Aluminum Casters
- ☐ 6 x 1 ¼ Soft Roll Casters
- ☐ 6 x 1 ¼ Pneumatic (air up) Casters
- ☐ 6 x 1 ½ Poly Casters
- ☐ 6 x 1 ½ Machined Aluminum Casters
- ☐ 8 x 1 Poly Casters
- ☐ 8 x 1 ¼ Soft Roll Casters
- ☐ 8 x 1 ¼ Pneumatic (air up) Casters

What types of caster related problems have you experienced (Check all that apply)?

- ☐ Frequent air loss and/or flats on pneumatic (air up) tires
- ☐ Tires wear out
- ☐ Tire roll-off (i.e. tire rolls off the caster or tire rolls off the drive wheel)
- ☐ Caster shimmy (i.e. the casters or drive wheels wiggle when you roll)
- ☐ Caster material cracks, breaks, peels apart or shreds
- ☐ Casters or drive wheels leave marks on carpet or other types of flooring
- ☐ Foreign matter (i.e. hair, thread, dirt, etc.) gets caught in casters
- ☐ Caster bolts and nuts loosen up
- ☐ Bearings wear out and/or freeze-up
- ☐ Fork or caster breaks

Number the following surfaces according to the difficulty you experience when pushing/rolling over them

1 is most difficult, 9 is the easiest.

	1	2	3	4	5	6	7	8	9
Carpet or rugs									
Hardwood or vinyl flooring									
Rubber flooring or rubber mats									
Grass									
Gravel or loose dirt									
Wet surfaces									
Concrete sidewalk									
Icy surfaces									
Asphalt									

Which surface causes the most damage to your casters?

- ☐ Carpet or rugs
- ☐ Gravel or loose dirt
- ☐ Rubber flooring or rubber mats
- ☐ Grass
- ☐ Hardwood or vinyl flooring
- ☐ Wet surfaces
- ☐ Concrete sidewalk
- ☐ Icy surfaces
- ☐ Asphalt

How often are the casters on your wheelchair replaced?

- ☐ Every 6 months
- ☐ Every 9 months
- ☐ Every year
- ☐ Every year and a half
- ☐ Every two years
- ☐ Every two and a half years
- ☐ Every three years

How often are the drive wheels on your manual wheelchair replaced?

- ☐ Every 6 months
- ☐ Every 9 months
- ☐ Every year
- ☐ Every year and a half
- ☐ Every two years
- ☐ Every two and a half years
- ☐ Every three years

Who participated in the selection of the casters a for your manual wheelchair?

☐ Myself
☐ Therapist
☐ Vendor
☐ Nurse

What factors were used for the selection of the casters?

☐ For function
☐ Special needs
☐ Cost
☐ None

How are replacement casters on your wheelchair paid for?

☐ Private Insurance
☐ Medicare
☐ Out-of-pocket/ personal funds
☐ State Medicaid

How much do you spend out-of-pocket (using personal funds) on casters?

Dollar Amount $_____ per (time frame) _____

What caster effects and colors do you prefer? 1 is most desirable, 7 is the least.

	1	2	3	4	5	6	7
Black							
Blue							
Green							
Orange							
Grey							
Red							
Yellow							
Clear							
Lighted							

What front suspension system do you have on your current wheelchair?

☐ Frog Legs
☐ Frog Legs Uni-Tine Forks
☐ Bull Frogs
☐ None

What is your gender?
- ☐ Male
- ☐ Female

What is your ethnicity?
- ☐ Asian, Asian Indian or Pacific Islander
- ☐ Black or African-American
- ☐ Hispanic or Latino
- ☐ Native American or Alaskan Native
- ☐ White/Caucasian
- ☐ Other

Where is your home located?
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- ☐ Urban neighborhood/inner city

What is your current level of employment? (Check all that apply)
- ☐ Employed full-time
- ☐ Employed part-time
- ☐ Parenting/Homemaker
- ☐ Full-time student
- ☐ Part-time student
- ☐ Unemployed
- ☐ Unable to work

What is the highest level of education you have completed?
- ☐ No high school
- ☐ Some high school
- ☐ High school diploma or GED
- ☐ Completed 1-3 years of college (i.e. an associate's or technical degree)
- ☐ Completed four-year bachelor's degree
- ☐ Some graduate work
- ☐ Completed master's
- ☐ Completed doctorate
- ☐ Completed professional degree such as MD, JD, RN
- ☐ Other

What is your total average monthly household income?
- ☐ Less than $600
- ☐ $600-$1199
- ☐ $1200-$1999
- ☐ $2000-$2999
- ☐ $3000-$4999
- ☐ $5000 or more

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☐ active (full-time employee or student, leave home more than once per day, more around outside the home, access community services)
☐ very active (in addition to "active," play a sport like wheelchair basketball or tennis at least once per week)

Additional Comments:

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Focus Group Questioning Protocol

Part I Complete paperwork and do introductions (30 minutes)

- Complete the ***Research Consent, Media Release, W-9*** and collect information from participants using wheelchairs using the ***Participant Demographics Form***.
- Moderator Introduction/Introduction of other researchers/assistants and ground rules
- Participant introductions

Part II Discuss casters and drive wheel problems (30 minutes)

Describe problems (that users/ have you) experienced with casters/power wheels-

- Effectiveness--How **important** are **casters** and **power drive wheels**,
    - Day in the life of..., caster and power drive wheel **use**--what comes with whc or separate selection, Pneumatic vs hard roll
    - What **types of surfaces** are difficult, cause wear
    - **(T/V)** What characteristics of **user, environment, tasks** are considered
    - **(T/V) Assume/Outcome:** Therapists prescribe and vendors select
- Reliability, Operability-
    - **Problems caused by Rough ride** over bumpy surfaces or obstacles
    - Casters get out of alignment-causes **shimmy** or vibration when rolling
    - Casters **dig** into surface making rolling difficult
    - **Marks** on carpet or other types of flooring from casters /power drive
- Durability-
    - Casters and drive wheel tires **wearing** out to quickly
    - Caster bolts, nuts loosen up, axle problems, fork problems
    - Bearings wear out and/or freeze-up
    - Problems with **suspension systems**
- Maintenance and Adjustment-
    - **Foreign matter** (i.e. hair, thread, dirt, etc.) gets caught in casters
    - Making **adjustments to** casters and power drive wheels
    - **Air loss/flats** on pneumatic (air up) casters and power drive tires
- Physical security/safety-
    - Caster or power drive wheel **tire roll-off** (i.e. tire rolls off the caster)
    - Caster **fails suddenly** and /or material cracks, breaks, peels apart or
    - Build **static electricity** and getting shocked, knock out electronics, EMI
- Comfort Acceptance/ Aesthetics-
    - How important is caster/drive wheel **style and color, look, weight**
- Procurement
    - Problems with **reimbursement** for caster/drive wheels
    - Problems with service calls and maintenance--Cost of labor, who pays
    - Medicare part reimbursement allowance vs what customer wants and is willing to pay out of pocket for
- **How important is the need for innovation in casters/drive wheels**

Part III-Discuss IDEAL caster/ power drive wheel (30 minutes)

How should an IDEAL caster/ PDW perform-

- Reliability, Operability-
  - **Overall ride**-how does it ride over rough outdoor surfaces,
  - How is caster /PDW **tire roll off prevented**
  - how are casters prevented from getting **caught** in places like elevator doors and drain grates, edges of sidewalks, etc
  - **Shock absorption** and **rolling resistance**-does it act like a shock absorber, if so, how much flexibility is offered and how flexible is the caster/ PDW
  - Stability-how does the caster/power drive wheel **ride over rough** or bumpy surfaces, soft surfaces, obstacles
  - Alignment, **vibration** or shimmy-does the caster ever shimmy or get out of alignment
  - Parts-does it have multiple parts or is it a **one-piece system**
- Durability-
  - Wear-**how long does the caster** / power drive wheel tire last
- Maintenance and Adjustment-
  - **Air maintenance**/ flat prevention-does it ever lose air (power drive)
  - **Adjustment**-what adjustment should be made to improve the ride, alignment, etc and who will make them (user, caregiver, vendor, therapist, etc)
- Physical security/safety-
  - **Sudden failure**-what keeps caster/ power drive wheel from failing, cracking, breaking, peeling, shredding
  - How does it handle static electricity buildup and EMI
- Comfort, Acceptance-
  - **Aesthetics/Style**-what about colors and effects, materials are desired
- Need for **innovation**
  - **How important is the need for innovation in this area**
  - (T/V) What increases your clinical/ business success
  - (T/V) What influences you buying decision most (user request, outcome study, technical reports, etc.

Part IV-Tweel demonstration and evaluation (30 minutes)

Demonstrate Tweel features—CBS news report, PPT slides, show prototype, wheelchair with Tweel mounted. Discuss ***improvements*** that should be made to the Tweel to make it match the ideal caster/power drive wheel-

- Reliability, Operability-
  - Rough terrain /obstacle performance
  - Enhanced shock absorption/ flex/ Vibration dampening
  - Increased stability on surfaces that are not level
  - Self-alignment
  - One piece system
  - Weight advantage over other casters/power drive wheels
- Durability-
  - Increased wear life
- Maintenance and Adjustment-
  - Elimination of air maintenance (power drive wheel)
  - Non-marking rubber tread
- Physical security/ safety-
  - No sudden failure
- Comfort, Acceptance-
  - Multiple colors, no effects
  - Pneumatic-like performance from non-pneumatic caster/drive wheel
  - Eliminates the need for suspension system
- Procurement-how to obtain
  - Would this take a Specific request or would you use generic need

Complete Dot Voting Exercise using the above features.

- Need for **innovation**
  - **What demand for this type of innovation in casters/pdw exists**
  - (T/V) What **medical need** do you think an improved Tweel might fill
  - (T/V) What other casters/ drive wheel alternatives may fill this need
- Name **recognition**
  - How many of you have heard of **Michelin**
  - How many of you consider the Michelin brand to be **high quality**
  - How would the Michelin brand **influence** you when selecting/testing casters and power drive wheels

Part V-Wrap up

- Pass out cash, have participants sign Cash Disbursement Form
- Thank participants, Download recorded data to laptop, Breakdown equipment

Field Trial Protocol

Introduction

The purpose of this study is to determine the changes in perception power wheelchair users experience when new casters and drive wheels are installed on their power wheelchair. The goal of the study is to better understand how the users' perception changes over time and at what point in the study do they no longer perceive differences. We will conduct the field trial over a 2 month period. During the study the participant will be required traverse various surfaces over the first three weeks of the study, they will need to fill out an on-line survey once a week for the first three weeks of the study, and participate in 2 phone surveys. We will collect information from the participants during these interviews and surveys that will allow us to determine if changes are being notices by the user and if so, what kinds of changes they have experienced.

Study Process

1. Recruit participants.
2. Perform force deflection testing on all Tweels. Record data.
3. Participants come to CATEA. Participant signs informed consent.
4. Participant and wheelchair go to shop: Tweels and Cateye monitor installed. Final protocol, participant instructions, and questions to be discussed.
5. Access to on-line survey and demonstration prior to participant departure.
6. After 1 week, participant to fill out the on-line survey (at the end of week 1).
7. One week later, participant to fill out on-line survey (at the end of week 2).
8. One week later, participant to fill out on-line survey (at the end of week 3).
9. First phone interview. (during week 4).
10. Follow-up phone interview (during week 7).
11. Participant and wheelchair go to shop: Tweels and Cateye removed, current wheels reinstalled.
12. Debrief.
13. Pay participant. Sign off sheet and W-9.
14. Participant finished with study
15. Perform force deflection on Tweels post use. Compare results with pre test.
16. Data analysis

Inclusion/Exclusion Based on Casters and Drive Wheel Types

Participants will be adult, full-time power wheelchair users. Subjects must be able to participate in telephone questionnaires given in English and must have Internet access to take a web-based survey. In addition, subjects' wheelchairs must be able to accept 2" wide Tweel casters and/or a 12.5" diameter Tweel drive wheel. Power chairs with domed caster housings or single fork casters will not accept the Tweel caster can not be included in the study. The Tweel casters are 2" wide so the participants' caster forks will need to be able to accept the casters.

Participant Recruitment

We will contact individuals from three groups, those who participated in the power wheelchair focus group, members of the Consumer Advisory Network, comprised of individuals who have consented to be contacted about research at CATEA, and power wheelchair users who have a relationship with Shepherd Center. Certain inclusion and exclusion criteria are available from the demographic and wheelchair information collected on each focus group participant and CAN member. We will look at the specific data from each participant's wheelchair to determine if we will be able to install the Tweel casters and/or drive wheels.

We will contact each wheelchair user to:
1) Determine if they would be interested in participating in the field trial.
2) Meet the criteria based on drive wheel and/or caster dimensions, drive wheel 12.5" x 2" and casters 6" x 2".
3) Be able to communicate, in English, and be able to complete both telephone interviews and on-line surveys.
4) Be willing to participate in the 2 month study.
4) The participant must be an active power wheelchair user, will be required to leave their residence and participate in outdoor activities.

Methods

Pre- and Post-use Measurements of Tweel Performance and Wear
Force-Deflection Characteristics
Prior to the field trial study we will conduct instrumented testing with a Zwick static testing machine on each of the Tweel drive wheels and casters to determine the force-deflection under load prior to use. We will record the load deflection for each Tweel drive wheel and caster prior to use and will re-test each Tweel after use to determine if the load deflection has changed over the use cycle.

Tread Depth Measurements

Measurements of the tread depth will be taken both pre and post use. We will use calipers to measure the depth of the tread prior to use at three locations on the wheel, document those depths for each Tweel drive wheel. We will retake the measurements post use to determine how the use has affected the tread life. The tread depth data will be compared to the data collected from the Cateye which will tell us the total distance the participant traveled during the study.

CatEye - Distance Measurement

We will attach a CatEye distance measurement device to the drive wheel of each power chair. The CatEye uses a magnet and a sensor to measure wheel revolution. It is a self contained system and will not require an external power source. CatEye are used on bicycles to measure distance, cadence and pace. The CatEye will collect information on total distance traveled. It will be important for us to know the distance traveled when we analyze the wear of the Tweels. The CatEye will only give us an approximate distance based on left and right turns, we will only put the CatEye on one wheel, but the approximate distance traveled is sufficient for this study.

As described earlier, based on the power wheelchair and components, not every wheelchair will have Tweel drive wheels and/or Tweel casters installed. Based on the information collected on each participant selected for the study we will need to be prepared to install the CatEye on the different wheelchairs. The CatEye will be mounted to the Tweel drive wheel in some instances or on the participants current drive wheel if the Tweel drive wheels can not be used. We will have the ability to remove the drive wheels and install the CatEye which will simplify the installation process. Will know prior to installation if we will be applying the Cateye to the Tweel drive wheel or the participants current drive wheel.

Tweel and Instrument Attachment

The participants' wheelchair will be taken to the shop where the Tweels will be installed. The participants drive wheels and/or casters will be removed and placed in a box with the participants' information on it for later reinstallation. All hardware used for the participant current wheels will be used to install the Tweels.

During the installation of the Tweels we will install the CatEye distance counter. The magnet will be attached to the Tweel drive wheel or participants current drive wheel with epoxy adhesive. The magnet will be removed at the end of the study. The sensor will be attached to the frame of the wheelchair with two sided adhesive foam tape and zip ties. The sensor will need to be in close proximity to the magnet to measure the distance. The user readout will be place in a location so the user can see the distance traveled if inquired during the phone survey. The user will not need to reset or adjust the CatEye.

After the CatEye has been installed the drive wheel will be installed and the chair will be returned to the participant to begin the study.

Subject Engagement

After we have identified and recruited our participants we will ask each person to come to CATEA to go over the protocol and procedures of the study, install the Tweels and CatEye, photo document the set up, take depth measurements of the drive wheel treads.

The installation of the Tweels and CatEye should not take more than 30 minutes. During that time we will go over the protocol, receive informed consent, and give the participant disposable cameras. We will answer any questions during that time as to what the participant will need to do. We will give the participant a copy of the informed consent document with contact information to call if the participant has any additional questions or has problems with their equipment as well as a document that outlines the process of the study. We will be in contact with the participant throughout the study either by on-line survey or by telephone survey.
Photo Documentation of the Tweels Pre and Post Use
We will take photographs of the Tweel caster and drive wheels both pre and post use. The images will be used to compare the effects of extended use in everyday activities by power wheelchair users. We will take the same picture pre and post use for comparison.

The photographs to be taken will include orthographic images; front and top view of the Tweels on and off the chair (drive wheel and casters), photo of tread and physical appearance of tire. The images from pre and post use will need to be consistent for visual comparison. Additional pictures will be taken of the Tweels post test if there is any unusual wear or damage to the Tweels. Lastly, we will take side by side comparison pictures of an unused Tweel and the used Tweel as one more means to see the effects of everyday use on the Tweel drive wheels and casters.

Documentation of Use

Online survey (3 times)

We have pulled information from focus groups to create an on-line survey for the participants to fill out to evaluate the performance of the new casters and drive wheels in use. The survey questions will inquire opinion on performance over specific surfaces traversed, comfort, and durability compared to previous experience. The on-line surveys will be filled out once a week for the first three weeks of the study. During the initial set up of their wheelchair we will show each participant how to access the survey. This qualitative portion of the study will look at perception based on their current wheelchair experience. We will ask the participant satisfaction rating of their casters and drive wheels, any caster and drive wheel related problems or benefits, surfaces they traversed and any improvements over their current wheels, and asked if anything unexpected occurred. The on-line survey will also ask the participant to document any problems they encountered and tell us about them.

Photo documentation of problems by users

Each participant will receive 2 disposable cameras to photo document any obstacle that they have found to be too difficult to overcome or problems that occurred with the Tweels during the study. They will be asked, on the on-line survey, to note that a picture was taken and comment on the problem. We will review the images and descriptions from the on-line survey to better understand the issue the participant encountered. We will conduct a phone interview to better understand the problem.

Follow-up Phone calls to participants (week 4 and week 8)

We will contact, by phone, each participant during the fourth week of the field trial and at the end of the study to ask specific questions related to the feedback we received from each user's on-line survey and user perception. The call should not take more than 15 minutes

Data Analysis

We will analyze the data collected pre and post use to determine if use has affected the physical properties of the Tweels.

We will look at differences in tread depth for each user as compared to the distance traveled and surfaces traveled on. We will also review the pictures taken prior to use and post use to see if there was any unexpected damage to the Tweels. We will have unused Tweels for additional visual comparison.

We will conduct force deflection on the Tweels post use. This will allow us to determine if, over time and use, the force deflection changes. This is important information for Michelin as they may find it necessary to change the material properties of their wheels.

For the on-line survey and phone survey will review and categorize their comments for analysis. The participants in the field study were also involved in the focus group study. We heard a lot of information during the focus group regarding perception of durability and function. We hope to be able to go back to that data from the focus group and see if the users' perception changed after use. This information will be very helpful for use.

Field Trial Online Survey

Power Wheelchair User Opinion Survey
Q1.

Enter your user ID Number:
Enter Today's Date:
Enter weekly mileage from CATEYE:

Please visually inspect your Tweel™ products every other day and report any damage during your on-line survey.

The purpose of this survey is to collect information from your experience regarding the performance of the Tweel™ casters and drive wheels so that they can be improved to better meet user needs. Your responses will help us clarify specific ways that the Tweel™ casters and drive wheels can be improved.

Please answer only the questions that refer to the "new wheels" (casters and/or drive wheels) that were installed on your wheelchair.

About the Tweel™ CASTERS...

Q2 . Which of the following problems did you experience during the last seven days (last week)? Check all that apply.

☐ Casters give a rough ride over uneven or bumpy surfaces
☐ Casters flip and get stuck on cracks, gaps or obstacles, (i.e. a thresholds)
☐ Casters dig into or get stuck in soft surfaces (i.e. grass, sand, loose dirt)
☐ Casters lose traction / slip
☐ Casters shimmy or vibrate
☐ Casters shred, peel or crack
☐ Casters "roll up" or "push" throw rugs or mats
☐ Casters mark floors
☐ Caster have noticeable signs of wear (i.e. like from rolling over gravel)
☐ Foreign matter or debris gets caught in casters
☐ Casters track mud inside
Comments (text box):

Q3. Which of the following benefits did you experience during the last seven days (last week)? Check all that apply.

☐ Casters provide smooth ride over uneven or bumpy surfaces
☐ Casters absorb shock from hitting obstacles or barriers (i.e. a threshold)
☐ Casters go over cracks and gaps well (i.e. gaps between platform and train)
☐ Casters roll over soft surfaces well (i.e. grass, sand, loose dirt)
☐ Casters grip surfaces well, give good traction
☐ Casters do not shimmy or vibrate
☐ Casters turn and maneuver well
☐ Casters roll over soft objects well (i.e. throw rugs, mats)
☐ Casters have no noticeable signs of wear
☐ Casters do not mark floors
☐ Casters remove foreign matter or debris automatically (i.e. mud)
Comments:

Q4. Review the surfaces listed below. Check the surfaces you rolled over this week and indicate how the casters performed.

Check Box	Surface	The casters performed...				
	gravel / loose dirt	Very Well	Good	Poorly	Very Poorly	Do not know
	wet surfaces	Very Well	Good	Poorly	Very Poorly	Do not know
	soft outdoor surfaces/ grass/ sand	Very Well	Good	Poorly	Very Poorly	Do not know
	rubber flooring/ mats	Very Well	Good	Poorly	Very Poorly	Do not know
	carpet / throw rugs	Very Well	Good	Poorly	Very Poorly	Do not know
	asphalt / uneven surfaces	Very Well	Good	Poorly	Very Poorly	Do not know
	concrete sidewalks / cracks	Very Well	Good	Poorly	Very Poorly	Do not know
	curbs/ curb cuts	Very well	Good	Poorly	Very Poorly	Do not know
	hardwood / vinyl floors	Very Well	Good	Poorly	Very Poorly	Do not know
	ramps / slopes	Very Well	Good	Poorly	Very Poorly	Do not know

Comments:

Q5. While using the Tweel™ casters this week, tell us about a barrier that you could or could not overcome based on your previous WC experience. Comments (text box):

Q6. How would you rate your overall satisfaction with the Tweel casters this week?

☐ Very Satisfied ☐ Somewhat Satisfied ☐ Somewhat Dissatisfied ☐ Very Dissatisfied

Why? Comments:

About the Tweel™ DRIVE WHEELS...

Q7. Which of the following problems did you experience during the last seven days (last week)? Check all that apply.

☐ Drive wheels give a rough ride over uneven or bumpy surfaces
☐ Drive wheels dig into or get stuck in soft surfaces (i.e. grass, sand, loose dirt)
☐ Drive wheels lose traction / slip
☐ Drive wheels shimmy or vibrate
☐ Drive wheels shred, peel or crack
☐ Drive wheels "wind up" throw rugs or mats
☐ Drive wheels mark floors
☐ Drive wheels have noticeable signs of wear (i.e. like from rolling over gravel)
☐ Foreign matter or debris gets caught in drive wheels
☐ Drive wheels track mud inside

Comments:

Q8. Which of the following benefits did you experience during the last seven days (last week)? Check all that apply.

☐ Drive wheels provide smooth ride over uneven or bumpy surfaces
☐ Drive wheels absorb shock from hitting obstacles or barriers (i.e. a threshold)
☐ Drive wheels go over cracks and gaps well (i.e. gaps between platform and train)
☐ Drive wheels roll over soft surfaces well (i.e. grass, sand, loose dirt)
☐ Drive wheels grip surfaces well, give good traction
☐ Drive wheels do not shimmy or vibrate
☐ Drive wheels roll over soft objects well (i.e. throw rugs, mats)
☐ Drive wheels have no noticeable signs of wear
☐ Drive wheels do not mark floors
☐ Drive wheels remove foreign matter or debris automatically (i.e. mud)

Comments:

Q9. Review the surfaces listed below. Check the surfaces you rolled over this week and indicate how the drive wheels performed.

Check Box	Surface	The drive wheels performed...				
	gravel / loose dirt	Very Well	Good	Poorly	Very Poorly	Do not know
	wet surfaces	Very Well	Good	Poorly	Very Poorly	Do not know
	soft outdoor surfaces/ grass/ sand	Very Well	Good	Poorly	Very Poorly	Do not know
	rubber flooring/ mats	Very Well	Good	Poorly	Very Poorly	Do not know
	carpet / throw rugs	Very Well	Good	Poorly	Very Poorly	Do not know
	asphalt / uneven surfaces	Very Well	Good	Poorly	Very Poorly	Do not know
	concrete sidewalks / cracks	Very Well	Good	Poorly	Very Poorly	Do not know
	curbs/ curb cuts	Very well	Good	Poorly	Very Poorly	Do not know
	hardwood / vinyl floors	Very Well	Good	Poorly	Very Poorly	Do not know
	ramps / slopes	Very Well	Good	Poorly	Very Poorly	Do not know

Comments:

Q10. While using the Tweel™ drive wheels this week, tell us about a barrier that you could or could not overcome based on your previous WC experience.

Comments:

Q11. How would you rate your overall satisfaction with the Tweel drive wheels this week?

☐ Very Satisfied ☐ Somewhat Satisfied ☐ Somewhat Dissatisfied ☐ Very Dissatisfied

Why? Comments:

Q12. While using the new wheels did anything unexpected happen?

Comments:

Dot Voting Activity Report

Each focus group concluded with a Dot Voting Activity. This activity was used to establish a rough indicator as to the importance and priorities of the ideal product characteristics. Participants were instructed to cast votes for the statements that were most important to him or her. Statements that received the most number of votes reflect importance across participants but differences between focus groups are also evident. Different numbers of votes were permitted within the different wheelchair categories because of the different number of statements presented.

Table 1- Power Wheelchair Dot Voting Results: Caster and Power Drive Wheel

Desired Attributes/Feature/Function	Total	FG 1 Score	FG 2 Score
No Adjustment or Cleaning	17	7	10
Smooth Ride	12	3	9
Absorbs shock	10	5	5
Easy to Replace/ Change	10	5	5
Durable	8	4	4
Caster/ Drive wheel traction	7	0	7
Rolls over outdoor and indoor surfaces	6	6	0
One piece construction	4	0	4
Available in Colors	3	1	2
Sporty-doesn't look like medical device	3	1	2
Desired effects	3	0	3
No Noise	3	1	2
Keeps user level on uneven surfaces	2	1	1
Caster width and diameter	2	0	2
Adjustable suspension	2	2	0
Ball type caster	1	1	0
Maneuverable	1	1	0
Compatibility	1	0	1
Spinning rims	0	0	0
Wider Drive Wheel	0	0	0
Durable Drive wheel tread	0	0	0
Total	**95**	38	57

Table 2- Manual Wheelchair Dot Voting Results: Casters

Desired Attributes/Feature/Function	Total	FG 3 votes	FG 4 votes
Shock absorber/ suspension characteristics	6	2	4
Self Cleaning/ Debris resistant materials/ bearings	6	3	3
Traction/ Tread	5	0	5
No Flats/ No Failure	5	0	5
Ball type design	4	0	4
Variable flexibility	4	0	4
Weight	3	2	1
Style/ Aesthetics	3	1	2
Durability	3	0	3
Maneuverability/ Turning	2	2	0
Single piece construction	2	2	0
Width	1	1	0
Diameter	1	1	0
Maintenance	1	1	0
Vibration Dampening	1	1	0
Quick Release	1	0	1
Tire Contour	0	0	0
Total	**32**	16	16

Table 3- Vendor/Clinician Dot Voting Results: Casters and Power Drive Wheels

Desired Attribute/Feature/Function	Total	FG 5 votes	FG 6 votes
Casters			
Ride (Shock absorption/ flex) characteristics	14	8	6
Maneuverability	8	8	0
No maintenance	7	6	1
Caster Durability/ replacement	7	2	5
No failure No flats	5	0	5
Dimension (diameter and width) Choices	5	5	0
Aesthetics and style	4	3	1
Weight	2	0	2
Converts from outdoor to indoor use	2	2	0
Fork Design	1	0	1
Tune-able loading capacity	0	0	0
Manual caster Safety Locking Mechanism	0	0	0
Rolling Resistance	0	0	0
Non-marking	0	0	0
Noiseless	0	0	0
Medical Justification	0	0	0
Tread/Traction/ Grip	0	0	0
Total	**55**	34	21

Desired Attribute/Feature/Function	Total	FG 5 votes	FG 6 votes
Power Drive Wheels			
Shock absorption	11	8	3
Tread	9	9	0
No maintenance Self-cleaning	9	7	2
Ride	7	6	1
No failure No flats	7	1	6
Non-marking	3	3	0
Aesthetics/ effects	3	3	0
Weight	2	0	2
Multiple sizes	0	0	0
One piece construction	0	0	0
Tune-able load capacity	0	0	0
Durability	0	0	0
Non marking, noiseless tires	0	0	0
No trade offs	0	0	0
Medical Justification	0	0	0
Most influential and least useful product Information			
Totals	**51**	37	14

Wheelchair Info for Michelin

The Problem[1]

There is a need for improved tire wear without compromising ride and traction. Tires must be functional on varied surfaces — sand, rugs, snow, and smooth and rough surfaces — and must be non-marking. Tires should allow discharge of static electricity to prevent shocks to the user and damage to the electronics associated with power chairs. At the same time, tires and wheels should be light and inexpensive. In a 1994 study related to power wheelchairs, users reported that tires were the second most frequent repair behind batteries. Wheels have yearly maintenance problems 24% of the time. Although significant research has had a positive impact on manual wheelchair tires, little advancement has occurred with power chairs tires. This problem stems from the varied wheel diameter and the design and performance parameters associated with power chairs. Also, power wheelchairs introduce much larger stresses on the wheels and tires than manual chairs due their heavier loads.

Current Solutions

Common materials used include rubber, urethane, polyurethane, composite nylons, and kevlar-reinforced thin tubes. Research is in process on solid polyurethane foam tires, which combine the best features of the pneumatic (comfort, low rolling resistance) and solid tires (low maintenance). These materials have a microcellular structure that reduces weight while maintaining wear and rider comfort. One problem with the new solid tire designs is the tendency for the tire to become unseated from the rim. Radial tires, semi pneumatic designs, and inserts are also being researched.

Issues to Consider

In the area of tire and wheel performance, the main issues are reliability and durability without losing comfort and safety. Pneumatic tires provide great comfort but are a potential inhibitor of independent living, due to flat tire etc. The goal is to achieve the comfort level offered by pneumatic tires along with the reliability and durability offered by solid tires. Increase in durability will also provide economic relief to the end user. At present, power wheel chair tires cost almost $100. This is a big expenditure considering that present tires have a short life span and are therefore replaced quite frequently. There is a need to innovate or use materials and design that can bring down the cost of the tire, increase the durability of the tire while maintaining reliability and comfort level. And most importantly, tires should be non-marking. Black tires meet most of the requirements of an ideal tire but suffer from the big disadvantage that they are marking and are therefore not used in the industry.

- Are the problem of static charge build up and durability more critical to the power wheelchair industry than manual wheelchair industry?
- Are the newer solid urethane and polyurethane foam tires meeting users' needs adequately? If not, why not?

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[1] Rehabilitation Engineering Research Center on Technology Transfer. (May 25 & 26, 1999). *Stakeholder Forum on Wheeled Mobility*. Retrieved, October 3, 2005, from http://cosmos.buffalo.edu/t2rerc/pubs/forums/mobility/mobility.pdf

An issue relating to wheel improvement brings into question if it is beneficial to reduce the wheel weight for power chairs. Spoke wheels perform well but requires a lot of maintenance. Probably an ideal wheel will be one that has the weight and power of spoke wheels while the cost and maintenance of plastic wheels. A misaligned wheel requires a lot more effort to push. It is frame structure that mainly controls wheel alignment. For manual wheelchairs, wheels should require minimum effort to push. Technology innovation, like geared hub wheels, is required to make the wheels easier to push. Though considerable improvements have been done in the wheel bearing, it is still a high maintenance item. Further improvement is required in this field.

- For power chairs, is weight irrelevant? Is the goal for wheel materials to merely match the weight and strength of spoke wheels but improve in the area of cost and maintenance?
- Wheel misalignment affects tires wear rate as well as rolling resistance. Is this a serious problem?

In the literature we found articles that cited the major barrier in the area of tires and wheels as the fact that the total market is not large enough to support investment in R&D by traditional tire and wheel manufacturers. Some believe that development of better tires will require government funding for research at universities. Another concept discussed in the literature is that all wheelchair manufacturers should cooperate to develop a specification with a single tire supplier who could then address the industry's problem.

- Is industry consortia on tires and wheels feasible as a means to develop adequate R&D to meet the industry's needs?
- Are varied customer needs a problem inherent in tire and wheel product selection? Could modularity apply to tires/wheel systems?
-

Things to remember about manual wheelchair tires[2]

Pneumatics give:

- Soft ride
- Low rolling resistance
- High wear rates
- High maintenance
- Lower weight

Solid tire give:

- hard ride
- high rolling resistance
- low wear rates
- low maintenance
- rim roll off problems

State of Existing Technologies

- Polyurethane tires with sealed air tube inside do not require any maintenance.

They have many desirable tire properties but don't have good traction and are slippery to grip. Thus they provide compromised performance.

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[2] Stephen H. Sprigle, John G. Thacker & Belinda O. Morris. (1994). Understanding the Technology When Selecting Wheelchairs. Arlington, VA. RESNA press.

- Tubeless inserts are heavy and difficult to install.
- Pneumatic tires have the highest performance but the poorest durability and reliability.
- Some manual wheelchair tires get dry on their sides with use. This creates blisters etc. on the hands of user who directly pushes on tires.
- Some manual wheelchair tires have too smooth side walls. Therefore user have hard time propelling such tires as their hands slip when they propel such tires directly.
- Mountain bikes manufacturers are working on self-shedding (self-cleaning) tire designs.
- MEMS technology is available for tire applications but is likely to have a very high cost ($6000).
- Electrically conductive tires are available but at a very high cost.

Barriers to Realization of Ideal Technology

- Small market for the wheelchair tires prevents manufacturer from investing their money into research in this field. This disadvantage may be overcome for manual wheelchair tires by leveraging bicycle tire market.
- Current reimbursement policy also hinders development in this area. Industry in U.S. is governed by "K" codes.
- There is resistance to change on the part of manufacturer.
- Consumers are not vocal about their wheelchairs, cost, things that break etc.
- Some wheelchair users use parking brakes to slow down the chair. This leads to more wear of the tires. Users should be educated about the efficient use of tires.
- Tires and wheels need to be aligned properly. Any misalignment increases the tire wear, which reduces the life cycle of the tire.

Common Wheelchair Caster and Wheel Sizes

	Casters	Drive Wheel
	3 x 1	
	5 x 1	
Manual Wheelchair	6 x 1	
	6 x 2	
	8 x 1	
	8 x 1.25	
	8 x 1.75	
	8 x 2	
Power Wheelchair	6 x 2	10 x 3
	6 x 1.3	10.5 x 3.5
	8 x 2	12.5 x 2.25
	8 x 2.25	14 x 3
	9 x 2	
	8 x 1.75	
	8 x 2	

Note: One or 2 Sunrise power models have a 4" caster but that was not norm.

GENERAL

Factors affecting wheelchair performance[3]

There are number a number of factors that affect the performance attainable by an individual using a wheelchair. Unfortunately, there is no single criterion for performance (except in the case of single use wheelchairs; e.g., racing wheelchairs). At best, a general-use wheelchair is the result of a series of design compromises. Most efforts to enhance a particular aspect of performance result in deterioration in another area of performance.

Wheelchair performance can be loosely defined as the efficacy with which a user can accomplish tasks of living from the perspective of mobility. In most cases, these criteria are difficult to quantify. Propulsion efficiency, energy costs and rolling resistance are often reported as performance factors for manual wheelchairs. Speed, range, climbing ability, etc., are performance factors for powered wheelchairs. However, the relatively widespread use of these factors is often more related to the fact that they can easily be quantified than to their general efficacy as estimates of wheelchair performance.

Manual wheelchairs-Specific factors

Individuals with limited mobility and muscle function have to overcome two principles of physics while propelling their wheelchairs: friction and inertia. **Friction** is the resistance to relative motion between two bodies in contact. With wheelchairs the friction is produced by air drag, wheel bearing torque, and tire rolling resistance. **Inertia** is the resistance to motion due to mass. With wheelchairs, inertia affects response (fast or sluggish) and is due to the total weight, weight distribution, and relevance to overall performance based on primary use considerations, a number of factors are both quantifiable and applicable for all wheelchairs. These factors are generally independent of user interaction and can be improved (optimized) for all wheelchairs. Those specific to manual wheelchairs include:

- Rolling resistance
- Control and maneuverability
- Wheelchair mass and mass distribution

Rolling resistance is affected by tire material, wheel diameter, tire width, wheel alignment, normal loading (weight) and mass distribution, and terrain surface texture. The weight of the wheelchair has an approximate linear relationship with rolling resistance and results in only marginal changes over the practical range of loads. For example, changing from a standard manual wheelchair (45 pounds) to a lightweight (25 pounds) with a 160 pound individual will change the rolling resistance by only 7.5%.

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[3] Stephen H. Sprigle, John G. Thacker & Belinda O. Morris. (1994). Understanding the Technology When Selecting Wheelchairs. Arlington, VA. RESNA press.

ROLLING RESISTANCE

Rolling resistance[4]

Rolling resistance is defined as the force necessary to keep the tire rolling at a constant velocity over a particular surface. The deformation of both the tire and the surface contributes to the rolling resistance. Rolling resistance of a tire is dependent upon the surface it rolls upon. In general, the softer or rougher the terrain, the higher the rolling resistance. When wheelchair tires are compared one to another, the surface is kept constant. During rolling, the cross section of the tire will change shape as it comes in contact with the ground. The ability to spring back to its original shape with little loss in energy will result in low rolling resistance of the tire. This is called hysteresis loss. One simple way to compare rolling the rolling resistance of two different tires are to drop them on a hard floor and observe which one bounces higher. A high bounce indicates low hysteresis energy loss which translates to low rolling resistance. Another way to lower rolling resistance is to reduce the amount of material deformed. Reducing the material volume of solid tires compromises ride comfort, giving a hard ride and the tires wear out sooner.

Rolling resistance increases linearly with load, though the load (and rolling resistance) on each wheel varies because individuals do not sit symmetrically and may move their center of gravity in relation to rear wheels. Rolling resistance is not appreciably affected by speed in the range that wheelchair travel. Rolling resistance also decreases as the wheel diameter increases.

The air pressure of pneumatic tires will affect rolling resistance. On smooth surfaces (tile floors) a reduction of 50% in tire pressure will increase rolling resistance by about 10%.

1) Larger wheels with hard tires will give lower rolling resistance, although differences will not be marked on soft surfaces.
2) Large diameter wheels with soft tires will give higher turning resistances.
3) Small obstacles in the form of steps will greatly impede a wheelchair with small diameter wheels and hard tires. Large improvements are possible by using large diameters and soft tire.

Wheelchair Selection Manual: IAN DENISON PT ATP[5]

Rolling Facts

- The rolling resistance of a typical chair with 24" tires and 8" casters doubles when the center of gravity is moved from directly over the rear wheels, to mid way between the wheels and casters.
- Dense, low pile carpet has the same effect on rolling resistance as reducing tire pressure to 10 psi..

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[4] Stephen H. Sprigle, John G. Thacker & Belinda O. Morris. (1994). Understanding the Technology When Selecting Wheelchairs. Arlington, VA. RESNA press.

[5] Wheelchair Selection Manual: IAN DENISON PT ATP. Retrieved, October 3, 2005, from http://www.assistive-technology.ca/wheel.pdf

Tire Facts

- Solid tires have 35% more rolling resistance than conventional tires on hard surfaces
- High pressure sew up tires have 30% less rolling resistance

Tire Pressure Facts

- Most people don't notice air loss until pressure is down to 50%
- Tires take 7 weeks to lose 50% of their air

The ergonomics of different tyres and tire pressure during wheelchair propulsion[6]

In a study solid and oneumatic tires were tested to determine if the rolling resistance was affeted by tire pressure. 4 different tire pressures were used (100, 75, 50 and 25 of inflation). The second part of the test looked at the energy expended by the user at the different tire pressures. It was found that the solid tires performed worse than all three pneumatic tires even when tyres were under-inflated to 25% of tire pressure. Two of the pneumatic tires showed significant decreases in rolling between 100 and 50%. The physiological study showed that energy expenditure increased significantly at 50% of tire-inflation. .

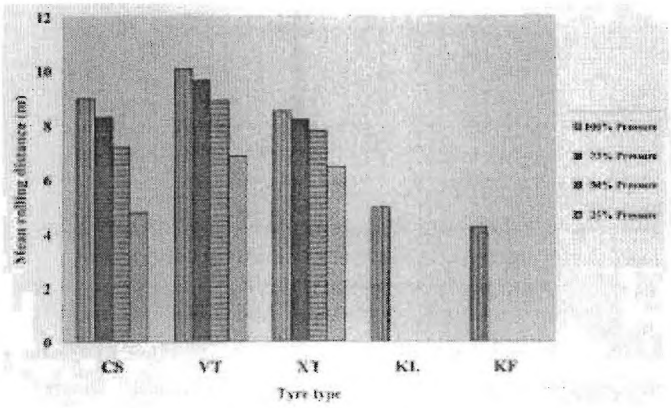

Fig.9. Rolling distance for all tire types at 100, 75, 50 and 25 % of their recommended inflation pressure

[6] Bonita Sawatzky, Won Kim & Ian Denison. (November 2004). The ergonomics of different tyres and tyre pressure during wheelchair propulsion. *Ergonomics*. 47(14): 1475-1483.

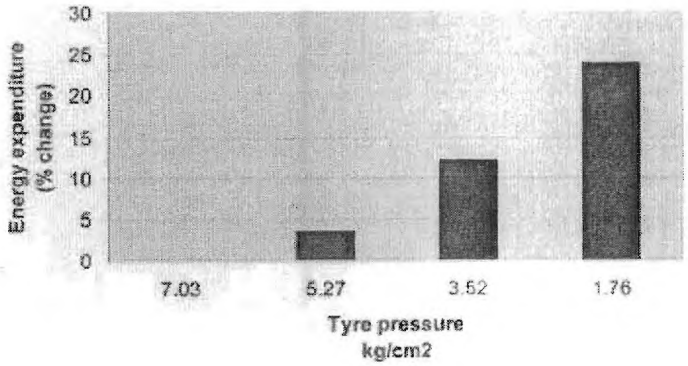

Fig.10. Percent change in energy expenditure while wheeling with VT tyres at 100, 75, 50 and 25 % recommended tire pressure

For the 15 adult participants, energy cost of wheeling at four different pressures with VT tires showed a 3, 12, and 25% increase in energy cost of wheeling at 75, 50, and 25% of recommended pressure. This represented a significant increase in energy cost of wheeling between tire pressures of 100 and 50 % ($p < 0.05$) and a further increase from 50 to 25% ($p < 0.01$) (figure 10). The rolling resistance of the VT tyres increased by 4.2, 11.8, and 32% for 75,50 and 25% tire pressure respectively. i

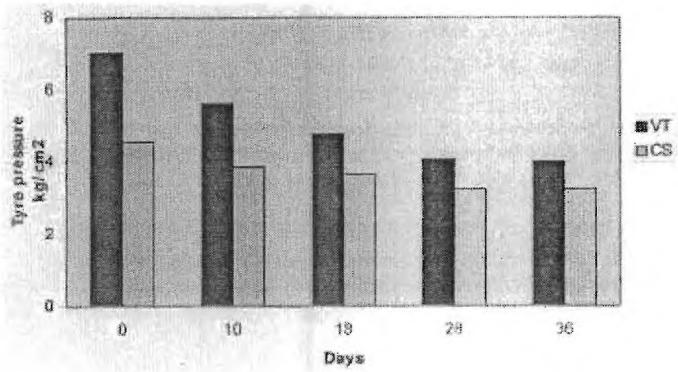

Fig.11. Changes in tire pressure with time

This study has shown that when inflated to at least 50% of the recommended pressure, pneumatic tires have less rolling resistance that solid tires, allowing ease of wheeling. There are many areas for both the wheelchair user and their caregivers that could potentially be affected by choosing inefficient tires. Wheelchair users using solid tires may experience increased fatigue from the added resistance, requiring healthcare workers to push them, rather than wheeling independently.

OBSTACLE CLEARANCE[7]

[7] Smith, Mark E. (2001). Obstacle Clearance. Retrieved, October 3, 2005, from http://www.wheelchairjunkie.com/obstacleclearance.html

The size of the caster wheel greatly influences the amount of effort used to climb over even small obstacles. The smaller he wheel, the greater the effort needed to climb an obstacle. However, increasing the diameter increases weight and inertia which in turn increases the potential for shimmy. Figure below illustrates that as the wheel radius increases, the ratio of effort (P) to load (W) decreases. For example, it takes the same amount of effort to climb a 4 inch curb with 12 inch radius casters as it does a 1 inch cub with 4 inch radius casters.

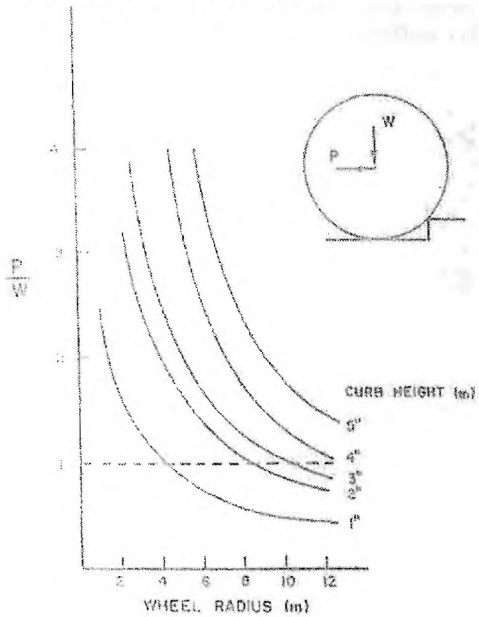

Fig.20. Caster wheel size versus effort

Wheelchair users who cannot perform a wheelie maneuver, rising the front casters off the ground while balancing on the rear wheels, should not have wheelchairs equipped with small caster wheels (diameters less than 6 inches). Small caster wheels tend to get caught in cracks. Small caster wheels do not have as much support on soft surfaces and tend to sink into the surface, requiring a large amount of effort to propel the wheelchair. Small diameter casters also have a higher rolling resistance than larger diameter casters. Rolling resistance also depends on the load on the wheel; large loads are undesirable on small diameter casters. The center of gravity of the user in the chair, which is determined by seated positioning and the forward-reward placement of the rear wheels, affects how much of the load is distributed on the casters.

Ground clearance and wheelbase

A power chair with 3.5 of ground clearance can roll over a 6"-tall obstacle. A powerchair with 4.5" inches of ground clearance cannot roll over a 6"-tall obstacle. Explanation is, ground clearance, and the height of an obstacle a powerchair can roll over, is not as cut and dry as merely measuring the lowest part of a powerchair in relationship to the ground. Wheelbase and anti-tip-wheel height play an equally important role in obstacle clearance.

For the most part, you either straddle obstacles or roll over them. When straddling an obstacle, as with a rock, it passes between your wheels, making ground clearance a literal concept: If the rock is 3" tall, and your battery tray is 3.5" off the ground, you have adequate ground clearance to drive over it. However, when rolling over an obstacle that spans the width of your chair - for example, a double-sided concrete parking space curb - ground clearance is dictated by wheelbase and anti-tip wheel clearance.

With a short wheelbase - that is, your drive wheels close to your casters - the powerchair is less likely to allow obstacles to fall between the wheels, avoiding "high-centering" on an obstacle. Put simply, front and rear wheels can simultaneously crawl over an obstacle, never allowing an obstacle's entirety to rest between the wheels. On the other hand, a long wheelbase allows obstacles to fall between the chair, which can lead to high-centering, the chair sitting on an obstacle, with all four wheels off the ground.

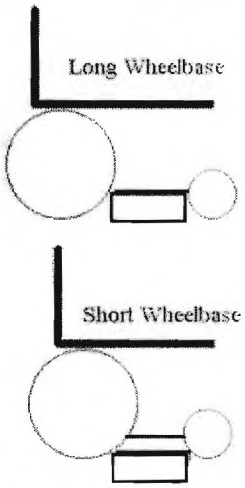

Fig.18. Long and short wheelbase

Anti-tip wheels, as well, play an important role in obstacle clearance. Low or unsuspended anti-tip wheels can cause drive wheels to dangle in the air when descending obstacles, commonly rough curb cuts and van lift lips. As casters and anti-tip wheels simultaneously contact the ground, as when you encounter a surface transition like a high doorway threshold, drive wheels may lose traction and spin free.

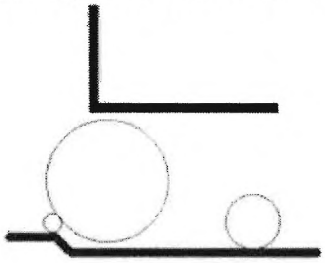

Fig.19. Anti-tip wheels

VIBRATION/INJURY

SUSPENSION

Seat and footrest shocks and vibrations in manual wheelchairs with and without suspension[8]

Objective: To examine differences in the shock and vibration transmitted to an occupant of a manual wheelchair with and without suspension caster forks and with and without rear-suspension systems.

Conclusions: Suspension caster forks reduce the shock and vibration exposure to the user of a manual wheelchair. Consumers should give Suspension caster forks serious consideration, especially if they are active or experiencing chronic pain. Rear-suspension systems reduce some of the factors related to shock and vibration exposure, but they are not clearly superior to traditional designs.

Suspension Systems

Manaul Wheelchairs

Caster Suspension

Frog Legs - Flex Forks, Classics, Ultra, and Bull Frogs.

Rear Suspension

Invacare Top End , Terminator Manual Wheelchair
Colours Boing
Quickie XTR

Power Wheelchairs

Most mid drive power wheelchairs have a suspension syatem to deal with bridging. Now many rear and front drive wheelchairs are adding suspension systems to their wheelchairs to reduce vibration.

The main problem with these suspension systems is that they are usually very heavy, relative in relation to the rest of the wheelchair, complicated and expensive.

Reference

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Technical Report 060301:
Powerchair caster and drive wheel research study

March 2006

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EXECUTIVE SUMMARY

Product Concept: A one-piece caster assembly and one-piece drive wheel assembly, constructed with a shear band and flexible fins or spokes, made of polyurethane, that provides users with the characteristics of a pneumatic ride on a non-pneumatic caster and drive wheel

Study Purpose: A study was undertaken to explore problems that power wheelchair users experienced with current caster and drive wheel products, identify product requirements for new casters and drive wheels and examine initial perceptions of the Tweel™ prototypes.

Problems with casters and drive wheels: Participants experienced problems when going off curbs, sometimes as high as four inches. Several users had experienced tire roll-off. Most sloping outdoor surfaces (i.e. sloped concrete sidewalks, ramps and driveways) presented traction problems, especially when wet. Sidewalk cracks and thresholds caused casters to swivel, get caught and stop the chair, often causing injury to the user. Participants experienced difficulty traversing gaps between surfaces, like the gap between train and platform. Indoors, most participants experienced problems with throw rugs, area rugs, rubber mats and thresholds. Throw rugs become entangled in the drive wheel. Participants reported significant problems with flats. Flats are catastrophic events that negatively impact user safety. Cleaning debris and mud from casters and drive wheels presented significant problems as well.

Important Product Requirements: Caster and drive wheel material should be self-cleaning and repel dirt. Casters should be designed to keep out or remove debris like hair, carpet fiber, etc. Casters and drive wheels should be airless and puncture proof. They should give users the smooth ride that pneumatic tires provide without the problem of flats. Casters and drive wheels should absorb vibration caused when hitting a barrier like a threshold, broken concrete sidewalk or rough asphalt. Casters and drive wheels should roll over gaps like the ones between the MARTA train and platform. Casters and drive wheels should last 5 to 7 years. A tread wear indicator should indicate the need for replacement. Tread should not mark floors. Casters and drive wheels provide improved traction, particularly on wet, slopped surfaces and when turning. They should roll over soft outdoor surfaces like sand without sinking in and hard surfaces like gravel without damage to materials. Casters and drive wheels should be one piece construction with no small parts. They should be available in multiple colors, should be lighted or at least reflective of light for added safety at night. They should look sporty and not make noise. They should keep the user level when rolling over uneven surfaces and should be adjustable and customizable for user's personal needs, environments, activities and personal characteristics.

Initial Impression of the Tweel™ Prototypes: Participants appeared to be impressed with the airless features of the Tweel™. The Tweel™ appeared to absorb shock well and provide good turning maneuverability, although some participants worried that the flat design would make turning more difficult and wanted more 'crown.' For other participants, the Tweel™ appeared to offer added traction because of the flat design. The material didn't appear to mark flooring. Participants liked the sporty look of the Tweel™, the size and weight, but wanted more color choices, reflective or lighted effects and dust covers to keep debris out of the fins. Participants commented that the Tweel™ appeared to be self-cleaning or at least be easier to clean. It seemed to participants that the Tweel™ would last at least 5 years and would wear evenly because of the flat design. But, some were worried that gravel would cause damage to the material. Participants said they would like to know more from tests with wheelchair users. They expressed concern that, over time, the Tweel™ would loose stiffness and this would decrease maneuverability and stability. Participants also seemed concerned that the materials would get dry and brittle and crack in cold weather. Most participants indicated that they had knowledge of Michelin products. They indicated that they believed that Michelin made quality products.

Most participants indicated that the brand would influence their decision to purchase casters and drive wheels made by Michelin.

Procurement: Focus group participants and online survey respondents were asked how often casters and drive wheels were replaced on their current chair. Several participants had never replaced their casters or drive wheels because the chair was relatively new. Twenty-four percent (24%) of focus group participants and 20% of web respondents replaced casters yearly. Yearly replacement of drive wheels was slightly higher, 29% for focus group participants and 25% for web respondents. If data from both participants and online survey respondents was combined, analysis appeared to indicate that at least 50% of users replaced casters within three years. Both groups indicated that the most used payment method for replacement of casters and drive wheels was private insurance. Personal funds were the next most used method for web respondents, while focus group participants reported using Medicare and Medicaid. Focus group participants were asked how many casters and drive wheels they replaced at one time. Of participants who had replaced casters and drive wheels, 65% reported replacing a *pair* of casters and 88% reported replacing a *pair* of drive wheels. All participants that had replaced casters and drive wheels had obtained the replacement parts from a durable medical equipment (DME) supplier, after consulting the vendor/supplier.

Average Personal Funds Spent For Products

Group	Product	Average	Median	Range
Focus Group Participants				
	Casters	$75.00 per pair/year	$75.00 per pair/year	$50-$100 pair
	Drive Wheels	$93.75 per pair/year	$100.00 per pair/year	$75-$200 pair
Online Survey Respondents				
	Casters	$ 71.14 per pair/year	$75.00 per pair/year	$24-$100 per pair

Purpose

Power wheelchair caster and drive wheel performance are critical to effective wheeled mobility. Casters and drive wheels must perform effectively, be reliable and safe, durable and acceptable to wheelchair users. The purpose of this study was to understand the problems that **power wheelchair users** experienced with current caster and drive wheel products and their initial impression of the Tweel™ prototypes. This study has uncovered caster and drive wheel "product requirements" important to the power wheelchair users involved. The goal of the study was to collect information that could be used by Michelin to complete the research and development aspects of products based upon the Tweel™ Assembly technology. A service agreement between Michelin and the Center for Assistive Technology & Environmental Access (CATEA) was used to accomplish this purpose. To ensure development of an effective product that meets or exceeds customers' requirements, Michelin has been engaged throughout the process.

The specific objectives of this study were to: 1) engage power wheelchair users; 2) identify, describe and explore user requirements inherent in various environments and tasks that involve casters and drive wheels; 3) collect, synthesize and interpret data from user focus groups and surveys; and 4) generate a set of product requirements for caster and power drive wheels; and 5) report the initial perception of participants for the Tweel™ prototypes.

This study has generated many product requirements that are important to end-users. End-users (power wheelchair users) involved in this study, are a subset of all product customers. The selected metro Atlanta area focus group sites covered a variety of lifestyle factors relevant to the use of power wheelchairs—such as land contours, environmental conditions (temperature, humidity, rain, sand, etc.); and ethnic differences (cultural practices).

Methodology

Focus group input is both prompted by and structured under the following criteria (**Table 1**), refined by research conducted by the Rehabilitation Engineering Research Center on Technology Transfer (T2RERC). These 11 criteria are device-independent; that is, they can be applied to the evaluation of any assistive technology device or product, including wheelchair casters and drive wheels. This study used eight of the 11 criteria as general guides to developing tailored, specific and probing questions for the questioning protocol.

Table 1—Eleven Device-Independent Evaluation Criteria

Criterion	Definition
*Effectiveness-	In what ways does the device improve one's living situation, enhances functional capability and independence.
*Reliability-	The degree to which a device is dependable, consistent and predictable in its performance and levels of accuracy under reasonable use.
*Durability-	The extent to which a device delivers continued operations for an extended period of time.

*Physical Security/ Safety-	The physical security a device affords a user and how well it protects the user, care provider or family member from potential harm, bodily injury or infection.
*Comfort/Acceptance-	The extent to which a user feels physically comfortable with the device and does not experience pain or discomfort with use; how aesthetically appealing the user finds the device and the user's psychological comfort when using it in public or private.
*Operability-	The extent to which the device is easy to use, is adaptable and flexible, and affords easy access to controls and displays.
*Maintenance/Repairability-	The degree to which the device is easy to maintain and repair (either by the end-user, a local repair shop or a supplier).
*Affordability-	The degree to which a person can purchase, maintain and repair a device without financial hardship.
Portability-	The influence of the device's size and weight on the user's ability to move, carry, relocate and operate it in varied locations.
Securability-	How well an end-user believes a device affords physical control and security from theft or vandalism.
Learnability-	The perspective of the device's ease of assembly, initial learning requirements, and time and effort to master use.

* Denotes criteria used in this study. (From: Lane, J., Usiak, D., Stone, V., Scherer, M., 1997. The voice of the customer: End-users define the ideal battery charger. Assistive Technology, 9, 130-139).

We used focus group methods described in Greenbaum (Greenbaum, T., 1999, *Moderating focus groups; A practical guide for group facilitation,* Sage Publications) and Krueger and Morgan (Krueger, R., and Morgan, D. 1997, *The focus group kit, volumes 1-6*, Sage Publications). Additionally, Patton's description of participatory-action research methods has been used (Patton, M., 2002, *Qualitative research & evaluation methods*, Third Edition, Sage Publications). We used mixed methods described in Creswell (Creswell, J., 2003, *Research design: Qualitative, quantitative, and mixed methods approaches*, Second Edition, Sage Publications) and Mertens (Mertens, D., 1998, *Research methods in education and psychology*, Sage Publications). We used survey methods described in Bourque and Fielder (Bourque, L., and Fielder, E., *The survey kit 3: How to conduct self-administered and mail surveys,* 1995 Sage Publications).

Procedures

Because little research has been conducted to identify the customer requirements for power wheelchair casters and drive wheels, descriptive, exploratory and mixed methods were used in this study. Powerchair users were asked to participate in focus groups and surveys to understand the problems, needs, issues, and environments associated with caster and drive wheel use. Focus groups and surveys allowed for rapid and in-depth data collection. Subsequent data analysis has been used to describe and explore interrelationships between users, their environments and activities and caster and drive wheel use. Product requirements generated as a result of this study are grounded in the perception and experience of participants.

The **Appendix** includes examples of the **Pre-Focus Group Survey** and the **Focus Group Questioning Protocol**. We also combined the analysis with the results of an online survey, posted on our website. We have collected and analyzed 20 completed online surveys from powerchair users. An example of the **online Power Wheelchair User Survey** is also found in the **Appendix**.

Recruiting, Participation and Demographics

We convened two focus groups with a total of 17 participants. We recruited power wheelchair users from disABILITY Link (Link), a Center for Independent Living, in Decatur, Georgia and from Shepherd Center in Atlanta, a rehabilitation center for spinal cord injury.

Focus group participants were given a survey to complete prior to participating in the focus group. This pre-focus group survey served to activate participant's background and experience, while providing quantifiable data. We also posted a version of this survey online on our website (http://mobilityrerc.catea.org) and sent out an email to interested individuals and groups to solicit input.

Survey results from focus group participants indicated that the age range was from 25 to 57 years of age. The average age was 44. The sample recruited addressed many factors relevant to the use of power wheelchairs. Participants were recruited based on their personal experience with power wheelchairs, rather then being selected at random. An *a posteriori* analysis of focus group and online survey data showed the sample to be diverse with respect to gender, ethnicity, home location, employment status, monthly household income and activity level. **Table 2** contains demographic information on focus group participants and online survey respondents.

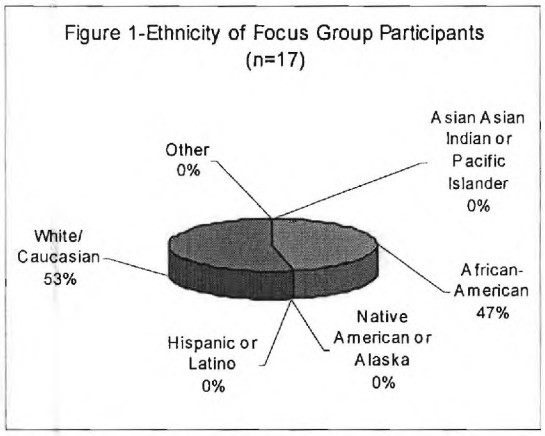
Table 2—Demographic Characteristics: Focus Groups & Survey Respondents

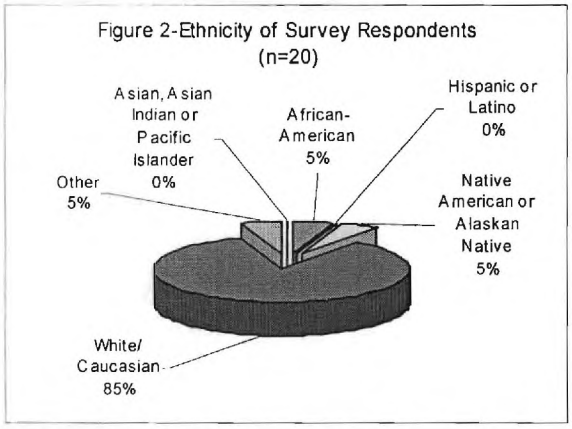
Variable		# of Focus Group Participants	%	#of online Survey Respondents	%
Gender	Female	9	53	7	35
	Male	8	47	13	65
	Total	17	100	20	100
Ethnicity	Asian, Indian or Pacific Islander	0	0	0	0
	African American	8	47	1	5
	Hispanic or Latino	0	0	0	0
	Native American or Alaskan Native	0	0	1	5
	Caucasian	9	53	17	85
	Other	0	0	1	5
	Total	17	100	20	100
Home Location					
	Rural community/ in the country	0	0	4	20
	Small to mid-sized town	1	6	4	20
	Suburban neighborhood	7	41	8	40
	Urban neighborhood / inner city	9	53	4	20
	Total	17	100	20	100
Employment Status					
	Employed Full-time	8	47	7	35
	Employed Part-time	2	12	6	30
	Student	2	12	0	0
	Unemployed	3	18	0	0
	Unable to Work	2	11	7	35
	Total	17	100	20	100

Variable		# of Focus Group Participants	%	#of online Survey Respondents	%
Monthly Household Income					
Did Not Answer		5	29	2	10
<$600		2	12	0	0
$600-1199		0	0	3	15
$1200-1999		1	6	3	15
$2000-2999		1	6	5	25
$3000-4999		6	35	4	20
$5000 or more		2	12	3	15
	Total	17	100	20	100
Activity Level					
Very low		1	6	5	25
Low		1	6	0	0
Moderate		3	18	6	30
High		8	47	7	35
Very high		4	23	2	10
	Total	17	100	20	100

The following figures compared selected demographic characteristics (cultural, lifestyle and environmental differences) important to caster and drive wheel use.

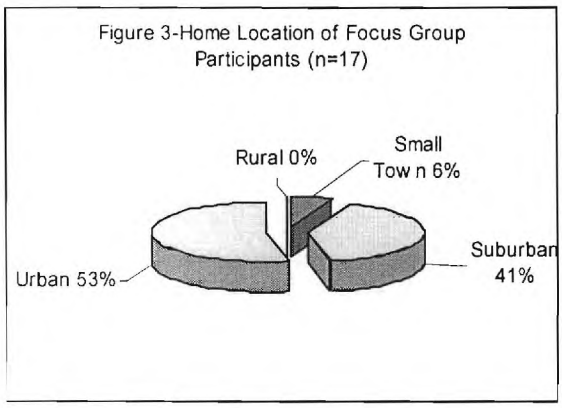
Figures 1 & 2—Ethnicity

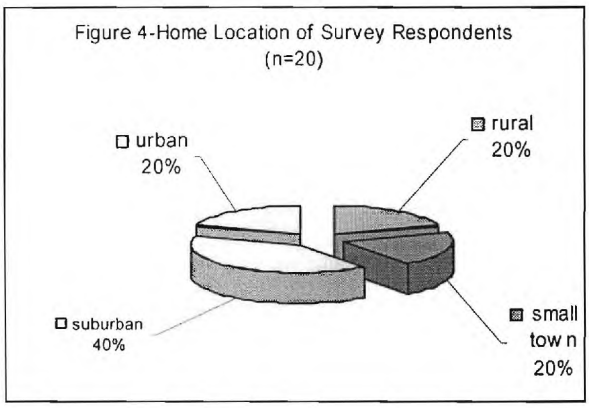




Focus group participants were almost evenly split between African-American and White/ Caucasian. The majority of online survey respondents were Caucasian. The 'digital divide,' may account for such a large percentage of White/Caucasian survey respondents (85%). The 'digital divide' suggests that internet access is growing at a much slower pace in non-white households. It is interesting to note that due to internet/web posting, at least one Native American was able to respond to the online survey.

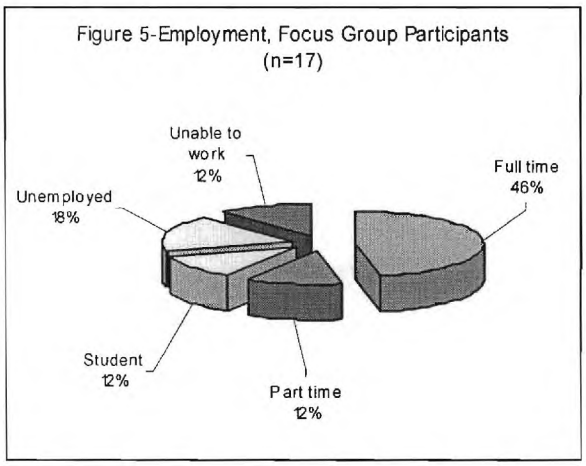
Figure 3 & 4—Home Location

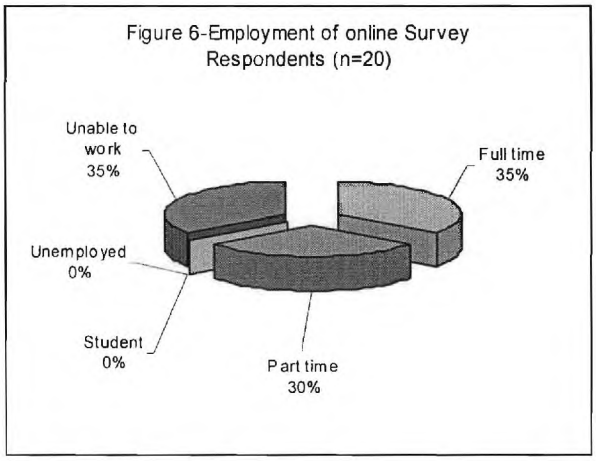




As the figures illustrate, a majority of focus group participants lived in urban areas and as majority of online survey respondents lived in suburban areas. Taken together, the data represents diverse environments of use and lifestyles with respect to different outdoor and indoor surfaces, transportation and housing options. Users living in urban environments discussed caster and drive wheel problems with outdoor surfaces including, slopes, ramps, broken and cracked concrete and uneven surfaces like asphalt. Suburban focus group participants were much more likely to discuss problems with grass, sand, gravel, loose dirt and mud. Urban dwellers discussed problems using public transit, while suburbanites discussed caster related problems using private modes of transportation (like vans with lifts). Suburban dwellers discussed problems with casters and drive wheels that they experienced in their own homes.

Figure 5 & 6—Employment

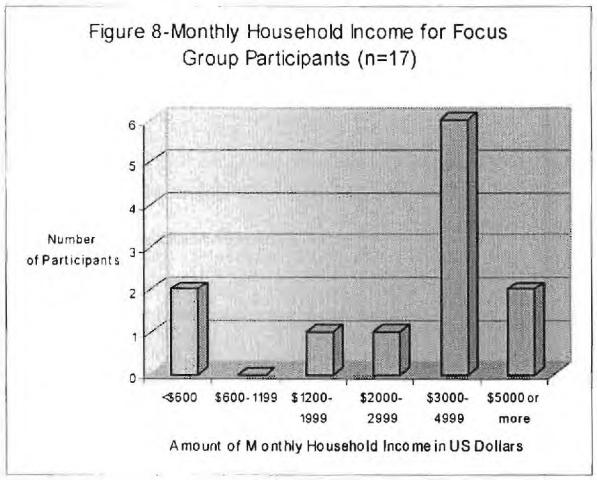


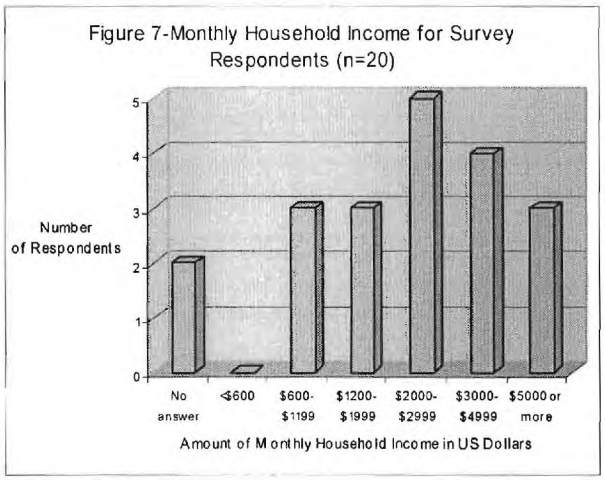


Full-time employment was highest among focus group participants at 46%. Online survey respondents tended to have greater levels of part-time employment, but greater percentages were unable to work. Both groups reported slightly higher overall employment levels than national averages. National averages for employment of people with significant disabilities has remained around 30% for the last several year.

Diverse employment situations were represented in the sample and were reflected in income and lifestyle differences.

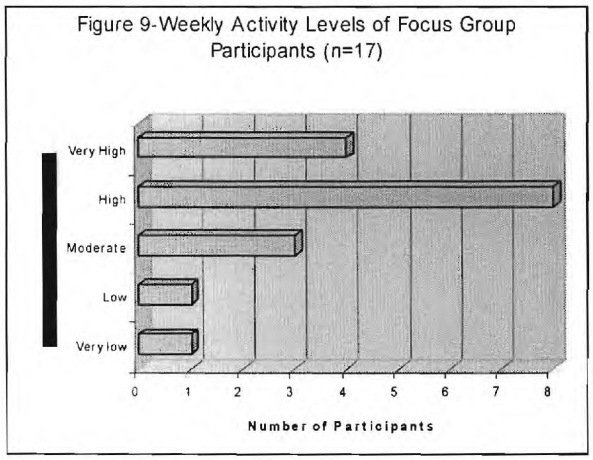
Figures 7 & 8—Monthly Household Income

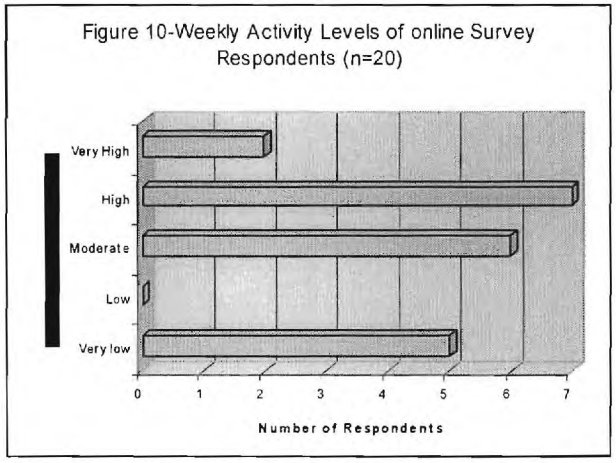




More full-time employment among focus group participants may account for more monthly household incomes in the $3000-$4999 range. Online survey respondents appeared to be distributed across income categories, with more part-time employment. Generally, higher levels of employment and income indicate higher levels of discretionary income. A higher level of discretionary income usually means higher probability that funds will be available for the purchase of replacement products. On the other hand, costs associated with caster and drive wheel repair and replacement may be more important to users who must pay for repair and/or replacement parts with out-of-pocket personal funds.

Figure 9 & 10—Weekly Activity Level





Almost half of focus group participants (8 of 17) and a third of survey respondents (7 of 20) reported high weekly activity levels. Overall weekly activity levels for focus group

participants were slightly higher than for survey respondents. More activity translates into richer and more diverse experiences. Active powerchair users place grater demands on their equipment and have greater performance expectations. Often, active users are better informed about their equipment and have a better understanding of the problems they encounter.

Logistics and Data Capture

Informed consent from all human subjects was obtained prior to participating in surveys and focus groups. The *Research Consent Form* was placed on the website and survey respondents were asked to indicate their acceptance of the online *Consent*. After agreeing to the *Consent*, respondents completed the survey. The online survey took approximately 10 minutes to complete. Online survey respondents did not receive any incentive for completing the survey.

We convened two focus groups with power wheelchair users. Each focus group lasted approximately 2 hours and a light meal was served. Participants were told that there were no financial costs to participate in the study and that their participation was voluntary. Participants were asked to read and sign the *Consent*. The *Consent* was read to those who asked for assistance. Participants were given a copy of the signed, completed document. The signed, completed originals were stored in a secure location at CATEA. To protect the privacy of participants, records were associated with a code number rather than a name. Participants were paid $30 at the end of the focus group. Focus group sessions were recorded, transcribed and analyzed.

Focus Group Discussion Format

To prepare the focus group questioning protocol, we first identified key members of the cross-functional research team (commercial partner-Michelin, technical partner-rehabilitation engineer, and human factors partner-industrial designer, moderator) and asked them for input and issues. We also drew upon the personal experience of key informants (experienced power wheelchair users), standards, reports, academic research, interviews with Michelin experts, and other information sources. The focus group moderator worked with these partners to create the focus group questioning protocol.

Team members provided focus group issues related to current product use and design concepts and approaches. The commercial partner provided key issues about market issues, design concepts and issues related to manufacturing and distribution. The human factors/usability team members focused on use issues. Systematic preparation of probing questions lessens the likelihood that critical product requirements will be overlooked. The focus group questioning protocol is attached to this report. The focus group used the following discussion format:

Part 1-Complete Pre-Focus Group Survey
Part 2-Discuss problems with current caster and drive wheel products

1. What types of indoor and outdoor surfaces and barriers do you have problems with and why
2. How important are your casters and drive wheels in your everyday routine
3. What makes casters and drive wheels wear out and why and how often do you replace them
4. What maintenance and adjustment problems do you experience
5. What health and safety problems do you experience

6. How would you describe the "ride" of your casters and drive wheels
7. What do you think of the appearance of your casters and drive wheels

Part 3-Discuss IDEAL caster and drive wheel characteristics

1. What types of indoor and outdoor surfaces should casters and drive wheels handle
2. How do casters and drive wheels perform on indoor and outdoor surfaces and over barriers
3. How much/little traction do casters and drive wheels provide
4. How is shock absorbed and how much flex should casters and drive wheels have
5. How do casters and drive wheels handle uneven surfaces
6. How long does the caster / power drive wheel tire last
7. What sort of maintenance do casters/drive wheels need, do they require air
8. Do casters / drive wheels ever need adjustments, if so how are made and who does it
9. Do casters / power drive wheels fail, crack, break, peel, shred, roll of the hub, etc.
10. How do they handle static electricity buildup and EMI
11. What about colors and effects, materials desired
12. How important is the need for casters and drive wheels

Part 4-Tweel™ Demonstration and Evaluation

1. How well will the caster / drive wheel perform on rough terrain / over obstacles
2. How well will the caster / drive wheel absorb shock/ flex/ dampen vibration
3. How stable will the caster/ drive wheel be on surfaces that are not level
4. How well will the caster / drive wheel self-align
5. Does this appear to be a one piece system
6. Does the caster / drive appear to have a weight advantage over other casters/ drive wheels
7. How long will the caster / drive wear
8. What do you think of the air-less maintenance
9. Do you think that the rubber tread will mark floors
10. Any chance of sudden failure
11. What about colors and effects
12. What do you think of the pneumatic-like performance from non-pneumatic
13. Would you need a suspension system with the Tweel, why or why not
14. Have you heard of Michelin, do you consider the Michelin brand to be high quality
15. How would the Michelin brand influence you when select casters and power drive wheels

Part 5-Complete Dot Voting Activity

Findings

A transcript of focus group discussions was prepared and analyzed for content. Each focus group was content analyzed independently and both focus groups were analyzed together to find common themes. Many themes were identified across both groups. In this report, findings from focus group data are followed by data from both surveys. Survey data is summarized and presented in figures. What follows is an attempt to synthesize and interpret focus group and survey data.

Focus Group Data

Outdoor Surfaces and Barriers

Participants disucssed problems with casters and drive wheels on a great many outdoor and indoor surfaces and barriers. Chief amoung these were sidewalk cracks and uneven sidewalk concrete. Rolling over these barriers caused a rough, bumpy ride, because casters and drive wheels didn't absorb shock created when the caster and/or drive wheel hit these barriers. It appears that most participants used sidewalks when possible, but reported that they had to go off curbs to get around barriers or obsticles that blocked sidewalks. When curb cuts were non-existent, users are forced to go off curbs to cross streets. Several participants discussed the problems they experienced

when going off curbs as high as four inches. Current casters don't flex or absorb the shock of going off curbs. If the caster catches on the barrier, the chair is stopped and the force created sometimes causes injury to the user. Several users reported being 'thrown out' of the chair when striking a barrier. Some users reported tire roll-off when striking a barrier. Cracks in concrete present problems because they can cause casters to swivel and get caught and stop the wheelchair completely, causing injury to the user. In fact, several participants described this event in vivid detail. A participant commented that, "if I don't hit cracks just right, my caster will swivel, my feet pop off of the foot pedals and cause injury to my feet or cause a spasm." Another user described a similar experience. "I was going down the sidewalk and hit a crack and came out of my chair and broke my leg."

Gaps between surfaces presented another major issue for power wheelchair users. Several participants reported getting casters caught when boarding MARTA trains. Casters get caught in the gap between the edge of the platform and the door of the train. This was a scarry situation for users because they couldn't move forward or backward without assistance. This was potentially a life-threating situation for public transit riders. Public transit riders also described the loss of drive wheel traction when boarding busses via ramps and lifts.

On sloped concrete sidewalks, ramps and driveways, casters and drive wheels lost traction, especially on wet surfaces. Loss of traction was mentioned often when participants discussed their outdoor activities and the routes they travel. They described the difficulty that hills and slopes present. Rain makes climbing these hills and slopes even more difficult and dangerous. One participant mentioned problems with ice and snow and discussed the use of dog chain on casters and drive wheels to improve traction on snow and icy outdoor surfaces.

Uneven surfaces, including asphalt, presented problems. Asphalt presented unique challenges, because users couldn't always see uneven surfaces in asphalt. They described stricking cracks and pot holes and being 'thrown' from their wheelchair, breaking casters or experiencing tire roll-off.

Participants descirbed problems rolling over soft surfaces including grass, loose dirt, gravel, mud and sand. Most talked about having been stuck in soft surfaces. Several participants wanted a caster that would be useful on soft outdoor surfaces, including sand. They said they would enjoy more trips to the beach, if their casters would not get stuck in sand. One participant wanted a special caster attachment that could be installed to use on sand.

Several participants described how gravel, rocks and other debris "chew up" casters and/or caused "chunks of rubber" to go missing from both casters and drive wheels. Twigs, small branches, clipings from bushes, wire, trash, etc., get caught between casters and forks and turn the caster and caused it to stick, stopping the caster and potentially injuring the user. Smaller debris, like hair, string, and carpet fibers get caught and wrapped around caster and drive wheel axles, causing rolling resistance.

Indoor Surfaces and Barriers

Most participants experienced problems with throw rugs, area rugs, rubber mats and thresholds. Throw rugs were a significant problem. "I've been stuck a couple of time where [throw rugs] get caught in the [drive] wheel, it's just awful, you get stuck and cannot go anywhere." Casters also caused problems with throw rugs. Commented one participant, "my casters want to push the rug and bunch it up or the rug gets bunched up in the caster and twisted." Rubber mats caused users problems. Some rubber mats got twisted around casters and drive wheels and other types of rubber mats caused users to lose traction. Tracking across rubber mats was sometimes hazzardous; one user stated, "I have to have someone hold the door open and take a running start to get over the rubber mat at the front door of the bank and hope I don't hit anyone or anything."

Similar to barriers found outdoors, door thresholds caused casters to spin or swivel, get stuck aginst the edge of the threshold and stop the wheelchair completely, sometime causing injury to the user. One participant described a strategy she uses to deal with a threshold in her home, "I have to go over it backwards, just to get over it." Small, soft objects found in the home, like pet chew toys, caused problems. "I cannot get casters to roll over my dogs chew toys, soft cloth toys. Whatever hits the caster, like soft things, knots, makes it turn and get stuck. It won't roll over it." Carpet also appears to negatively impact caster performance. Participants seemed to agree that casters didn't turn well on carpets that were medium to thick pile.

Wear and Replacement

Focus group participants, who had replaced casters and drive wheels, reported that replacement depended a great deal on activity and terrain. About a quarter of focus group participants replaced casters and drive wheels every year. A few users replaced them more often; another quarter replaced them at about three years. Some had not replaced casters or drive wheels because their chair was relatively new. Several users reported that casters seemed to wear out because, "they do the turning," or because they rub on wheelchair foot pedals and users shoes. Most participants complained that they couldn't see their casters and drive wheels easily and therefore didn't inspect them often. As one participant pointed out, "I replaced them all [both casters and drive wheels]. They looked fine to me, still had tread, but I changed them because the vendor recommended it." In some instances, casters and forks are replaced because, "the caster doesn't take the shock and the fork gets it and once they [forks and casters] are bent you have to replace them."

Flat Repair, Adjustment and Cleaning

Flats are catastrophic events that negatively impacted user safety and well being. Participants described terrible problems with flats. One participant said, "I have air in my front casters and I've had them go flat. I've been stuck in my van, stuck in my Easy Lock!" Flats required the assistance of others to repair and often contributed to significant down time. This was a concern for all users and contributed to lost productivity for participants who were employed. To avoid this situation, most participants have given up the comfortable ride associated with pneumatic tires. Instead, most participants said they had turned to gel and "hard-roll" casters and non-

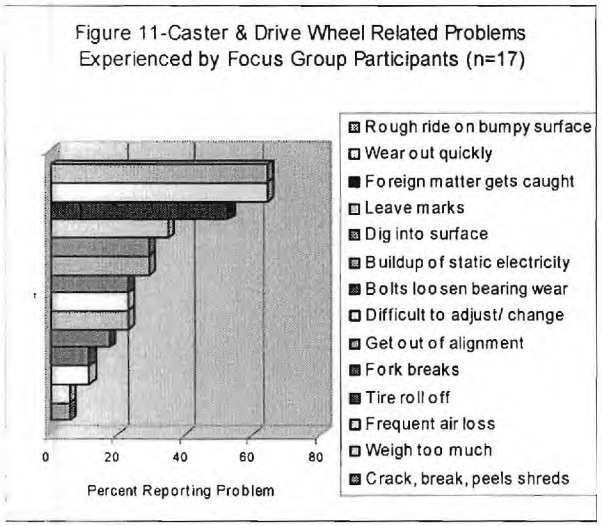
pneumatic drive wheel tires. These offered less shock absorption, but didn't fail catastrophically. One participant summed up the trade off, "air tires provide some suspension, but you have to worry about flats and proper inflation. With hard rubber, you feel every little thing you go over."

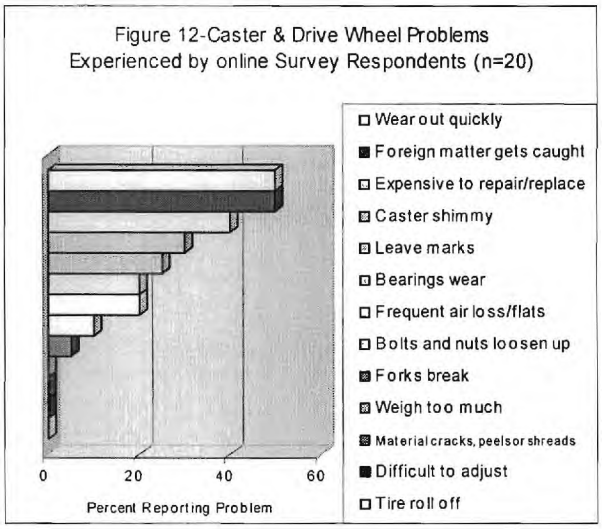
Several participants reported problems with caster shimmy, even with repeated adjustment. "Every time I get new wheels or casters they shimmy and shake. I can go to the [vendor's] shop and get the back casters adjusted and the adjustment might last for a day or so, but by the next day, they are shimmying again." Cleaning was also an issue for users. Drive wheels in particular, seemed to track dirt, mud and debris indoors. One participant pointed out, "I have to take the hose and clean it [wheels and casters]. I get yelled at, if I track mud and dirt into the house."

Survey Data

Suvey data was collected from both focus group participants and from online survey respondents. The questions asked in the surveys were slightly different, so the results are presented separately. A total of 17 focus group participants completed the pre-focus group survey and 20 powerchair users responded to the online survey.

Figures 11 & 12—Caster and Drive Wheel Related Problems





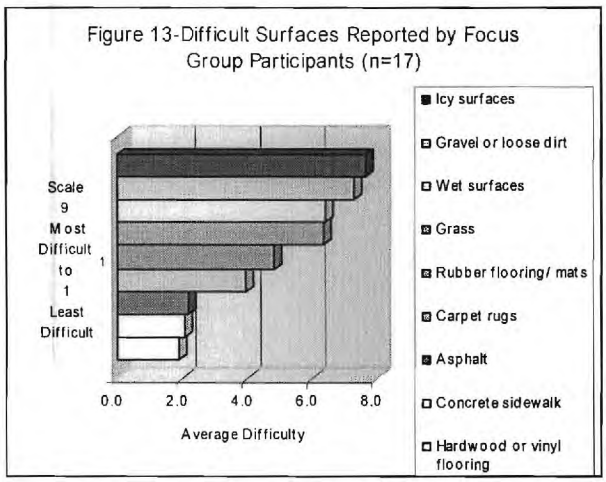
Based on **Figures 11 and 12**, it appeared that 60% of focus group participants and 50% of online survey respondents agreed that the most significant types of problems experienced with casters and drive wheels were:

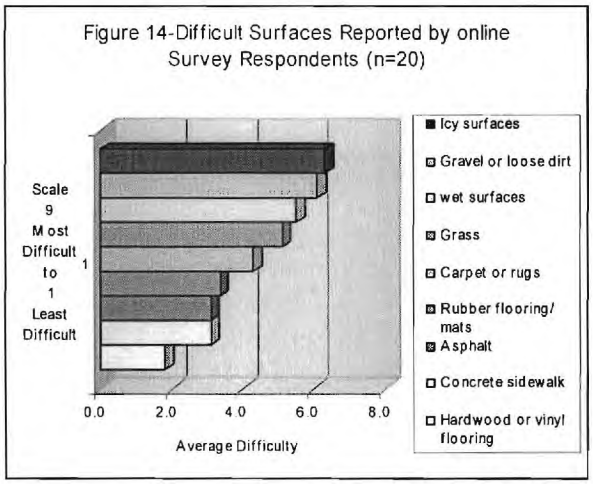
- caster and drive wheel wear
- foreign matter that gets caught in casters and drive wheels

Concerning the issue of 'caster and drive wheel wear,' focus group participants reported that they could not see their casters or drive wheels easily, thus making it very difficult to inspect them for wear. They reported that other people had to help them with this task. Vendors and suppliers seemed to play an important role in inspecting casters and

drive wheels for wear and making recommendations for replacement. Concerning 'foreign matter and debris getting caught in casters and drive wheels,' focus groups reported on these issues in some detail. Twigs, small branches, thread, wire, and trash were just some examples of debris that was reported to get stuck between casters and forks and wound around caster axles. Drive wheels in particular, seemed to track dirt, mud and debris indoors. More than 60% of focus group participants selected 'rough ride over bumpy surfaces' as the most significant problem. This survey data seemed to be correleted with what participants discussed druing focus groups. Participants were quite vocal about the fact that current caster and drive wheel products don't absorb the shock of going over bumpy surfaces. Many participants reported giving up on penumatic casters because of flats and moving to 'hard roll' or 'gel' filled casters. They complained that non-penumatic casters increased the jaring ride and vibration they experienced.

Figures 13 & 14—Difficult Surfaces

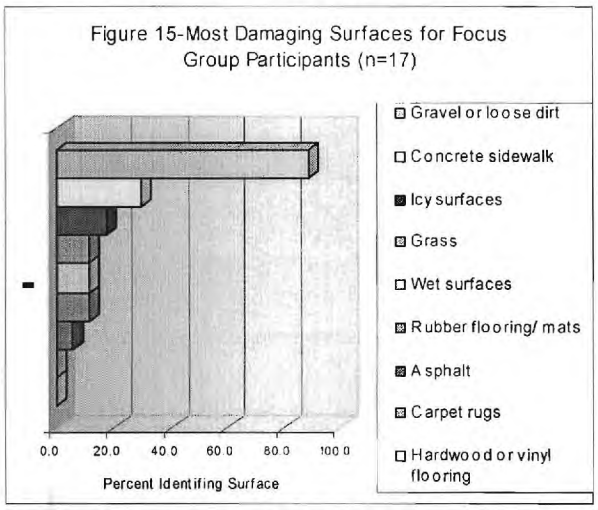


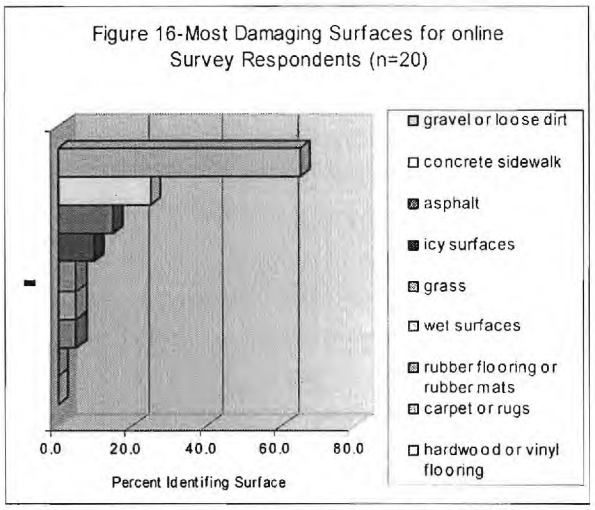


Focus group participants and online survey respondents were asked to order the difficulty of surfaces they rolled over, from nine (most difficult surface) to one (least difficult surface). **Figures 13 and 14** summarized the data. Scores for each surface were averaged. Rankings from both groups appeared to be very similar. Focus group participants ranked icy surfaces followed by gravel as the most difficult surfaces and hardwood and vinyl flooring as the easiest surfaces to roll over. Their scores were only slightly different from online survey respondents' scores. Rankings of rubber flooring/mats and carpet/rugs were reversed.

Data about problems with surfaces was reflected in focus group discussions. One participant mentioned problems with ice and snow and discussed the use of dog chain on casters and drive wheels to improve traction on snow and icy outdoor surfaces. Participants described how gravel, rocks and debris damaged both casters and drive wheels. It was broken and cracked sidewalks and gaps in concrete that caused users significant problems, not the sidewalk *per se*. Focus groups reported that casters and drive wheels lost traction on wet surfaces and would sink into soft surfaces like grass.

Figures 15 & 16—Surfaces Causing Most Damage To Caster and Drive Wheel





Powerchair users were asked to indicate the types of surfaces that caused the most damage to their casters and drive wheels. The percentage of users who reported damage from each surface type is summarized in **Figures 15 and 16.** Both focus group participants and survey respondents identified gravel/loose dirt and concrete sidewalks as most damaging. Discussions during focus groups also reflected similar concerns. Several participants described how gravel, rocks and debris 'chew up' casters and/or take out 'chunks of rubber' from both casters and drive wheels. Online survey respondents ranked asphalt higher than did focus group participants, but focus group participants described problems with asphalt, including cracks, potholes and uneven pavement. There seemed to be broad agreement between focus group participants and online survey respondents regarding damage to casters and drive wheels.

Conclusion

After a discussion of problems with current products, focus group participants were asked to discuss characteristics of their 'ideal' casters and drive wheels. These "Product Requirement Statements" are the characteristics and features that a product should have in order to satisfy the needs and wants expressed by product customers. Because Michelin plans to launch the Tweel™ in the power wheelchair caster and drive wheel markets, they are interested in what end-users had to say. Input from other product customers (service technicians, vendors, clinicians) is important and will be included in later reports.

Each focus group was concluded using a Dot Voting Activity. This activity was used to establish a rough indicator as to the importance and priorities of the ideal product characteristics. Attention should go to the categories of statements that received the most number of votes by participants. During focus groups, participants cast votes for the category or categories that were most important to him or her. No within-criteria ranking is implied in the following table. Statements listed below are verbatim statements made by end-users. Verbatim statements, while difficult to interpret for establishing design guidelines or performance specifications, do lend authenticity to

expressed end-users wants and needs. **Table 3** lists the product requirements statements from content analysis of focus group data.

Table 3— Ideal Caster and Drive Wheel "Product Requirement" Statements

Category	Product Requirement Statements	Total Score	Fg 1 Score	Fg 2 Score
Adjustment and Cleaning	• Bolts and nuts do not become loose • Self cleaning, won't track dirt into the house • Materials repel dirt • Is easy to replace--easy to change out caster/drive wheel • Has no air--don't want to air up or change flats • Puncture proof caster • Designed to keep out hair, carpet fibers, etc • Designed with a way to remove foreign matter	17	7	10
Ride	• No vibration or shimmy • Want the soft, smooth ride of an air caster without the problem of flats • Caster and drive wheel work together to smooth out the ride, reduces vibration so I don't look like I'm shivering and shaking or sliding out of my chair going down the street • Air tire ride without flats	12	3	9
Absorbs shock	• Takes the shock going from one surface up or down to another • Doesn't make me spasm • Absorbs the shock of hitting a barrier and doesn't turn sideways • Casters absorb shock • Gives a smooth ride over bumpy surfaces	10	5	5
Replacement	• Shouldn't cost any more to replace than your typical car tire	10	5	5
Durability	• Lasts between 5 to 7 years • last for 2 ½ years • 5 years warranty similar to car tires • Lasts as long as wheelchair, or at least 5 yrs • Standard part of wheelchair, not extra	8	4	4
Caster/ Drive wheel traction	• Want both caster and drive wheels to grip surfaces • For added traction, needs to grip surface • Sometimes on sidewalks and drive ways, you need the casters and drive wheels to get traction when turning	7	0	7
Rolls over outdoor and indoor surfaces	• Gets good traction on wet surfaces • Rolls over rocks, gravel and sand • Must roll over high thresholds	6	6	0
One piece construction	• One piece design, no small parts • Want only one part to change when I have to change a caster or drive wheel • One piece on and off, easy release	4	0	4
Available in Colors	• Lighter colors show more dirt, so I want colors that don't show dirt • Prefers black, grey, purple, blue, green, yellow	3	1	2
Sporty-doesn't look like medical device	• Slick looking, Sporty, low profile, not bulky, attractive • the existing rims look cheep [interior plastic] • available with decorative lug nuts, dust covers	3	1	2
Desired effects	• Can light up wheel for added safety after dark • Want to be able to turn feature on/off so it is not distractive	3	0	3

Category	Product Requirement Statements	Total Score	Fg 1 Score	Fg 2 Score
No Noise	• Makes no noise • Quite operation, no squeaking, like on clean, waxed floors	3	1	2
Keeps user level on uneven surfaces	• Keeps you level when rolling over tree roots, sticks, cracks and uneven sidewalks, smooth transition over uneven surfaces • Both casters perform, even if they are on different levels	2	1	1
Caster width and diameter	• I'd like to see the caster bigger than 4" [in diameter] so I can roll over more obstacles • 2 to 3 inches wide, wider is better • Wide enough to not fall down gaps like between the MARTA train and the platform, the elevator, etc. • 2 inches will allows you to go over obstacles, but not make turning more difficult • Wider caster means more contact surface, better traction • Comes in multiple widths for different functions • Smaller diameter makes it easier to roll, but larger diameter makes it easier to roll over obstacles	2	0	2
Adjustable suspension	• User can easily adjust the suspension just like adjustable backs [supports] on wheelchairs, customized for the users need, function, weight	2	2	0
Ball type caster	• Prevents carpet and rugs from rolling up in the caster • Prevents debris from being collected • Doesn't get caught on edges of sidewalks	1	1	0
Maneuverable	• Don't want to lose easy turning, even though wheels are wider, should turn in same space	1	1	0
Compatibility	• Caster is compatible across manufacturers and suspension systems • Caster is standard equipment on powerchair, otherwise insurance won't cover	1	0	1
Spinning rims	• Want the rim to keep turning just like show rims on cars and SUV's do	0	0	0
Drive Wheel	• 5 inches wide • Wide enough so it will go over grates and not get caught in cracks • Comes in multiple widths for different functions • It must be wider than the widest gap, like between MARTA train and platform, about 3 inches	0	0	0
Drive wheel tread	• Tread does not wear • Tread wear indicator, tread changes color to indicate needed replacement • Smooth tread to reduce the amount of dirt that collects • Grooved caster tread • Goes over gravel without being damaged • Leaves no marks on flooring	0	0	0
	Totals	95	38	57

Tweel™ Evaluation

After reviewing a demonstration of the Tweel™ caster and drive wheel, participants were asked to offer an initial impression of the Tweel™ and evaluate it against their 'ideal' caster and drive wheel. The initial reaction to the Tweel™ was somewhat mixed. Some comments were very positive, "I would try them in a minute, you could pop mine off and put them on and I'll take them home with me." "It addresses 80% of the things on the list." "It eliminates air and that's good, I don't like to deal with air for maintenance reasons and for accident reasons; air is a safety, functional, and

maintenance issue." Some initial responses were more skeptical. "You'd have to actually let me use that tire, use it myself." "I'd like to know about the results of testing against the ones that are already in use and hear from users who test them."

Table 4 contains the positive comments about the Tweel™. **Table 5** lists negative comments. Negative comments are based on participant's initial impression of the prototype without the opportunity to test it. Negative comments may present opportunities for improvements. No rank ordering of the following statements has been done. Some statements below are vague, over-generalized, or unrealistic in terms of the constraints under which Michelin is operating.

Table 4—Positive Comments on the Tweel™

Positive Comparisons
• It looks like it will take a lot of shock
• It looks like it gives you shock absorption
• This design would make it easier to roll over something like a curb, because it would give so much
• It looks like it would go over a threshold
• I like the smoothness of the caster, it will rotate on the rug easier
• I like the caster tread--too much tread will make it harder to turn
• The drive wheel will get better traction because it's flat
• Doesn't look like it would mark the floors
• It feels like you'd get an air ride from the caster, without the air
• It looks like a sports car tire, not like a medical device
• Kids would love the green colored caster
• The drive wheel looks lighter than my drive wheel
• The size means that I can roll over more things easier
• They look like a one-piece design
• They eliminate air and that's good
• They would be easier to clean than the ones I have
• I could pressure wash them
• If you run over mud with these, it would dry in those little cracks and just fall off
• The drive wheel looks like it would maybe last at least 5 years, based on the thickness of the rubber
• If someone tested it and it does last as long as current products, then I'm cool with that
• It looks like the drive wheel would wear evenly--it's flat, not thick in the middle

Table 5—Negative Comments on the Tweel™

Negative Comments and Possible Opportunities for Improvements
• When the caster gets pushed down, it looks like it makes it harder to turn, because you've got more caster in contact with the surface
• It looks like you'd get more traction with the drive wheel, but turns may be a different thing
• I would like more curvature on the surface of the caster to make turns easier
• I would like to see someone heavy test it and demonstrate it
• I want to know how much flex wear it would take until it doesn't absorb anymore
• It looks like they will lose stability as the flex wears out
• Looks like they will lose stiffness and slow you down because you are putting so much pressure on it
• It looks like I would get caster shimmy
• If I ran the caster over gravel repeatedly, it looks like it would chew it
• I want more caster colors, at least gray tread with black hub or center and vice versa, maybe a silver hub area with black tread
• I'd like dust covers and decorative lugs
• I want white walls that reflect car lights
• I want the entire caster to glow in the dark for use after dark
• They look like debris collectors--you'd get so much dust and dirt in the fins
• I would get rocks stuck in the fins

Negative Comments and Possible Opportunities for Improvements
• I could see how a lot of dirt and grit would get stuck in there over time
• It looks like they would track sand and water inside
• It doesn't look like they would last as long as the ones I have now
• It looks like the caster fins will crack in cold weather, or get dry and brittle
• It looks like the fins might break
• I don't see getting any traction with the caster, on your hands it doesn't feel like you get any traction
• The caster would slide on wet surfaces
• I want to see tread on the casters

Finally, participants were asked to indicate by show of hands if they knew of Michelin. Almost all participants in both focus groups indicated that they had knowledge of Michelin products. All participants indicated that they believed that Michelin made quality products. Most participants indicated that the brand would influence their decision to purchase casters and drive wheels made by Michelin.

Procurement

Focus group and online survey data provided information about the procurement behavior of powerchair users. Users were asked about the frequency of caster and drive wheel replacement, what assistance they sought out when making replacement decisions, what influenced their product selection, how replacement products were paid for, how much was spent out-of-pocket for replacement products and what their preferences were for caster colors and effects.

Figures 17, 18 & 19—Caster Replacement Frequency and Number

Figure 17-Caster Replacement Frequency for Focus Group Participants (n=17)

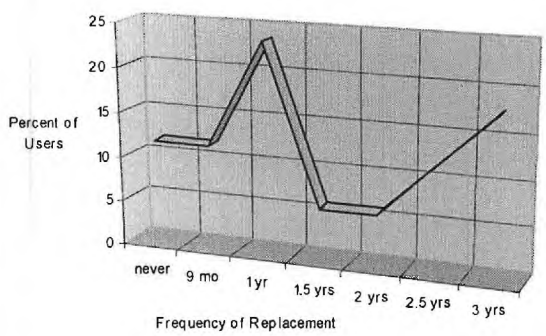
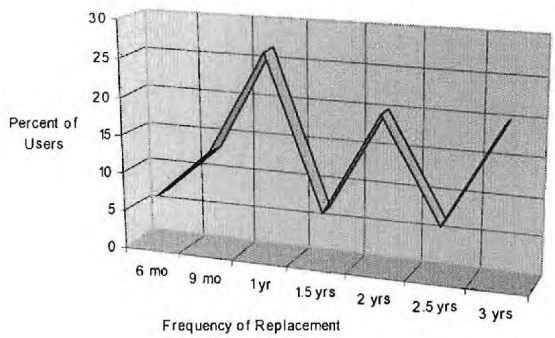
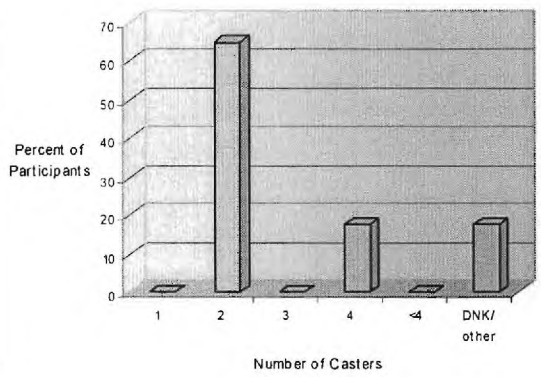


Figure 18-Caster Replacement Frequency for online Survey Respondents (n=15)



The percentage of users that replaced casters at different time intervals is indicated in **Figure 17** for focus group participants and in **Figure 18** for online survey respondents. Twenty-four percent (24%) of focus group participants replaced casters yearly, although for some participants, casters were replaced about every three years (18%).

Figure 19-Number of Casters Replaced at One Time, Focus Group Participants (n=17)



For survey respondents, 27% reported replacing casters after one year, while 20% replaced them after 2 years and 20% replaced them after three years.

If both data sets were combined, analysis appeared to indicate that at least 50% of users replaced casters within three years.

Several focus group participants reported having never changed a set of casters on their powerchair. Low activity levels may account for part of this situation and/or lack of access to funding and/or lack of access to vendors and suppliers.

Most focus group participants (65%) replaced a *pair* of casters; a much smaller percentage (18%) replaced four casters at one time (**Figure 19**). Several participants were using powerchairs that utilized four casters and therefore probably replace all four casters at the same time.

Figures 20, 21 & 22—Drive Wheel Replacement Frequency and Number

Figure 20-Drive Wheel Replacement Frequency for Focus Group Participants (n=17)

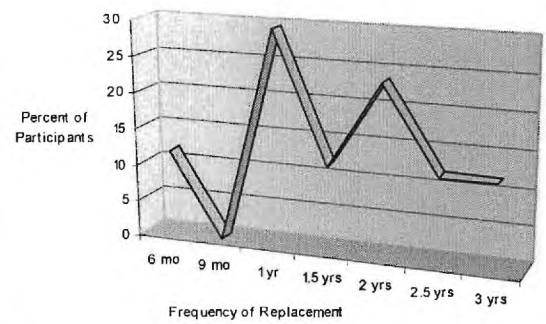
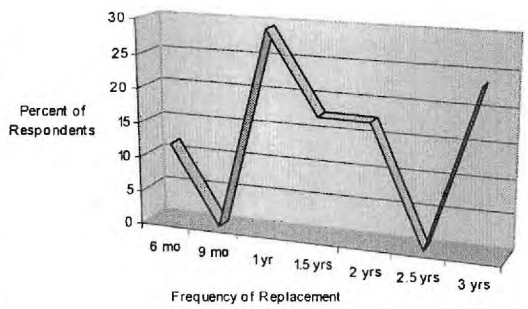
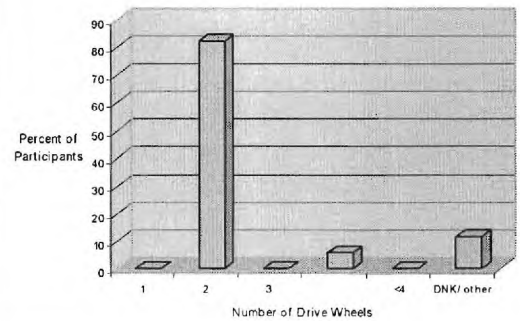


Figure 21-Drive Wheel Replacement Frequency for online Survey Respondents (n=17)



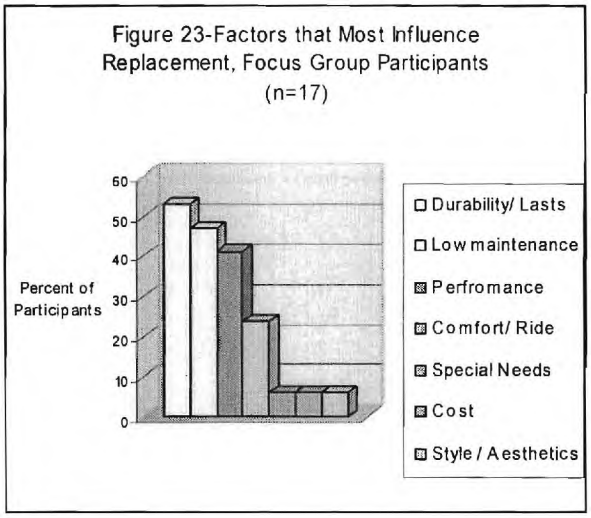
Users were asked how often drive wheels were replaced. The percentage of focus group participants that replaced drive wheels at different intervals is indicated in **Figure 20** and the percentage of online survey respondents that replaced drive wheels at different intervals is indicated in **Figure 21**. Among focus group participants, 29% replaced drive wheels yearly, while 24% replaced them every

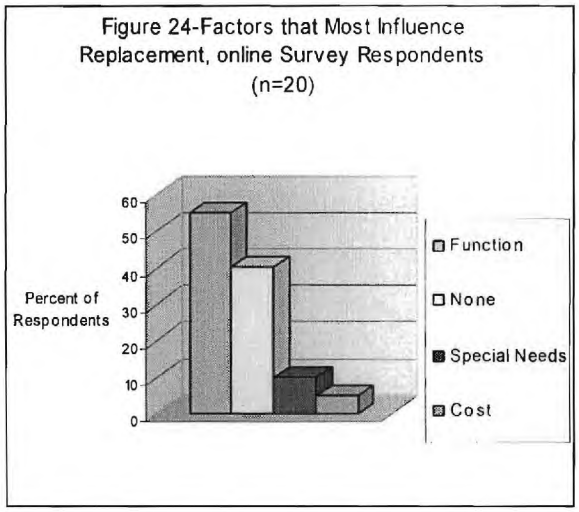
Figrue 22-Number of Drive Wheels Replaced at One Time, Focus Group Participants (n=17)



two years. Data from online survey respondents was very similar, with 29% replacing drive wheels after one year and 18% after 1.5 years and another 18% replacing them after 2 years. Overall, drive wheels appeared to be replaced more often than casters. While almost 1/3rd of users surveyed replaced drive wheels yearly, more than a 1/3rd replaced drive wheels between 1.5 and 2 years. According to **Figure 22**, almost all focus group participants (88%) reported that they replaced a *pair* of drive wheels.

Figures 23 & 24—Influences on Replacement

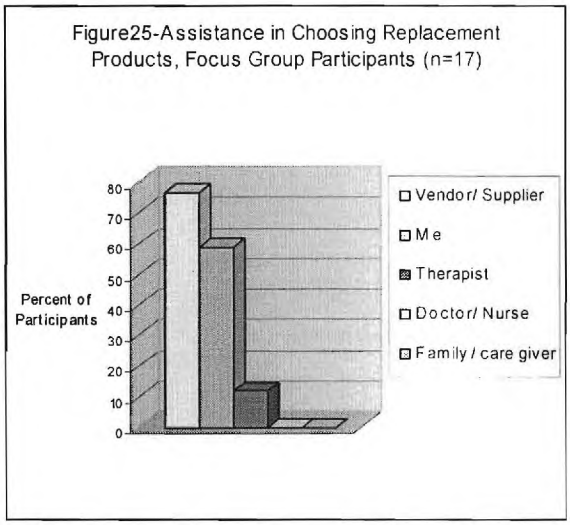




Users were asked to select the factors that had the most influence on casters and drive wheel selection. Answer choices were different on the focus group survey and the online survey. Nevertheless, it was noted that product function was important to most online survey respondents, while focus group participants were most influenced by product durability, low maintenance and performance. During focus groups, participants discussed problems with these same factors. It appeared that users wanted caster and drive wheel products that lasted longer than current products, didn't require much maintenance and performed well on all sorts of outdoor and indoor surfaces.

Forty percent of online survey respondents selected 'None.' Several factors might account this selection. First, according to focus group participants most users were not often given a choice about the casters and drive wheels they wanted for their chairs. Their choice was constrained by what insurance would cover. During focus groups, participants were insistent that the Tweel™ must be a standard part of the powerchair, not an upgrade, because insurance would not cover the Tweel™ as an upgrade. So, while users want products that are more durable, easy to maintain and perform well on all types of surfaces, they also recognized that their choices were often limited by insurance funding/reimbursement. Because both participants and online survey respondents reported using these funding sources, cost was not cited as a major factor in determining product selection.

Figures 25 & 26—Assistance in Choosing Replacement Products



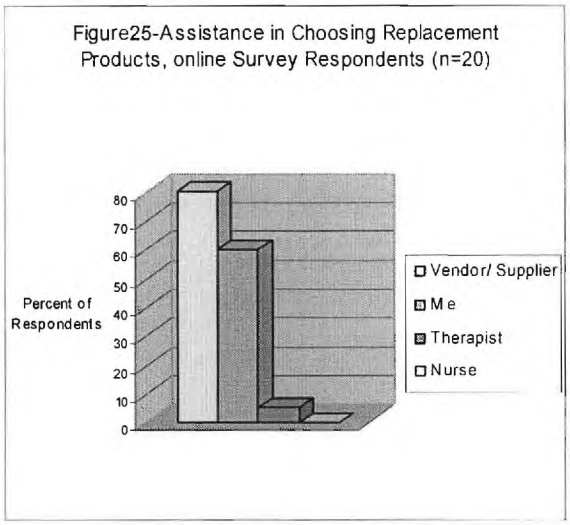
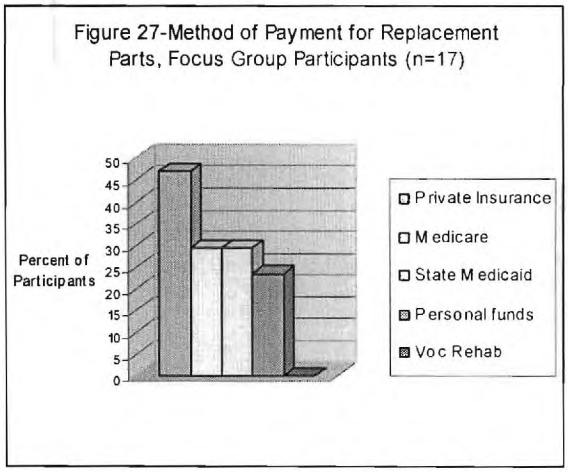
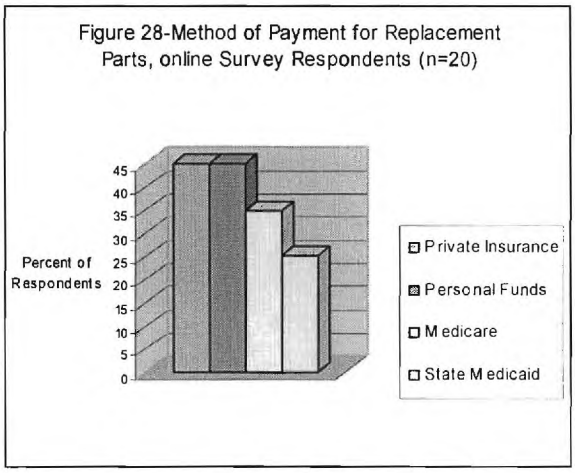


Figure 25 illustrates that a majority of focus group participants (76%) consult vendors and suppliers about caster and drive wheel replacement. **Figure 26** indicates that online survey respondents relied on the assistance of vendors 80% of the time. During focus groups, participants reported relying on their vendor or supplier for assistance in determining when casters and drive wheels should be replaced. Those participants who had replaced casters and drive wheels had obtained the replacement parts through a local vendor of durable medical equipment (DME). Most vendors also handled billing and collections. By all accounts, vendors and suppliers appeared to play a significant role in replacement of casters and drive wheels.

Figures 27 & 28— Payment Methods for Replacement Parts





According to **Figure 27**, a majority of focus group participants (47%) relied on private insurance to cover the cost of replacement casters and drive wheels. Medicare and state Medicaid insurance were the next most used funding sources, followed by

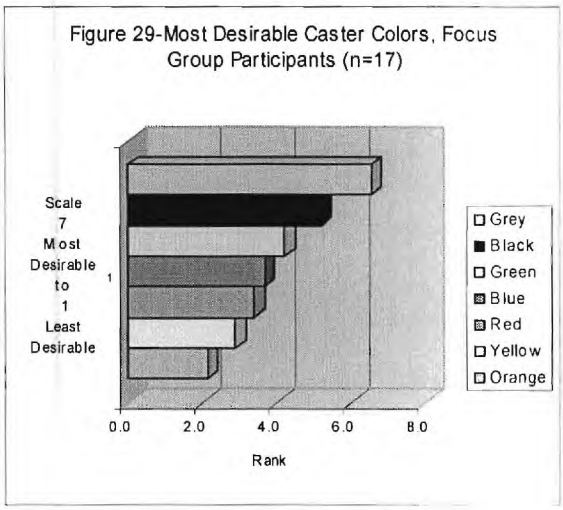
personal funds. No participants used vocational rehabilitation funding to obtain replacement parts. **Figure 28** again notes that a majority of users (45%) relied on private insurance, but an equal percent (45%) used personal funds to obtain replacements. So, while private insurance is an important source of funding for those who have it, those who do not, rely on Medicare or Medicaid. When insurance will not cover the cost for replacement, personal funds are used. This data correlates well with focus group comments. During focus groups, users discussed the need for Tweel™ products to come as standard parts of the powerchair, not as upgrades. If Tweel™ products come standard; it was believed that replacement parts would be paid for through insurance.

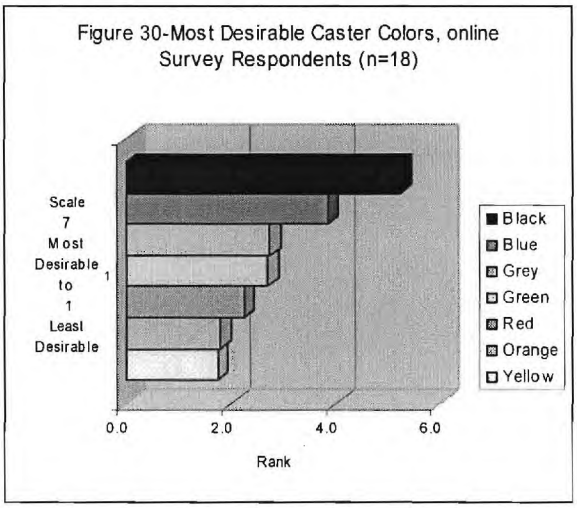
Table 6 —Personal Funds Spent for Current Products

Group	Product	Average	Median	Range
Focus Group Participants				
	Casters	$75.00 per pair/year	$75.00 per pair/year	$50-$100 pair
	Drive Wheels	$93.75 per pair/year	$100.00 per pair/year	$75-$200 pair
Online Survey Respondents				
	Casters	$ 71.14 per pair/year	$75.00 per pair/year	$24-$100 per pair

Table 6 summaries the data from users who paid for replacement products using personal funds. Focus group participants who had replaced casters reported spending on average $75 per pair per year, while online survey respondents reported spending slightly less, or $71.14 per pair per year. Focus group participants reported spending more for replacement drive wheels each year, on average $93.75 per pair per year.

Figures 29 & 30—Most Desirable Caster Colors

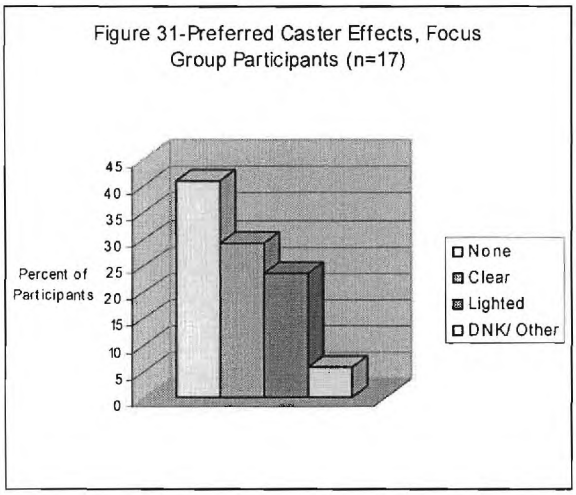


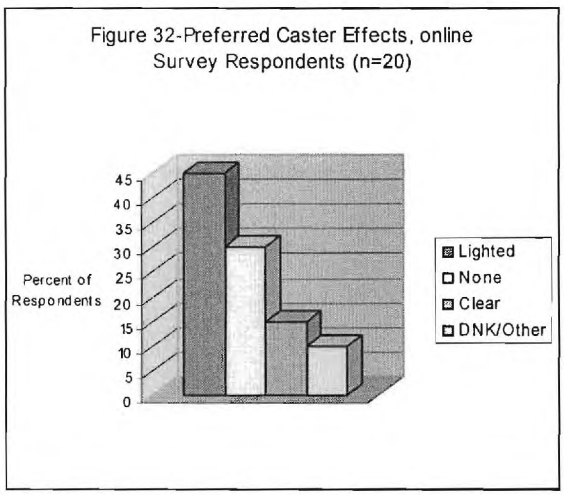


Users were asked which caster colors they desired the most. Color choices were ranked from most desired (7) to least desired (1). The resulting scores were averaged. The results are illustrated in **Figures 29 and 30**. Rankings from both groups were similar, with focus groups ranking grey as the most preferred, followed by black and green.

Online survey respondents desired black, followed by blue and grey. During focus groups, there were mixed reactions to the Tweel™ caster and drive wheel colors. Some participants liked both the black and the green colored casters. Comments ranged from "cool" and "sporty" to "looks cheep." Darker colors were reported to show less dirt.

Figures 31 and 32—Preferred Caster Effect





Users with asked to select a preferred caster effect. As **Figures 31** illustrates, more than 1/3rd (41%) of focus group participants didn't want a caster effect, while another 1/3rd wanted a clear caster and 1/4th wanted lighted casters. **Figure 32** indicates that almost half (45%) of online survey respondents wanted lighted casters while another 1/3rd didn't want effects. During focus groups, participants discussed more types of effects, including glow-in-the-dark casters, casters with spinning rims and lighted casters for safety after dark. Lighter colors (including clear) were thought to be more difficulty to keep clean. Participants were insistent that if effects like lighting were included, users wanted to be able to control these, i.e. users didn't want them "on" all the time. They wanted a switch to turn the effect on or off based on the environment they were in.

Appendix

The **Appendix** includes the pre-focus group survey and the focus group discussion script.

Pre-Focus Group Survey

This short survey is related to power wheelchair caster and drive wheel use. There are two parts to the survey. The survey will take about 10 minutes to complete. **Part I** asks about your current equipment, your satisfaction with this equipment, problems you experience using casters and power drive wheels and how often you replace these parts. **Part II** asks for some basic information about your situation.

Part I-Your Current Equipment, Problems & Replacement
For each question below, place an "X" in the box that best describes your situation.
Your answers will be confidential.

What is the make (manufacturer) and model of your current wheelchair?

Make _____

Model _____

What size of caster wheels are on your power wheelchair?

☐ 4 x 2 Casters
☐ 5 x 2 Casters
☐ 6 x 1 ¼ Casters
☐ 6 x 2 Casters
☐ 8 x 1 ¾ Casters
☐ 8 x 2 Casters
☐ 8 x 2 ¼ Casters
☐ 9 x 2 Casters

What type of caster wheels are they? Are these casters...

☐ Air up (pneumatic)
☐ Hard Roll (non-pneumatic)

How satisfied are you with the performance of these caster wheels?

☐ very satisfied ☐ somewhat satisfied ☐ somewhat dissatisfied ☐ very dissatisfied

What size of power drive wheels are on your power wheelchair?

☐ 10 x 3
☐ 10 ½ x 3 ½
☐ Other size _____
☐ 12 ½ x 2 ¼
☐ 14 x 3

What type of power drive wheels are they? Are these power drive wheels...

☐ Air up (pneumatic)
☐ Hard Roll (non-pneumatic)

How satisfied are you with the performance of these power drive wheels?

☐ very satisfied ☐ somewhat satisfied ☐ somewhat dissatisfied ☐ very dissatisfied

What types of caster and/or power drive wheel related problems have you experienced (Check all that apply)?

- ☐ Rough ride on bumpy surfaces sometimes jars me or makes my back/butt hurt
- ☐ Dig into surfaces making it difficult to roll over the surface
- ☐ Frequent air loss and/or flats on pneumatic (air up) tires
- ☐ Wear out to quickly
- ☐ Tire roll-off (i.e. tire rolls off the caster)
- ☐ Get out of alignment, shimmy or wiggle and vibrate
- ☐ Fail suddenly and/or material cracks, breaks, peels apart or shreds
- ☐ Leave marks on carpet or other types of flooring
- ☐ Foreign matter (i.e. hair, thread, dirt, etc.) gets caught in casters
- ☐ Buildup static electricity and shock me
- ☐ Are difficult to adjust and change out
- ☐ Weigh too much
- ☐ Caster bolts and nuts loosen up and/or bearings wear out or freeze-up
- ☐ Caster fork breaks

Order the following surfaces according to the difficulty you experience when rolling over them--1 is most difficult, 9 is the easiest.

_____ Carpet or rugs	_____ Gravel or loose dirt
_____ Rubber flooring or rubber mats	_____ Grass
_____ Hardwood or vinyl flooring	_____ Wet surfaces
_____ Concrete sidewalk	_____ Icy surfaces
_____ Asphalt	_____ Other _____

Which surface causes the most damage to your casters or drive wheels (Choose one)?

☐ Carpet or rugs	☐ Gravel or loose dirt
☐ Rubber flooring or rubber mats	☐ Grass
☐ Hardwood or vinyl flooring	☐ Wet surfaces
☐ Concrete sidewalk	☐ Icy surfaces
☐ Asphalt	_____ Other _____

Which of the following most influences your selection of casters and power drive wheel tires?

☐ Comfort/ride	☐ Cost
☐ Performance	☐ Style/ Aesthetics
☐ Durability/ Lasts long time	☐ Special needs
☐ Low maintenance	☐ Other _____

How are replacement casters and power drive wheel tires on your wheelchair usually paid for?

☐ Private Insurance	☐ Medicare
☐ Out-of-pocket/ personal funds	☐ State Medicaid

☐ Vocational Rehab ☐ Other _____

Who participates in the selection of casters and power drive wheel tires for your wheelchair (Check all that apply)?

☐ Me ☐ My family/care giver/attendant
☐ Vendor/Supplier ☐ Therapist
☐ Doctor/Nurse ☐ Other _____

How often are the casters on your wheelchair replaced?

☐ Every 6 months ☐ Every two years
☐ Every 9 months ☐ Every two and a half years
☐ Every year ☐ Every three years
☐ Every year and a half ☐ Other _____

How often are the drive wheel tires on your wheelchair replaced?

☐ Every 6 months ☐ Every two years
☐ Every 9 months ☐ Every two and a half years
☐ Every year ☐ Every three years
☐ Every year and a half ☐ Other _____

How many casters do you typically obtain/replace at one time?

☐ one ☐ two
☐ three ☐ four
☐ more than four ☐ Don't' know/other _____

How much do you spend out-of-pocket (using personal funds) on the caster(s) during the period you checked above?

Dollar amount $_____ per (time frame) _____

How many drive wheel tires do you typically obtain/replace at one time?

☐ one ☐ two
☐ three ☐ four
☐ more than four ☐ Don't know/other _____

How much do you spend out-of-pocket (using personal funds) on the drive wheel tire(s) during the period you checked above?

Dollar amount $_____ per (time frame) _____

From where are your casters and drive wheel tires obtained or purchased?

☐ Local DME vendor supplier ☐ Catalog sales _____
☐ Bike/Skate Boarding shop ☐ Internet site _____
☐ Other _____ ☐ Do not know

Rank the following caster and drive wheel tire colors from 1 (most desirable) to 7 (least desirable)

_____ Black
_____ Green
_____ Grey
_____ Yellow
_____ Blue
_____ Orange
_____ Red
_____ Other color _____

Select the following caster effects that you prefer?

☐ Clear ☐ Lighted ☐ None ☐ Other _____

What front suspension system do you have on your wheelchair?

☐ Frog Legs
☐ Bull Frogs
☐ Frog Legs Uni-Tine Forks
☐ Do not know
☐ None
☐ Other _____

How satisfied are you with this suspension system?

☐ very satisfied ☐ somewhat satisfied ☐ somewhat dissatisfied ☐ very dissatisfied

Part III-Please tell us a little about you...
What is your year of birth? 19 ___ ___

What is your gender? ☐ **Male** ☐ **Female**

What is your ethnicity?

☐ Asian or Pacific Islander
☐ African-American
☐ Native American or Alaskan Native
☐ Other _____
☐ Asian Indian or Middle Easterner
☐ Hispanic or Latino
☐ White/Caucasian

Where is your home located?

☐ Rural community/in the country
☐ Small to mid-sized town
☐ Suburban neighborhood
☐ Urban neighborhood/inner city

What is your current level of employment? (Check all that apply)

☐ Employed full-time
☐ Parenting/Homemaker
☐ Part-time student
☐ Unable to work
☐ Employed part-time
☐ Full-time student
☐ Unemployed
☐ Other _____

How do you rate your weekly activity level?

☐ **very low** (unemployed, only leave home about once or twice weekly)
☐ **low** (unemployed, leave home about once per day, move around inside home)

- ☐ **moderate** (at least a part-time employee or student, leave home more than once per day and move outside home, access community services outside home)
- ☐ **high** (full-time employee or student, leave home more than once per day, more around outside the home, access community services)
- ☐ **very high** (in addition to "active," play a sport like wheelchair basketball or tennis at least once per week)

What is your total average monthly household income? (Optional)

- ☐ Less than $600
- ☐ $600-$1199
- ☐ $1200-$1999
- ☐ $2000-$2999
- ☐ $3000-$4999
- ☐ $5000 or more

Focus Group Questioning Protocol

Part I Complete paperwork and do introductions (30 minutes)

- Complete the ***Research Consent, Media Release, W-9*** and collect information from participants using wheelchairs using the ***Participant Demographics Form***.
- Moderator Introduction/Introduction of other researchers/assistants and ground rules
- Participant introductions

Part II Discuss casters and drive wheel problems (30 minutes)

Describe problems (that users/ have you) experienced with casters/power wheels-

- Effectiveness--How **important** are **casters** and **power drive wheels**,
  - Day in the life of..., caster and power drive wheel **use**--what comes with whc or separate selection, Pneumatic vs hard roll
  - What **types of surfaces** are difficult, cause wear
  - **(T/V)** What characteristics of **user, environment, tasks** are considered
  - **(T/V) Assume/Outcome:** Therapists prescribe and vendors select
- Reliability, Operability-
  - **Problems caused by Rough ride** over bumpy surfaces or obstacles
  - Casters get out of alignment-causes **shimmy** or vibration when rolling
  - Casters **dig** into surface making rolling difficult
  - **Marks** on carpet or other types of flooring from casters /power drive
- Durability-
  - Casters and drive wheel tires **wearing** out to quickly
  - Caster bolts, nuts loosen up, axle problems, fork problems
  - Bearings wear out and/or freeze-up
  - Problems with **suspension systems**
- Maintenance and Adjustment-
  - **Foreign matter** (i.e. hair, thread, dirt, etc.) gets caught in casters
  - Making **adjustments to** casters and power drive wheels
  - **Air loss/flats** on pneumatic (air up) casters and power drive tires
- Physical security/safety-
  - Caster or power drive wheel **tire roll-off** (i.e. tire rolls off the caster)
  - Caster **fails suddenly** and /or material cracks, breaks, peels apart or
  - Build **static electricity** and getting shocked, knock out electronics, EMI
- Comfort Acceptance/ Aesthetics-
  - How important is caster/drive wheel **style and color, look, weight**
- Procurement
  - Problems with **reimbursement** for caster/drive wheels
  - Problems with service calls and maintenance--Cost of labor, who pays
  - Medicare part reimbursement allowance vs what customer wants and is willing to pay out of pocket for
- **How important is the need for innovation in casters/drive wheels**

Part III-Discuss IDEAL caster/ power drive wheel (30 minutes)

How should an IDEAL caster/ PDW perform-

- Reliability, Operability-
  - **Overall ride**-how does it ride over rough outdoor surfaces,
  - How is caster /PDW **tire roll off prevented**
  - how are casters prevented from getting **caught** in places like elevator doors and drain grates, edges of sidewalks, etc

  - **Shock absorption** and **rolling resistance**-does it act like a shock absorber, if so, how much flexibility is offered and how flexible is the caster/ PDW
  - Stability-how does the caster/power drive wheel **ride over rough** or bumpy surfaces, soft surfaces, obstacles
  - Alignment, **vibration** or shimmy-does the caster ever shimmy or get out of alignment
  - Parts-does it have multiple parts or is it a **one-piece system**
- Durability-
  - Wear-**how long does the caster** / power drive wheel tire last
- Maintenance and Adjustment-
  - **Air maintenance**/ flat prevention-does it ever lose air (power drive)
  - **Adjustment**-what adjustment should be made to improve the ride, alignment, etc and who will make them (user, caregiver, vendor, therapist, etc)
- Physical security/safety-
  - **Sudden failure**-what keeps caster/ power drive wheel from failing, cracking, breaking, peeling, shredding
  - How does it handle static electricity buildup and EMI
- Comfort, Acceptance-
  - **Aesthetics/Style**-what about colors and effects, materials are desired
- Need for **innovation**
  - **How important is the need for innovation in this area**
  - (T/V) What increases your clinical/ business success
  - (T/V) What influences you buying decision most (user request, outcome study, technical reports, etc.

Part IV-Tweel demonstration and evaluation (30 minutes)
Demonstrate Tweel features—CBS news report, PPT slides, show prototype, wheelchair with Tweel mounted. Discuss ***improvements*** that should be made to the Tweel to make it match the ideal caster/power drive wheel-

- Reliability, Operability-
  - Rough terrain /obstacle performance
  - Enhanced shock absorption/ flex/ Vibration dampening
  - Increased stability on surfaces that are not level
  - Self-alignment
  - One piece system
  - Weight advantage over other casters/power drive wheels
- Durability-
  - Increased wear life
- Maintenance and Adjustment-
  - Elimination of air maintenance (power drive wheel)
  - Non-marking rubber tread
- Physical security/ safety-

    - No sudden failure
- Comfort, Acceptance-
    - Multiple colors, no effects
    - Pneumatic-like performance from non-pneumatic caster/drive wheel
    - Eliminates the need for suspension system
- Procurement-how to obtain
    - Would this take a Specific request or would you use generic need

Complete Dot Voting Exercise using the above features.

- Need for **innovation**
    - **What demand for this type of innovation in casters/pdw exists**
    - (T/V) What **medical need** do you think an improved Tweel might fill
    - (T/V) What other casters/ drive wheel alternatives may fill this need
- Name **recognition**
    - How many of you have heard of **Michelin**
    - How many of you consider the Michelin brand to be **high quality**
    - How would the Michelin brand **influence** you when selecting/testing casters and power drive wheels

Part V-Wrap up

- Pass out cash, have participants sign Cash Disbursement Form
- Thank participants, Download recorded data to laptop, Breakdown equipment

Online Power Wheelchair User Survey

What is the make (manufacturer) and model of your current wheelchair?

Make: _____
Model:_____

What casters are on your power wheelchair?

☐ 4 x 2 Casters (☐--Air up—OR—Hard Roll--☐)
☐ 5 x 2 Casters (☐--Air up—OR—Hard Roll--☐)
☐ 6 x 1 ¼ Casters (☐--Air up—OR—Hard Roll--☐)
☐ 6 x 2 Casters (☐--Air up—OR—Hard Roll--☐)
☐ 8 x 1 ¾ Casters (☐--Air up—OR—Hard Roll--☐)
☐ 8 x 2 Casters (☐--Air up—OR—Hard Roll--☐)
☐ 8 x 2 ¼ Casters (☐--Air up—OR—Hard Roll--☐)
☐ 9 x 2 Casters (☐--Air up—OR—Hard Roll--☐)

What power drive wheels are on you power wheelchair?

☐ 10 x 3
☐ 10 ½ x 3 ½
☐ 12 ½ x 2 ¼
☐ 14 x 3

What types of caster and/or power drive wheel related problems have you experienced (Check all that apply)?

☐ Frequent air loss and/or flats on pneumatic (air up) tires
☐ Tires wear out
☐ Tire roll-off (i.e. tire rolls off the caster or tire rolls off the drive wheel)
☐ Caster shimmy (i.e. the casters or drive wheels wiggle when you roll)
☐ Caster material cracks, breaks, peels apart or shreds
☐ Casters or drive wheels leave marks on carpet or other types of flooring
☐ Foreign matter (i.e. hair, thread, dirt, etc.) gets caught in casters
☐ Casters or power drive wheels buildup static electricity and I get shocked
☐ Casters and power drive wheels are difficult to adjust
☐ Casters and power drive wheels weigh too much
☐ Casters and power drive wheels are expensive to repair/replace
☐ Caster bolts and nuts loosen up
☐ Bearings wear out and/or freeze-up
☐ Fork or caster breaks

5. Number the following surfaces according to the difficulty you experience when pushing/rolling over them

1 is most difficult, 9 is the easiest.

_____ Carpet or rugs
_____ Hardwood or vinyl flooring
_____ Rubber Flooring or rubber mats

_____ Grass
_____ Gravel or loose dirt
_____ Wet surfaces
_____ Concrete sidewalk
_____ Icy surfaces
_____ Asphalt

Which surface causes the most damage to your casters or drive wheels?

☐ Carpet or rugs
☐ Gravel or loose dirt
☐ Rubber flooring or rubber mats
☐ Grass
☐ Hardwood or vinyl flooring
☐ Wet surfaces
☐ Concrete sidewalk
☐ Icy surfaces
☐ Asphalt

How often are the casters on your wheelchair replaced?

☐ Every 6 months
☐ Every 9 months
☐ Every year
☐ Every year and a half
☐ Every two years
☐ Every two and a half years
☐ Every three years

How often are the drive wheels on your <u>power</u> wheelchair replaced?

☐ Every 6 months
☐ Every 9 months
☐ Every year
☐ Every year and a half
☐ Every two years
☐ Every two and a half years
☐ Every three years

Who participated in the selection of the casters and drive wheels for your power wheelchair?

☐ Myself
☐ Therapist
☐ Vendor
☐ Nurse

What factors were used for the selection of the casters and drive wheels?

☐ For function
☐ Special needs
☐ Cost
☐ None

How are replacement casters on your wheelchair paid for?

☐ Private Insurance
☐ Medicare
☐ Out-of-pocket/ personal funds
☐ State Medicaid

How much do you spend out-of-pocket (using personal funds) on casters?

Dollar Amount _____ Time Frame _____

What caster colors do you prefer? *1 is most desirable, 7 is the least.*

Black ____
Blue _____
Green _____
Orange _____
Grey _____
Red _____
Yellow _____
Clear _____
Lighted _____

What front suspension system do you have on your current wheelchair?

☐ Frog Legs
☐ Frog Legs Uni-Tine Forks
☐ Bull Frogs
☐ None

What is your gender?

☐ **Male**
☐ **Female**

What is your ethnicity?

☐ Asian, Asian Indian or Pacific Islander
☐ Black or African-American
☐ Hispanic or Latino
☐ Native American or Alaskan Native

☐ White/Caucasian
☐ Other

Where is your home located?

☐ Rural community/in the country
☐ Small to mid-sized town
☐ Suburban neighborhood
☐ Urban neighborhood/inner city

What is your current level of employment? (Check all that apply)

☐ Employed full-time
☐ Employed part-time
☐ Parenting/Homemaker
☐ Full-time student
☐ Part-time student
☐ Unemployed
☐ Unable to work

What is the highest level of education you have completed?

☐ No high school
☐ Some high school
☐ High school diploma or GED
☐ Completed 1-3 years of college (i.e. an associate's or technical degree)
☐ Completed four-year bachelor's degree
☐ Some graduate work
☐ Completed master's
☐ Completed doctorate
☐ Completed professional degree such as MD, JD, RN
☐ Other _____

What is your total average monthly household income?

Less than $600
☐ $600-$1199
☐ $1200-$1999
☐ $2000-$2999
☐ $3000-$4999
☐ $5000 or more

How do you rate your weekly activity level? Are you

☐ **not very active** (unemployed, leave home once per day, move around inside)
☐ **moderately active** (at least a part-time employee or student, leave home more than once per day and move around outside home, access community services outside home)
☐ **active** (full-time employee or student, leave home more than once per day, more around outside the home, access community services)
☐ **very active** (in addition to "active," play a sport like wheelchair basketball or tennis at least once per week)

Additional Comments:

Vibrations and traction analysis of Tweel™ technology tires

Abstract:

The objective of this study was to analyze the difference in ride accelerations and comfort between Tweel™ technology tires and standard solid core tires used in power wheelchairs. Testing included driving an instrumented power wheelchair over several different surfaces and sets of obstacles. Accelerations were used to determine the health effects and perceived comfort level by the user. Additionally, a trained test driver provided subjective evaluation which was used to correlate the instrumented testing to human perception. Traction was tested by traveling along a banked turn till the wheelchair tires lost grip. The Tweel™ technology tires performed similarly to standard wheelchair tires while traversing different surfaces and obstacles. Tweel™ tires provided better traction than standard tires in both wet and dry conditions. With some material and performance improvements, Tweel™ technology should prove to be a superior option to the standard solid foam-core tires supplied with the wheelchairs.

Introduction:

Extensive studies have been conducted in the past that show the benefits of using a pneumatic tire over solid foam core tires especially in manual wheelchairs. Benefits include lower rolling resistance and a more comfortable ride[1-3]. However, pneumatic tires have a shorter lifespan and require maintenance. The Tweel™ technology tested in this study was designed to have properties of a pneumatic tire while maintaining the low maintenance of a solid core tire.

A few studies have been conducted that relate ride comfort to acceleration data [4-6]. In particular simulated road courses have been set up to replicate the surfaces and obstacles that wheelchair users negotiate during everyday mobility. Additionally, standards set by ISO, SAE and other standards bodies specify the limit of vibration exposure of a seated person [7, 8].

The objective of this study was to analyze the difference in ride accelerations and comfort between Tweel™ technology tires and standard solid core tires used in power wheelchairs. Testing included driving an instrumented power wheelchair over several different surfaces and sets of obstacles. In order to validate the results from the instrumented testing, a subjective test was also conducted with the help of Michelin test drivers.

Focus group participants identified tire traction as a major area of concern (focus group results are included in a separate report). To address this concern, traction under dry and wet conditions were measured.

Methods:

All tests were preformed at the Lauren's Proving Grounds, operated by Michelin Americas.

Testing followed the ISO standard (ISO 2631-1) for evaluation of human exposure to whole-body vibration[8] . ISO 2631 is the most accepted standard for vehicle vibration studies and establishes limits for safety, fatigue and comfort. The *exposure limit* is based upon the time of exposure to accelerations and reflects the maximum allowable limit for human safety. Exceeding the exposure limit is never recommended. The *fatigue-decreased*

proficiency boundary reflects the point at which a significant risk of impairing operator ability exists. The fatigue-decreased proficiency boundary is set to ½ of the acceleration levels of the maximum exposure limits. The *reduced comfort boundary* considers occupant comfort. This boundary is set to 1/3 of the acceleration levels of the fatigue-decreased proficiency boundary. ISO2631 specifies the location and orientation for the accelerometer as well as different data analysis methods that could be used.

Accelerometer

A tri-axial accelerometer (PCB 356B08) was mounted underneath the seat of the wheelchair with a magnet (Figure 1). The accelerometer was positioned such that it was approximately underneath the ischial tuberosities of the seated person. The axes of the accelerometer were aligned with the axes of the motion of the wheelchair according to the ISO standard. Z-axis was aligned with the vertical, Y-axis toward the left and the X-axis was aligned with the forward direction of the wheelchair.

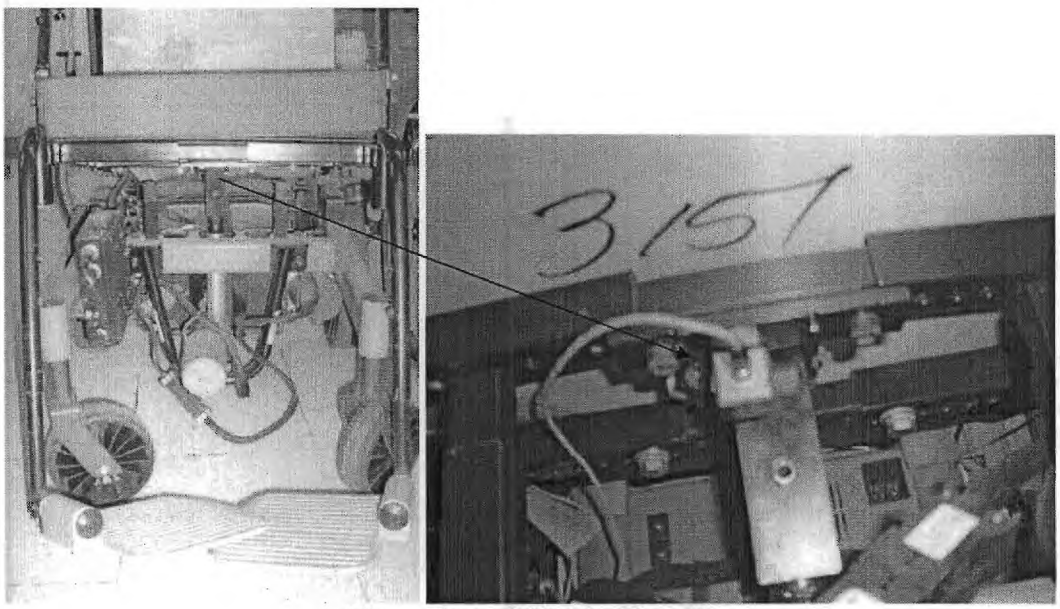


Figure 1: Accelerator mounting

The accelerometer compensated for gravity within its internal electronics, therefore simplifying data analysis. Magnet attachment afforded convenience and was consistent with Michelin procedures. The frequency range effected due to mounting the accelerometer using a magnet (>10000 Hz) was well outside our applicable frequency range. The accelerometer was also light weight, high sensitivity and low drift making it ideal for the application. An OROS (OR2516) DAC system was used in conjunction with the accelerometer and readings were sampled at 1024Hz. Each individual axis was recorded in a separate channel in the DAC system.

Although the zero drift of the accelerometer was noted it was not taken into account in the analysis. Drift is a slow process and the effect can be considered as the DC component of the power spectral density. Since it was a comparison test the DC component would have an approximately equal deviation from zero on all the runs therefore it would not influence the overall result.

Surfaces

Five different surfaces were selected that represent those traversed in everyday use: two types of concrete (rough and smooth), asphalt, grass and gravel. The wheelchair was driven four times over each of the surfaces at two different speeds for a distance of 20m. The tests were then repeated with Tweel™ drive wheels and casters resulting in a total of 80 test runs over the different surfaces.

Surfaces were traversed at 1m/s and 1.5m/s. The speed of the wheelchair was set using a GPS system (Race logic Vbox III) which could measure deviations as low as 1cm and speed to the nearest 0.045 m/s. Due to power limitations the GPS readings were not recorded during the test; however the speed was verified with a stop watch. The run was considered acceptable if the wheelchair traveled the 20m distance within 0.2 seconds of the desired time. These two wheelchair speeds bracket the average walking speed of 1.2 m/s. In everyday mobility, some power wheelchair users will travel at speeds that greatly exceed walking speed but speeds are usually reduced while traversing rough surfaces.

Obstacles

Three different test runs were defined to mimic the types of obstacles that a wheelchair user might experience in daily activities. The first run consisted of a 0.9" flat edge riser in the concrete followed by 3 wooden strips with ¼", ½", and 1" heights followed by another .8" riser. The heights of the wooden strips were selected in accordance to the Americans with Disabilities Act (ADA) [9], which states that any obstacle over ¼" have a tapered edge. The ¼" strip had a flat edge, while the edges of the ½" and 1" strips were tapered by approximately 30 degrees.

The test was repeated on the same track but in the reverse direction resulting in the step-up obstacles (risers) becoming step-down obstacles. For the 3rd test run, the wheelchair was driven over a 35m strip of concrete with several different types of potholes ranging from .5"-2" in depth and 2"-24" in length (Figure 2). All the obstacles in all of the runs were at least 3 feet wide which ensured that all of the wheels traversed over them.

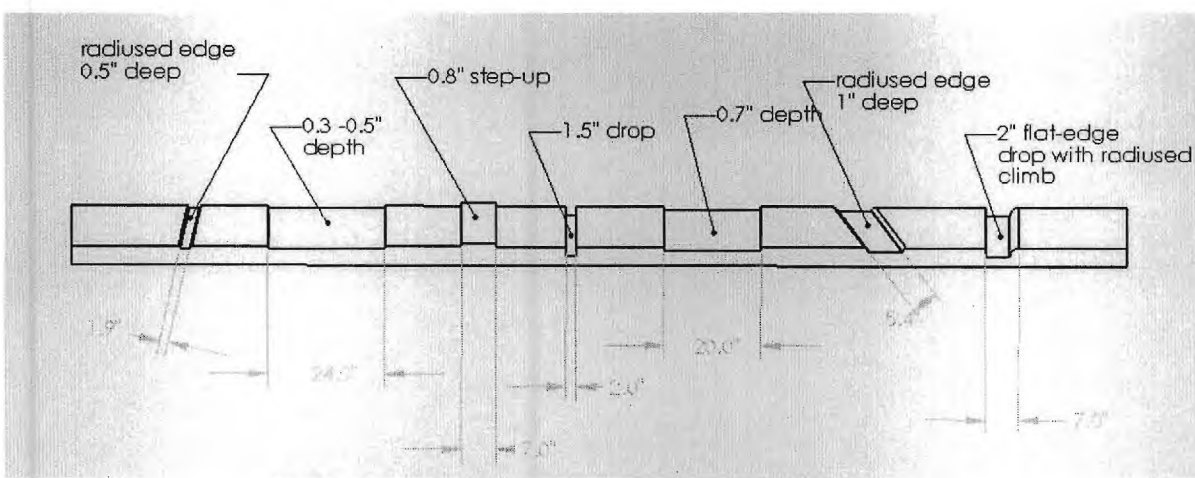


Figure 2: Obstacle course with potholes (3rd set);
Note: The distance between obstacles has been scaled down by a factor of 10.

Testing over obstacles was conducted at the low speed of 1m/s to permit stable control of the wheelchair. Each set of test was repeated 4 times. Similar to the surface tests, a

run was considered valid if the test time, recorded using a stopwatch, was within 0.5s of the calculated time reflecting the length of the test run.

Traction

Traction testing was conducted by traversing along a banked turn whose angle of inclination increased with distance with a maximum incline of 28° (figure 3). The wheelchair was driven along this banked turn until it lost traction and slipped downwards. The test was repeated using both sets of tires. Water was then poured over the surface with a hose and the tests were conducted while a constant stream of water was flowing over the surface. To test tire traction while going up an incline, the wheelchair was driven perpendicular to the banked-turn at specific locations so that the incline angle increased with each trial. The test was repeated until the wheelchair failed to climb the incline under both wet and dry conditions.

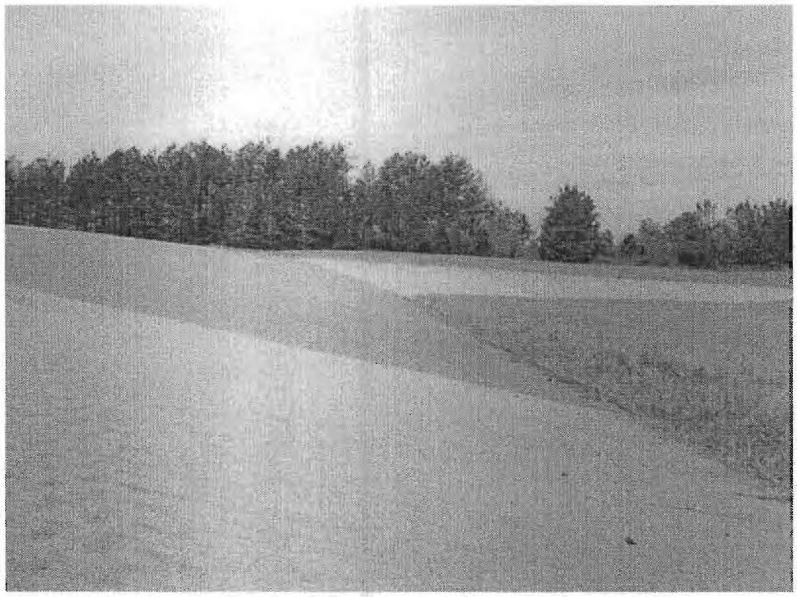


Figure 3: Banked Turn used for traction testing.

Traction Instrumentation:

A six axis inertial measurement unit (IMU; Racelogic IMU 01) containing 3 MEMS G-sensors and 3 MEMS Yaw-rate sensors was used for this testing along with the GPS system used in previous testing. The IMU was attached on the top of the wheelchair battery compartment with Velcro tape. The Battery compartment extends out underneath the chair, therefore the position of the IMU was under the user and approximately on the axis of rotation of the wheelchair (figure 4). The maximum available sampling rate of 100Hz was used.

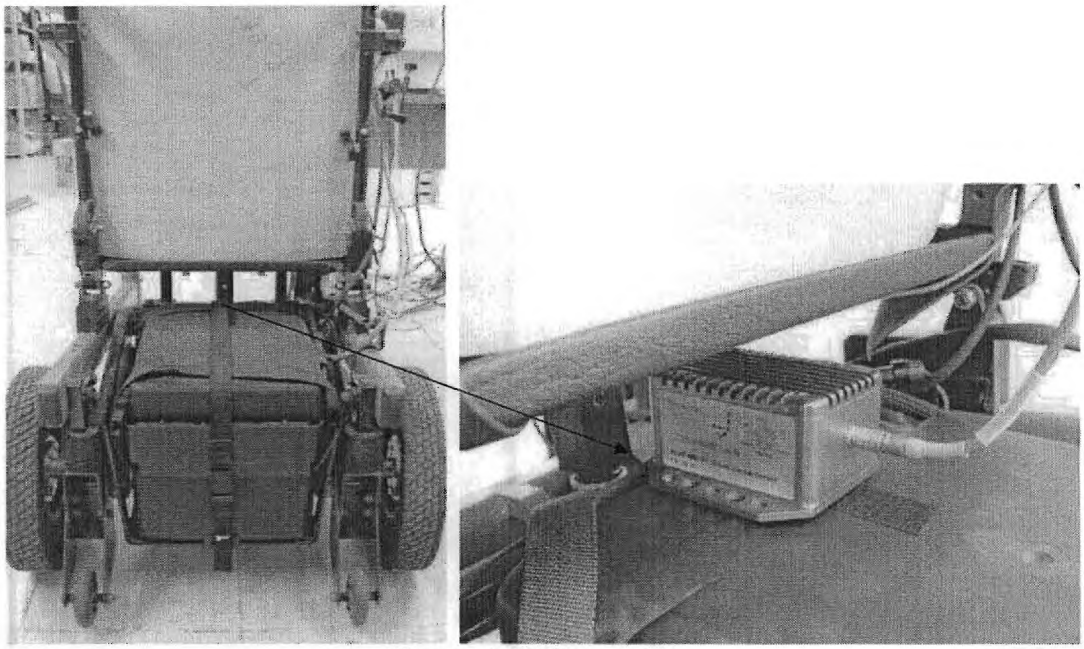


Figure 4: IMU mounting

Data Analysis:

Surfaces and Obstacles

The data was analyzed in accordance with the ISO standard (2631) for evaluation of vibration. A script was written in Matlab which ran the raw data through a combination of 4 filters as prescribed by the ISO standard. First two were Butterworth high pass and low pass filters, combining to form a band-pass filter (Equations 1 &2).

$$|H_h(p)| = \left| \frac{1}{1+\sqrt{2}\omega_1 / p + (\omega_1 / p)^2} \right| \quad (1)$$

$$|H_l(p)| = \left| \frac{1}{1+\sqrt{2}p / \omega_2 + (p / \omega_2)^2} \right| \quad (2)$$

Where

$\omega_1 = 2\pi f_1$

f_1 = Corner frequency (intersection of asymptotes) = 0.4 Hz

$\omega_2 = 2\pi f_2$

f_2 = Corner frequency = 100 Hz

Two additional filters were used to weigh the amplitude at different frequencies in accordance to the effect they have on the human body in the vertical direction. Only one additional filter was used for the weighing the vibrations in the horizontal plane.

These filters accounted for the acceleration-velocity transition (Eq.3) and upward step (Eq.4). The first filter can be associated as being proportional to acceleration at lower frequencies and velocity at higher frequencies. The second filter takes into account the

steepness of the slope; proportionality to jerk. The upward step filter was only used for data in the vertical (Z) direction.

$$|H_t(p)| = \left| \frac{1 + p/\omega_3}{1 + p/Q_4\omega_4 + (p/\omega_4)^2} \right| \qquad (3)$$

Where

$\omega_3 = 2\pi f_3$
$\omega_4 = 2\pi f_4$
$Q_4 = 0.63$

$f_3 = f_4 = 12.5$ Hz (For Vertical motion)
$f_3 = f_4 = 2$ Hz (For lateral motions)

$$|H_s(p)| = \left| \frac{1 + p/Q_5\omega_5 + (p/\omega_5)^2}{1 + p/Q_6\omega_6 + (p/\omega_6)^2} \cdot \left(\frac{\omega_5}{\omega_6} \right)^2 \right| \qquad (4)$$

Where

$Q_5 = Q_6 = 0.91$
$f_5 = 2.37$ Hz
$f_6 = 3.35$ Hz

After the raw data was processed through the filters it was converted to the frequency domain using a Fast Fourier Transform (FFT). The power spectral density of individual 1/3 octaves was calculated by integrating the area under the curve. The center value of the 1/3 octaves were calculated recursively using equation 5 as prescribed by the ISO standard.

$$f_2 = \left(2^{\frac{1}{3}} \right) \times f_1 \qquad (5)$$

$f_1 = 1$ Hz for first value

The cumulative power spectral density (PSD) for each of the axis was calculated using Eq.6. The last center frequency for the 1/3 octave was set at 80Hz as prescribed by the ISO standard. This cutoff frequency is completely covers the frequency typically experienced in vehicular dynamics (approximately 50HZ)[5, 10].

$$a_w = \left[\sum_i (a_{wi})^2 \right]^{\frac{1}{2}} \qquad (6)$$

a_w is the frequency-weighted acceleration
a_{wi} is the weighted r.m.s acceleration for the ith one-third octave band.

Acceleration root mean square (RMS) from the individual orthogonal axes were added according to Equation 7, resulting in the total value of weighted RMS acceleration.

$$a_v = \left(k_x^{\,2} a^2_{wx} + k_y^{\,2} a^2_{wy} + k_z^{\,2} a^2_{wz}\right)^{\frac{1}{2}} \quad (7)$$

Two different values for k_x and k_y were used, one for comfort and the other for health effects. The value for k_z was set constant at 1.

$k_x = k_y = 1.4$ (For effects on health)
$k_x = k_y = 1$ (For perceived comfort)

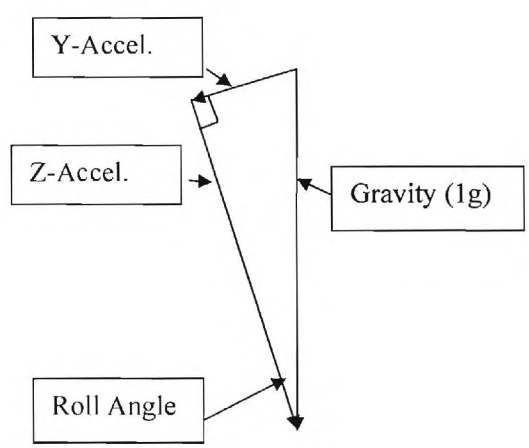
The results from the combined PSD values were used to determine if the tires differed with respect to rider comfort or health effects. For surface data analysis, a three-way ANOVA was used to tests the effects of tire type, speed and surface. For the obstacle analysis, a two-way ANOVA was used to test the effects of tire type and obstacle. Post-hoc pairwise comparisons were made using Tukey's test. P values for all tests are reported with results being discussed for values of $p<0.1$.

Traction

The objective of the traction testing was to compare the level of grip between the two tires under dry and wet conditions. This was achieved by determining the angle of inclination at which the wheelchair started slipping while traversing along a banked turn. The Y (sideways) and Z (vertical) axes acceleration were used to determine the angle of incline for the wheelchair (Eq.8) and a check factor was used to determine the accuracy of the result (Eq.9).

$$\theta = ATan\left(\frac{a_y}{a_z}\right) \quad (8)$$

$$\sqrt{a_y^{\,\wedge 2} + a_z^{\,\wedge 2}} = 1.0g \quad (9)$$



Yaw rate values were used to identify the point of slippage- the point at which traction was lost. Loss of traction had to be distinguished from yaw tendency produced by the downward turning tendency of the wheelchair. Loss of traction was defined using a yaw rate threshold of 10°/s. This threshold was defined by analyzing yaw values during stable motion.

Stable motion was defined by analyzing yaw-rate values over the time span between 10-20 seconds. This timeframe was determined via investigator experience, review of video tapes, and yaw acceleration profiles. Across all eight data collection trials, the average yaw-rate over this timeframe was approximately 0°/s (0.01) with an average standard deviation of 3.3°/s. A threshold at 10°/s represents a value that is approximately 3 standard deviations above the mean so avoids transient spikes in the yaw rate caused by wheelchair controller adjustments or slight changes in direction from the downward turning tendency.

The angle at which traction was lost was calculated using the Y and Z accelerations. This required the use of stable yaw rate values. A stable yaw rate- defined as a yaw acceleration <5°/sec for ≥ 2 secs- was used to define the point in time immediately before slippage occurred. Y& Z accelerations in the middle of this time frame (100 points) were used to calculate the side slope angle. Plots of yaw accelerations are shown in Figures 5 & 6 for the Tweel technology and standard tires, respectively. A complete set of acceleration graphs are included in Appendix D.

To corroborate the angle calculation, the mean and standard deviation of the check factor was calculated (Eq. 9; the Y and Z accelerations used for this calculation had units of g). Acceleration values in the middle of the region defined as stable movement (100 data points) were used to check if they added up to '1.00 g'. The result was considered valid if the mean check value was 1.00 g ± 0.02 g and the standard deviation was less than 0.05 (5% coefficient of variation). If an unstable region was picked- defined as a not meeting the above criteria- the defined area would be shifted incrementally until a stable region was found. The trends shown under wet conditions by both sets of tires were similar to their respective trends in dry condition.

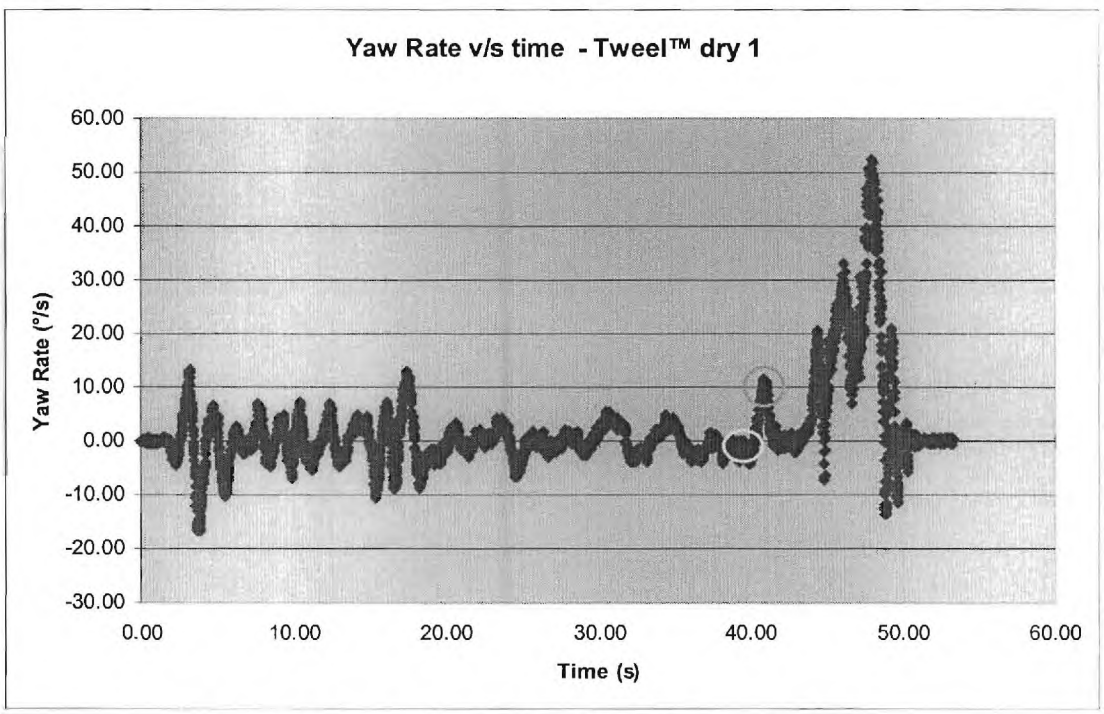


Figure 5: Tweel™ technology tires Yaw rate v/s time

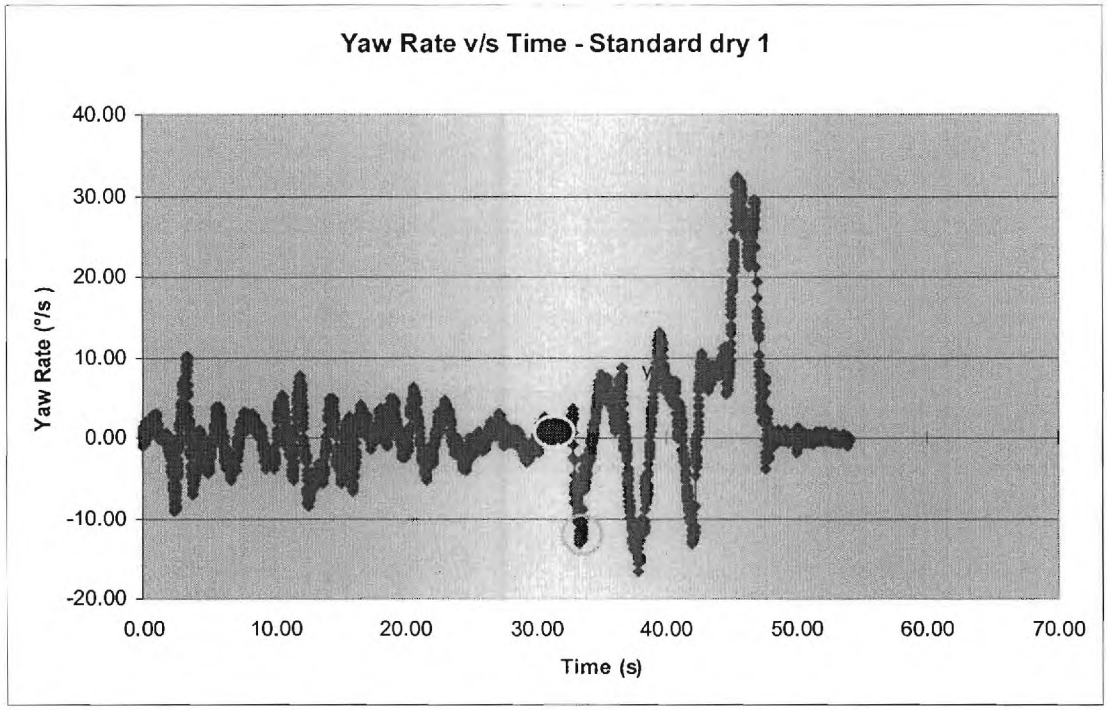


Figure 6: Standard tires Yaw rate v/s time

Results:

Surfaces and Obstacles

The average RMS value for both tires over different surfaces and obstacles with respect to health effects and perceived comfort are included in Table 1 and 2. No significant differences were found across tire type in the surface analysis ($p > 0.7$), suggesting the Tweel™ and standard tires performed in a similar manner. Similar results were seen for the obstacle analysis ($p > 0.105$); no significant difference could be seen in terms of health or comfort. Analysis of the surface type and speed factors produced significant differences for both health and comfort RMS variables. The obstacle analysis produced significant effects for obstacle type ($p = 0.000$) and the interaction between obstacle and tire type was significant ($p = 0.000$) for both health and comfort RMS values. Table 3 contains the results from the ANOVA testing

The complete set of data is included in Appendix A while the ANOVA analyses are posted in Appendix B and C for surfaces and obstacles, respectively.

Table 1: Average RMS Values for Health Effects

	Standard tire		Tweel™	
Surface	**1m/s**	**1.5m/s**	**1m/s**	**1.5m/s**
Asphalt (1)	1.002	1.298	1.199	1.348
Rough Concrete (2)	0.360	0.694	0.447	0.599
Smooth Concrete (3)	0.344	0.739	0.451	0.769
Grass (4)	1.231	1.739	1.110	1.562
Gravel (5)	2.334	3.208	2.404	3.108
Obstacle				
Obstacles run with riser (6)	1.836		1.953	
Obstacles run with step-down (7)	1.890		1.940	
Obstacle run with potholes (8)	2.259		2.153	

Table 2: Average RMS Values for Perceived Comfort

	Standard tire		Tweel™	
Surface	**1m/s**	**1.5m/s**	**1m/s**	**1.5m/s**
Asphalt (1)	0.978	1.256	1.170	1.296
Rough Concrete (2)	0.327	0.617	0.409	0.539
Smooth Concrete (3)	0.307	0.646	0.400	0.668
Grass (4)	1.160	1.649	1.032	1.492
Gravel (5)	2.287	3.162	2.355	3.061
Obstacles				
Obstacles run with riser (6)	1.786		1.902	
Obstacles run with step-down (7)	1.822		1.874	
Obstacle run with potholes (8)	2.167		2.080	

Table 3: Results of surface and obstacle ANOVA analysis (p values)

3-way ANOVA for *surface* data	Health	Comfort
Tire type	.876	.916
Surface	.000	.000
Speed	.000	.000
Surface*tire type	.104	.154
Speed * tire type	.056	.081
2-way ANOVA for *obstacle* data		
Tire type	.217	.105
Obstacle	.000	.000
Obstacle*tire type	.000	.000

Tukey's pairwise comparisons were used to identify differences in surface and obstacle accelerations. Differences occurred between all surfaces except for rough and smooth concrete (Table 4). Traversing obstacles in the step-up or step-down directions did not produce different accelerations but these obstacles were different than the accelerations produced by potholes (Table 5). These statistical results were the same for both and health and comfort RMS values. Overall, accelerations measured on gravel were the highest and

those on concrete were the lowest. Obstacle accelerations were higher than those measured on all surfaces except for gravel.

Table 4: p-values relating difference in RMS of different Surfaces (Health & Comfort)

Surfaces	1	2	3	4	5
Asphalt (1)	--	0.00	0.00	<0.03	0.00
Rough Concrete(2)		--	N.S.	0.0000	0.0000
Smooth Concrete (3)			--	0.0000	0.0000
Grass (4)				--	0.0000
Gravel (5)					--

Table 5: p-values relating difference in RMS of different Obstacles (Health & Comfort)

Obstacles	6	7	8
Run with risers (6)	--	N.S.	0.0000
Run with step-downs (7)		--	0.0000
Potholes (8)			--

The interaction between obstacles and tire type was significant for both Health and Comfort RMS values. Tukey's pairwise comparison reported significant differences between the Health RMS values for tire type within the riser obstacles and potholes (Table 6). Within the riser obstacles, the Tweel™ technology tires elicited higher accelerations but within the potholes, Tweel™ technology tires produced lower accelerations (Table 6).

Table 6: Tukey pairwise comparison of Obstacles and Tires

Health RMS values				Comfort RMS values		
Standard tires	Tweel technology	Sig p value		Standard tires	Tweel technology	Sig p value
1.835	1.953	.0056	**Riser obstacles**	1.785	1.902	.054
1.890	1.940	N.S	**Step-down obstacles**	1.821	1.873	N.S.
2.259	2.153	.014	**Potholes**	2.167	2.080	.052

Figures 7 and 8 characterize the daily occupational vibration exposure caution zone as set by the ISO standard (2631). In this zone, care must be taken to avoid potential health risks and above the zone health risks are likely. This recommendation is mainly based on exposures for a 4 to 8 hours period (240-400 minutes; shown by the pink boundary in the figures), and shorter durations need to be analyzed cautiously. While tables 7 and 8 characterize the caution time periods as prescribed by the ISO standard for the respective RMS values obtained from the tests. As it can be seen from those figures and tables that almost all the values are in or above the caution zone set by the ISO standard for a 4-8 hour period except for low speed on concrete for both sets of tires. In both cases the values for concrete at high speed are within the ISO caution zone, while asphalt is within the caution zone for standard tires at low speed for a 4-8 hour period. All other values are above the limit set by the ISO standard for a 4 hour period (RMS = $1.15 m/s^2$), suggesting that prolonged exposure to these levels of exposure could have detrimental health affects on the user.

Multiple sets of vibration can be added according to Equation 10. This equation calculates the energy-equivalent vibration magnitude corresponding to the total duration of exposure.

$$a_{w,e} = \left[\frac{\sum a^2_{wi} \cdot T_i}{\sum T_i} \right]^{\frac{1}{2}} \qquad (10)$$

Where

$a_{w,e}$ is the equivalent vibration magnitude (r.m.s. acceleration in m/s^2);
a_{wi} is the vibration magnitude (r.m.s. acceleration in m/s^2) for exposure duration T_i

Considering wheelchair users traverse over surfaces like asphalt and rough concrete for the majority of their outdoor travel while encountering a few obstacles, this could have a significant effect on their health overtime, if they lead active lives. For instance, in traveling outdoors, one assumes a 50-50 split between asphalt and concrete at a speed of 1.5 m/sec and duration of 4 hours, the equivalent vibration magnitude would be $1.04 m/s^2$ for both the Tweel™ and standard tires. This Value is just below the upper limit of RMS value ($1.15 m/s^2$) for a 4 hour period.

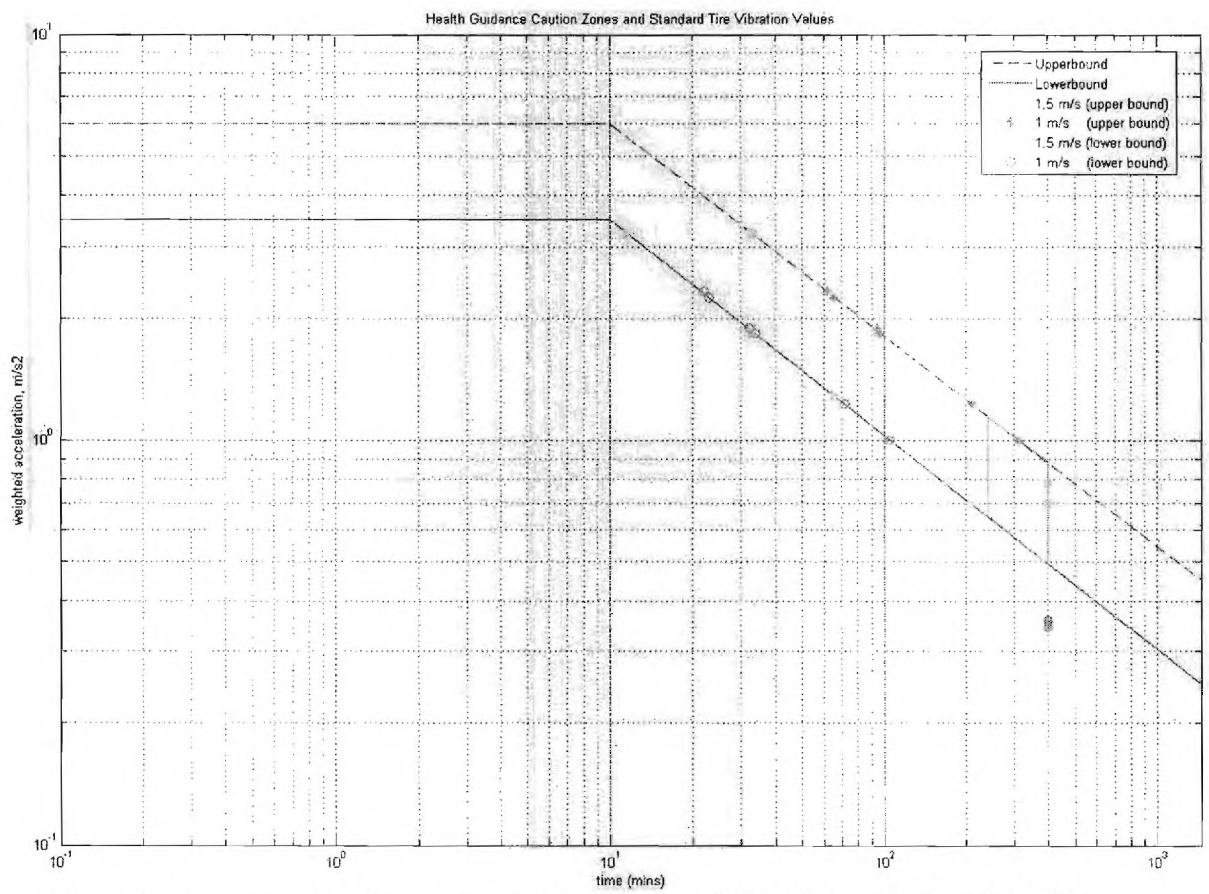


Figure 7: Exposure caution zone as specified by ISO 2631 and Standard Tire Vibrational values

Table 7: Caution zone time boundary for the respective Surfaces and obstacles in minutes for standard tires

Surfaces/Obstacles	Caution Zone time limits for 1m/s (mins)	Caution Zone time limits for 1.5 m/s (mins)
Asphalt	105 – 310	65 – 193
Rough Concrete	> 400	> 210
Smooth Concrete	> 400	> 170
Grass	72 -210	33 – 95
Gravel	22 – 62	11.5 – 33
Obstacles run with riser	34 -97	
Obstacles run with step-down	32 -94	
Obstacle run with potholes	23 -65	

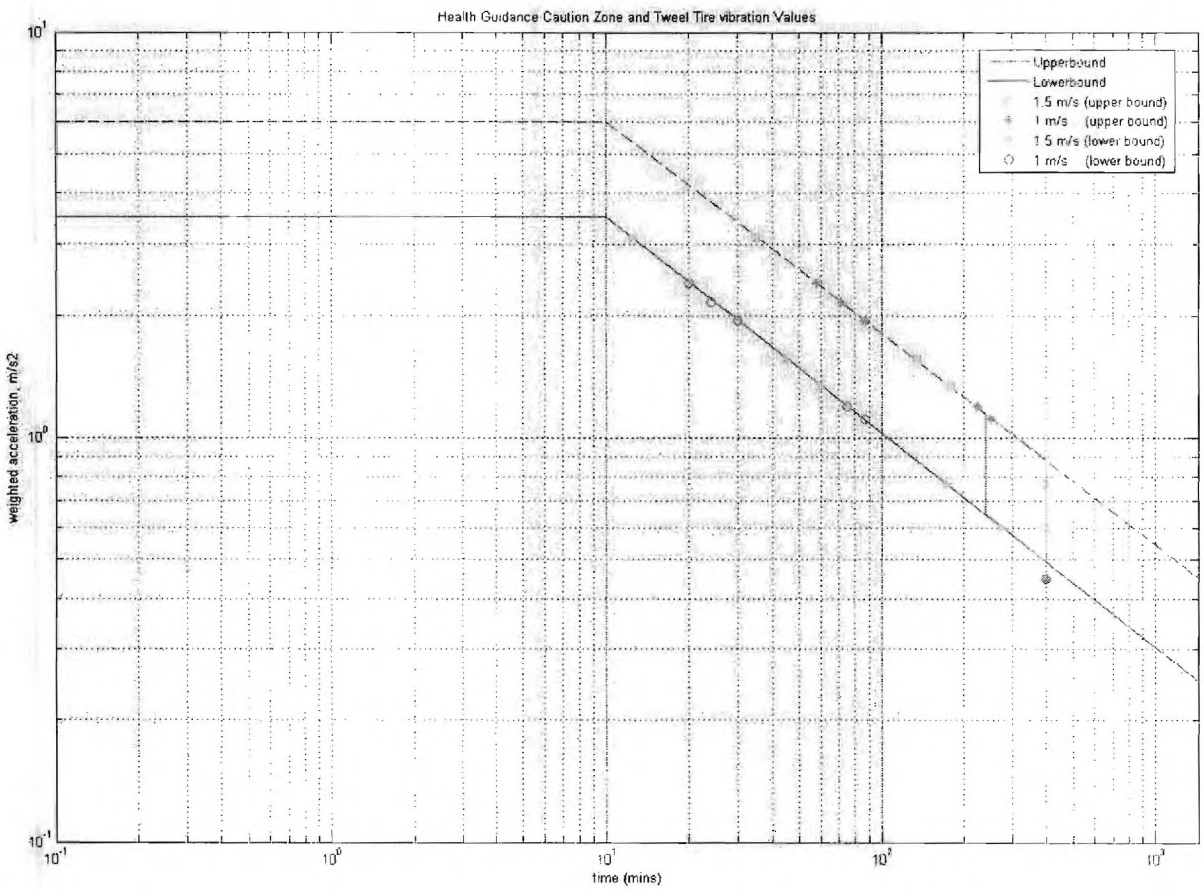


Figure 8: Exposure caution zone as specified by ISO 2631 and Tweel™ Tire Vibrational values

Table 8: Caution zone time boundary for the respective Surfaces and obstacles in minutes for Tweel™ Tire

Surface/Obstacles	Caution Zone time limits for 1 m/s (mins)	Caution Zone time limits for 1.5 m/s (mins)
Asphalt	75 – 225	60 – 180
Rough Concrete	>400	>274
Smooth Concrete	>400	>174
Grass	87 -252	45 – 135
Gravel	20 – 58	12.5 - 35
Obstacles run with riser	30 – 87	
Obstacles run with step-down	30 – 87	
Obstacle run with potholes	24 - 71	

The comfort level range prescribed by the ISO 2631 standard for public transportation is given in Table 9. The location of measurement prescribed for these values is similar to the one used in this study; vibration transmitted to the body is measured on the surface between the body and that surface. However this range may involve higher expectation in terms of other activities that a user might expect to achieve while traveling (e.g. reading, eating, writing, etc.).

The RMS values experienced by the wheelchair user are significantly high crossing the "Extremely Uncomfortable" boundary for Gravel and "Very Uncomfortable" range for Obstacles. Furthermore even in the best case scenarios it is still in the "A little uncomfortable" range. However these RMS values do not take into account the damping provided by the cushion, which is, one of the primary sources of damping in a wheelchair. Additionally the cushion used in wheelchairs is better than cushion used in most modes of public transportation; therefore the actual RMS values would be lower for both sets of tires.

Table 9: Perception of Comfort as experienced in Public Transport

Comfort level	R.M.S. Values	Surfaces/Obstacles
Not Uncomfortable	Less than 0.315m/s^2	
A little Uncomfortable	0.315 m/s^2 to 0.63 m/s^2	Concrete (low speed)
Fairly Uncomfortable	0.5 m/s^2 to 1 m/s^2	Concrete (High speed)
Uncomfortable	0.8 m/s^2 to 1.6 m/s^2	Asphalt, Grass(low speed)
Very Uncomfortable	1.25 m/s^2 to 2.5 m/s^2	Grass (high speed), All Obstacles
Extremely Uncomfortable	2 m/s^2	Gravel (high speed)

Subjective Testing

To get a subjective view on the difference between the two tires a trained driver rode the wheelchair over different surfaces to evaluate comfort differences. Although the driver did not prefer one set of tires over the other, he noted a few differences in vibration transmitted through the two sets of tires. He noted that he could feel the small changes in road surface more effectively while driving on Tweel™ tires; however the Tweel™ tires dampened the shocks from larger bumps more effectively than the standard tires.

Traction

As observed during testing the Tweel™ technology tires performed better than the standard foam core tires especially in wet conditions. The angles of inclination at which the wheelchairs slipped are shown in table 10 verify those results.

Table 10: Angle of inclination at slippage during traction testing

	Standard tire			Tweel™ technology tires		
	1st run (°)	2nd run (°)	Mean (°)	1st run (°)	2nd run (°)	Mean (°)
Dry	15.7	14.3	15	15.7	15.4	15.55
Wet	14.3	14.4	14.35	15.8	16.6	16.2

As observed while testing the two tires showed different patterns of traction loss. The standard tires experienced constant sideways slippage after a point as it traversed along the turn before it completely lost grip and slid downwards. This can be verified from figure 9 which shows that there is no dramatic change in angle and the trendline (moving average) has a few bumps signifying slight slippage with time before failing completely. While on the other hand the Tweel™ technology tires maintained a much better grip on the surface before suddenly loosing grip. This phenomenon can be clearly seen from figure 10 which shows the angle v/s time change drastically around 45s when the tires fail. The huge fluctuation in angle is due to the fact that Y-axis acceleration was used to calculate angle, which increases dramatically due to the effects of slippage.

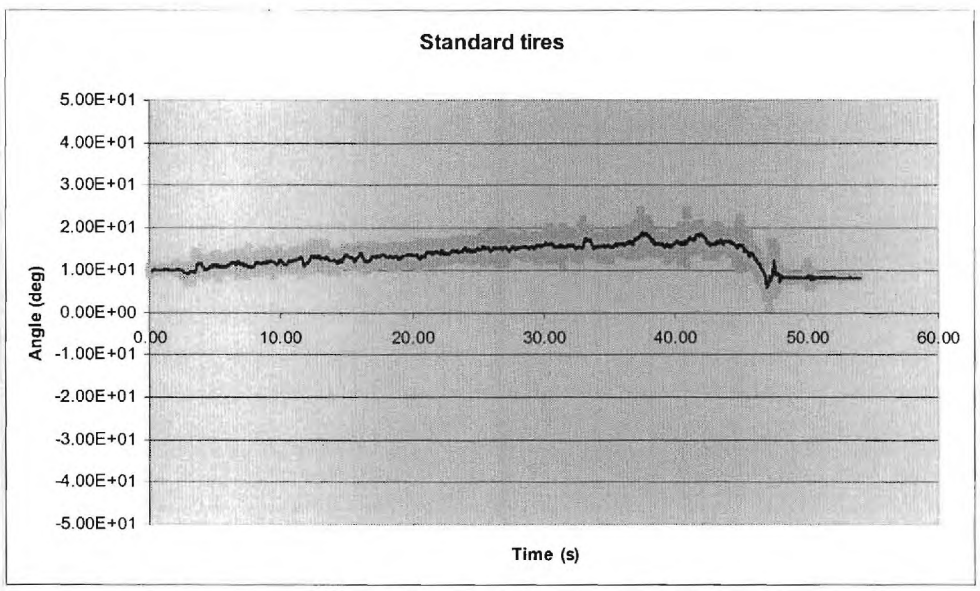


Figure 9: Angle of inclination v/s time

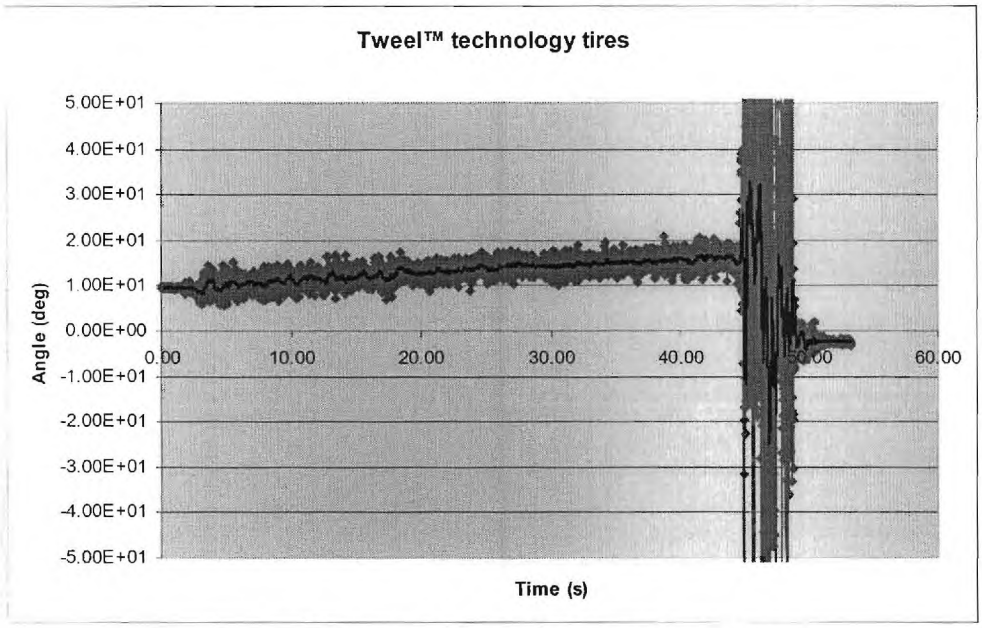


Figure 10: Angle of inclination v/s time

One unusual discovery was that the Tweel™ technology tires performed better in the wet than dry over the two trials. However this could not be statistically verified with more tests as water had already been poured over the surface and due to time constraints more dry runs could not be performed.

Alternatively, tests for climbing an incline plane under wet and dry conditions did not show any significant difference between the two tires. The tests were conducted until the wheelchair operator no longer felt safe driving up the incline. The angle of inclination was approximately 19° at that point and the wheelchair had started tipping backwards, prompting the operator to stop the test. Both sets of tires successfully completed the tests till that point. The contact patch (figure 11, 12) of the tires on the ground might explain the differences in the grip of the tires and the differences in results between the two tests.

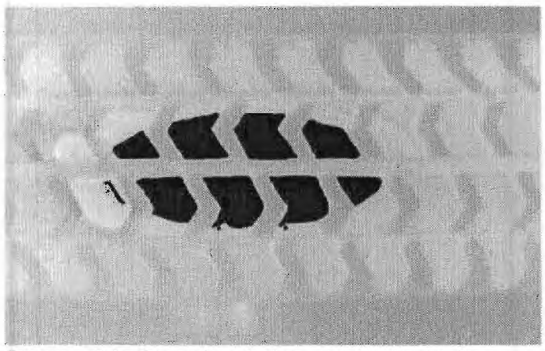


Figure 11: Standard tire contact patch

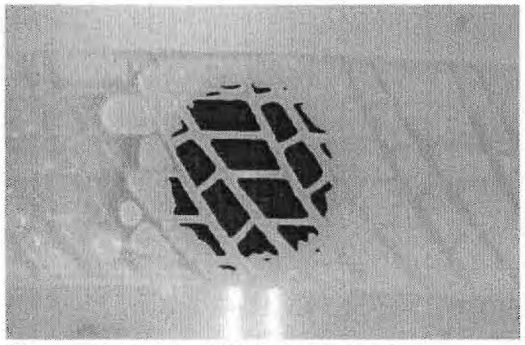


Figure 12: Tweel™ Drive wheel

It can be seen from figure 11 that the standard tire has and long oval contact patch to the ground similar to a bicycle wheel. On the other hand the Tweel™ drive wheel has a more round and horizontally wider patch to the ground (fig. 12) similar to a car wheel. This might be the reason why the Tweel™ tires have better sideways traction as they have a wider

contact area in that direction. The contact surface area for the Tweel™ is also slightly higher at 7.2-cm^2 as compared to 6.8-cm^2 for the standard tire providing the Tweel™ tires with a better grip.

Conclusion:

The Tweel™ is a promising technology; however work needs to be done to improve the design and material properties. Although there were differences in the average RMS values for different surfaces the Tweel™ tires failed to produce any significant difference. A combination of asphalt and rough concrete would result in approximately the same levels of vibrations for both sets of tires. Furthermore while Tweel™ tires performed better than standard tires while traversing potholes, they performed worse over riser type obstacles.

If the Tweel™ technology tires can be re-engineered to have better dampening properties, leading to lower vibrational levels on different surfaces it could prove to be a more viable option. Furthermore that coupled with the fact that the Tweel™ technology tires proved to be a significantly better option for wet and dry traction the Tweel™ tires could become the next industry standard.

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Appendix A: RMS Values for Health Effects and Perceived Comfort

Health Effect RMS Values at 1m/s

		Standard Tires			
Asphalt	(1)	1.0097	0.9647	1.0195	1.0117
Rough Concrete	(2)	0.4061	0.3406	0.3615	0.3263
Smooth Concrete	(3)	0.3379	0.3334	0.3573	0.3451
Grass	(4)	1.2466	1.1808	1.2759	1.219
Gravel	(5)	2.2482	2.4753	2.1819	2.4178
Obstacles run with riser	(6)	1.838	1.8782	1.7656	1.8592
Obstacles run with step-down	(7)	1.8583	1.9144	1.886	1.902
Obstacle run with potholes	(8)	2.2608	2.2332	2.2574	2.2828
		Tweel™s			
Asphalt	(1)	1.2428	1.181	1.2152	1.1536
Rough Concrete	(2)	0.4465	0.4327	0.4867	0.4205
Smooth Concrete	(3)	0.4366	0.4443	0.4669	0.4556
Grass	(4)	1.0475	1.1041	1.2087	1.073
Gravel	(5)	2.3144	2.4219	2.5545	2.3182
Obstacles run with riser	(6)	1.9439	1.9639	1.9242	1.9795
Obstacles run with step-down	(7)	1.8712	1.8966	1.9872	2.0028
Obstacle run with potholes	(8)	2.189	2.1328	2.1691	2.1219

Health Effects RMS Values at 1.5m/s

		Standard Tires			
Asphalt	(1)	1.3717	1.2434	1.3736	1.1931
Rough Concrete	(2)	0.7944	0.5334	0.8049	0.6005
Smooth Concrete	(3)	0.6658	0.806	0.7769	0.6965
Grass	(4)	1.7873	1.6775	1.7884	1.699
Gravel	(5)	3.1825	3.3966	3.0391	3.2054
		Tweel™s			
Asphalt	(1)	1.3848	1.3237	1.2952	1.3848
Rough Concrete	(2)	0.6175	0.5961	0.6667	0.5022
Smooth Concrete	(3)	0.7893	0.7291	0.8884	0.6483
Grass	(4)	1.5558	1.5514	1.5343	1.6065
Gravel	(5)	3.2979	3.2952	2.7343	3.0722

Perceived Comfort RMS Values at 1m/s

		Standard Tires			
Asphalt	(1)	0.9831	0.9445	0.9931	0.9888
Rough Concrete	(2)	0.3674	0.3102	0.3272	0.2976
Smooth Concrete	(3)	0.3034	0.2958	0.3196	0.3074
Grass	(4)	1.1549	1.1207	1.2074	1.154
Gravel	(5)	2.2001	2.4203	2.1451	2.3694
Obstacles run with riser	(6)	1.7902	1.8181	1.7238	1.8084
Obstacles run with step-down	(7)	1.7915	1.8439	1.8105	1.8398
Obstacle run with potholes	(8)	2.1753	2.1471	2.1634	2.1802
		Tweel™s			
Asphalt	(1)	1.2179	1.1549	1.1829	1.1213
Rough Concrete	(2)	0.4062	0.3973	0.441	0.3883
Smooth Concrete	(3)	0.3887	0.3962	0.411	0.4056
Grass	(4)	0.9749	1.0334	1.1137	1.0021
Gravel	(5)	2.2683	2.3752	2.507	2.2607
Obstacles run with riser	(6)	1.8966	1.9098	1.8669	1.9339
Obstacles run with step-down	(7)	1.7976	1.8255	1.9338	1.9338
Obstacle run with potholes	(8)	2.1057	2.0635	2.0913	2.0583

Perceived Comfort RMS Values at 1.5m/s

		Standard Tires			
Asphalt	(1)	1.313	1.2109	1.3266	1.1645
Rough Concrete	(2)	0.7005	0.4819	0.7077	0.5457
Smooth Concrete	(3)	0.5888	0.6997	0.6766	0.6118
Grass	(4)	1.6875	1.595	1.6976	1.615
Gravel	(5)	3.1269	3.3453	3.0019	3.1634
		Tweel™s			
Asphalt	(1)	1.3372	1.2714	1.2468	1.3252
Rough Concrete	(2)	0.5537	0.5392	0.5902	0.4668
Smooth Concrete	(3)	0.6849	0.6342	0.7672	0.5713
Grass	(4)	1.4901	1.4857	1.4638	1.5263
Gravel	(5)	3.2494	3.242	2.6902	3.0276

Appendix B: ANOVA Analysis for surfaces

Descriptive Statistics: Health

Results for Wheel = 1

Variable	Surface	Mean	StDev	Minimum	Median	Maximum
Health	1	1.1484	0.1690	0.9647	1.1063	1.3736
	2	0.5210	0.1967	0.3263	0.4698	0.8049
	3	0.5399	0.2145	0.3334	0.5116	0.8060
	4	1.4843	0.2752	1.1808	1.4767	1.7884
	5	2.768	0.486	2.182	2.757	3.397

Results for Wheel = 2

Variable	Surface	Mean	StDev	Minimum	Median	Maximum
Health	1	1.2726	0.0887	1.1536	1.2690	1.3848
	2	0.5211	0.0935	0.4205	0.4945	0.6667
	3	0.6073	0.1801	0.4366	0.5576	0.8884
	4	1.3352	0.2477	1.0475	1.3715	1.6065
	5	2.751	0.418	2.314	2.644	3.298

Descriptive Statistics: Comfort

Results for Wheel = 1

Variable	Surface	Mean	StDev	Minimum	Median	Maximum
Comfort	1	1.1156	0.1572	0.9445	1.0788	1.3266
	2	0.4673	0.1697	0.2976	0.4247	0.7077
	3	0.4754	0.1838	0.2958	0.4542	0.6997
	4	1.4040	0.2649	1.1207	1.4012	1.6976
	5	2.722	0.485	2.145	2.711	3.345

Results for Wheel = 2

Variable	Surface	Mean	StDev	Minimum	Median	Maximum
Comfort	1	1.2322	0.0778	1.1213	1.2324	1.3372
	2	0.4728	0.0784	0.3883	0.4539	0.5902
	3	0.5324	0.1513	0.3887	0.4912	0.7672
	4	1.2613	0.2498	0.9749	1.2888	1.5263
	5	2.703	0.418	2.261	2.599	3.249

General Linear Model: Health, Comfort versus Wheel, Speed, Surface

Factor	Type	Levels	Values
Wheel	fixed	2	1, 2
Speed	fixed	2	1, 2
Surface	fixed	5	1, 2, 3, 4, 5

Analysis of Variance for Health, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wheel	1	0.0005	0.0005	0.0005	0.02	0.876
Speed	1	3.4552	3.4552	3.4552	163.37	0.000
Surface	4	52.5622	52.5622	13.1405	621.31	0.000
Wheel*Surface	4	0.1696	0.1696	0.0424	2.00	0.104
Wheel*Speed	1	0.0799	0.0799	0.0799	3.78	0.056
Error	68	1.4382	1.4382	0.0211		
Total	79	57.7055				

S = 0.145430 R-Sq = 97.51% R-Sq(adj) = 97.10%

Unusual Observations for Health

Obs	Health	Fit	SE Fit	Residual	St Resid	
34	3.39660	3.00777	0.05632	0.38883	2.90	R
37	2.24820	2.52893	0.05632	-0.28073	-2.09	R
39	2.18190	2.52893	0.05632	-0.34703	-2.59	R
73	3.29790	2.92730	0.05632	0.37060	2.76	R
74	3.29520	2.92730	0.05632	0.36790	2.74	R

R denotes an observation with a large standardized residual.

Analysis of Variance for Comfort, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wheel	1	0.0002	0.0002	0.0002	0.01	0.916
Speed	1	3.1074	3.1074	3.1074	142.74	0.000
Surface	4	53.0328	53.0328	13.2582	609.00	0.000
Wheel*Surface	4	0.1503	0.1503	0.0376	1.73	0.154
Wheel*Speed	1	0.0681	0.0681	0.0681	3.13	0.081
Error	68	1.4804	1.4804	0.0218		
Total	79	57.8392				

S = 0.147548 R-Sq = 97.44% R-Sq(adj) = 97.03%

Unusual Observations for Comfort

Obs	Comfort	Fit	SE Fit	Residual	St Resid	
34	3.34530	2.94781	0.05715	0.39749	2.92	R
37	2.20010	2.49529	0.05715	-0.29519	-2.17	R
39	2.14510	2.49529	0.05715	-0.35019	-2.57	R
73	3.24940	2.87047	0.05715	0.37893	2.79	R
74	3.24200	2.87047	0.05715	0.37153	2.73	R
80	2.26070	2.53464	0.05715	-0.27394	-2.01	R

R denotes an observation with a large standardized residual.

Tukey Simultaneous Tests
Response Variable Health
All Pairwise Comparisons among Levels of Surface
Surface = 1 subtracted from:

Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.6895	0.05142	-13.41	0.0000
3	-0.6369	0.05142	-12.39	0.0000
4	0.1992	0.05142	3.87	0.0022
5	1.5492	0.05142	30.13	0.0000

Surface = 2 subtracted from:

Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.05255	0.05142	1.022	0.8444
4	0.88870	0.05142	17.284	0.0000
5	2.23868	0.05142	43.539	0.0000

Surface = 3 subtracted from:

Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.8362	0.05142	16.26	0.0000
5	2.1861	0.05142	42.52	0.0000

Surface = 4 subtracted from:

Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	1.350	0.05142	26.26	0.0000

Tukey Simultaneous Tests
Response Variable Health
All Pairwise Comparisons among Levels of Wheel*Speed
Wheel = 1
Speed = 1 subtracted from:

Wheel	Speed	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	2	-0.4788	0.04599	-10.41	0.0000
2	1	-0.0581	0.04599	-1.26	0.5890
2	2	-0.4106	0.04599	-8.93	0.0000

Wheel = 1
Speed = 2 subtracted from:

Wheel	Speed	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	1	0.42072	0.04599	9.148	0.0000
2	2	0.06827	0.04599	1.484	0.4524

Wheel = 2
Speed = 1 subtracted from:

Wheel	Speed	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	2	-0.3525	0.04599	-7.664	0.0000

Tukey Simultaneous Tests
Response Variable Health
All Pairwise Comparisons among Levels of Wheel*Surface
Wheel = 1
Surface = 1 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	2	-0.6275	0.07271	-8.629	0.0000
1	3	-0.6086	0.07271	-8.369	0.0000
1	4	0.3359	0.07271	4.619	0.0007
1	5	1.6199	0.07271	22.278	0.0000
2	1	0.1242	0.07271	1.708	0.7870
2	2	-0.6273	0.07271	-8.627	0.0000
2	3	-0.5411	0.07271	-7.442	0.0000
2	4	0.1867	0.07271	2.568	0.2530
2	5	1.6027	0.07271	22.040	0.0000

Wheel = 1
Surface = 2 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	3	0.01890	0.07271	0.2599	1.0000
1	4	0.96335	0.07271	13.2483	0.0000
1	5	2.24739	0.07271	30.9069	0.0000
2	1	0.75168	0.07271	10.3373	0.0000
2	2	0.00015	0.07271	0.0021	1.0000
2	3	0.08635	0.07271	1.1875	0.9719
2	4	0.81420	0.07271	11.1972	0.0000
2	5	2.23011	0.07271	30.6693	0.0000

Wheel = 1
Surface = 3 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	4	0.94445	0.07271	12.9884	0.0000
1	5	2.22849	0.07271	30.6469	0.0000
2	1	0.73278	0.07271	10.0774	0.0000
2	2	-0.01875	0.07271	-0.2579	1.0000
2	3	0.06745	0.07271	0.9276	0.9950
2	4	0.79530	0.07271	10.9372	0.0000
2	5	2.21121	0.07271	30.4094	0.0000

Wheel = 1
Surface = 4 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	5	1.2840	0.07271	17.66	0.0000
2	1	-0.2117	0.07271	-2.91	0.1226
2	2	-0.9632	0.07271	-13.25	0.0000
2	3	-0.8770	0.07271	-12.06	0.0000
2	4	-0.1491	0.07271	-2.05	0.5672
2	5	1.2668	0.07271	17.42	0.0000

Wheel = 1
Surface = 5 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	1	-1.496	0.07271	-20.57	0.0000
2	2	-2.247	0.07271	-30.90	0.0000
2	3	-2.161	0.07271	-29.72	0.0000
2	4	-1.433	0.07271	-19.71	0.0000
2	5	-0.017	0.07271	-0.24	1.0000

Wheel = 2
Surface = 1 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	2	-0.7515	0.07271	-10.34	0.0000
2	3	-0.6653	0.07271	-9.15	0.0000
2	4	0.0625	0.07271	0.86	0.9972
2	5	1.4784	0.07271	20.33	0.0000

Wheel = 2
Surface = 2 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	3	0.08620	0.07271	1.185	0.9722
2	4	0.81405	0.07271	11.195	0.0000
2	5	2.22996	0.07271	30.667	0.0000

Wheel = 2
Surface = 3 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	4	0.7279	0.07271	10.01	0.0000
2	5	2.1438	0.07271	29.48	0.0000

Wheel = 2
Surface = 4 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	5	1.416	0.07271	19.47	0.0000

Tukey Simultaneous Tests
Response Variable Comfort
All Pairwise Comparisons among Levels of Surface
Surface = 1 subtracted from:

Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-0.7038	0.05217	-13.49	0.0000
3	-0.6700	0.05217	-12.84	0.0000
4	0.1588	0.05217	3.04	0.0267
5	1.5382	0.05217	29.49	0.0000

Surface = 2 subtracted from:

Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
3	0.03383	0.05217	0.6485	0.9663
4	0.86257	0.05217	16.5352	0.0000
5	2.24199	0.05217	42.9780	0.0000

Surface = 3 subtracted from:

Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
4	0.8287	0.05217	15.89	0.0000
5	2.2082	0.05217	42.33	0.0000

Surface = 4 subtracted from:

Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
5	1.379	0.05217	26.44	0.0000

Tukey Simultaneous Tests
Response Variable Comfort
All Pairwise Comparisons among Levels of Wheel*Speed
Wheel = 1
Speed = 1 subtracted from:

Wheel	Speed	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	2	-0.4525	0.04666	-9.698	0.0000
2	1	-0.0549	0.04666	-1.176	0.6442
2	2	-0.3907	0.04666	-8.373	0.0000

Wheel = 1
Speed = 2 subtracted from:

Wheel	Speed	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	1	0.39766	0.04666	8.523	0.0000
2	2	0.06183	0.04666	1.325	0.5503

Wheel = 2
Speed = 1 subtracted from:

Wheel	Speed	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	2	-0.3358	0.04666	-7.198	0.0000

Tukey Simultaneous Tests
Response Variable Comfort
All Pairwise Comparisons among Levels of Wheel*Surface
Wheel = 1
Surface = 1 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	2	-0.6483	0.07377	-8.787	0.0000
1	3	-0.6402	0.07377	-8.678	0.0000
1	4	0.2885	0.07377	3.910	0.0077
1	5	1.6060	0.07377	21.769	0.0000
2	1	0.1166	0.07377	1.581	0.8525
2	2	-0.6427	0.07377	-8.712	0.0000
2	3	-0.5832	0.07377	-7.905	0.0000
2	4	0.1457	0.07377	1.975	0.6191
2	5	1.5870	0.07377	21.512	0.0000

Wheel = 1
Surface = 2 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	3	0.00811	0.07377	0.1100	1.0000
1	4	0.93674	0.07377	12.6974	0.0000
1	5	2.25427	0.07377	30.5565	0.0000
2	1	0.76492	0.07377	10.3685	0.0000
2	2	0.00556	0.07377	0.0754	1.0000
2	3	0.06511	0.07377	0.8826	0.9965
2	4	0.79397	0.07377	10.7623	0.0000
2	5	2.23528	0.07377	30.2990	0.0000

Wheel = 1
Surface = 3 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	4	0.92863	0.07377	12.5874	0.0000
1	5	2.24616	0.07377	30.4466	0.0000
2	1	0.75681	0.07377	10.2585	0.0000
2	2	-0.00255	0.07377	-0.0346	1.0000
2	3	0.05700	0.07377	0.7726	0.9988
2	4	0.78586	0.07377	10.6523	0.0000
2	5	2.22716	0.07377	30.1890	0.0000

Wheel = 1
Surface = 4 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	5	1.3175	0.07377	17.86	0.0000
2	1	-0.1718	0.07377	-2.33	0.3846
2	2	-0.9312	0.07377	-12.62	0.0000
2	3	-0.8716	0.07377	-11.81	0.0000
2	4	-0.1428	0.07377	-1.94	0.6457
2	5	1.2985	0.07377	17.60	0.0000

Wheel = 1
Surface = 5 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	1	-1.489	0.07377	-20.19	0.0000
2	2	-2.249	0.07377	-30.48	0.0000
2	3	-2.189	0.07377	-29.67	0.0000
2	4	-1.460	0.07377	-19.79	0.0000
2	5	-0.019	0.07377	-0.26	1.0000

Wheel = 2
Surface = 1 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	2	-0.7594	0.07377	-10.29	0.0000
2	3	-0.6998	0.07377	-9.49	0.0000
2	4	0.0291	0.07377	0.39	1.0000
2	5	1.4704	0.07377	19.93	0.0000

Wheel = 2
Surface = 2 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	3	0.05955	0.07377	0.8072	0.9982
2	4	0.78841	0.07377	10.6869	0.0000
2	5	2.22971	0.07377	30.2236	0.0000

Wheel = 2
Surface = 3 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	4	0.7289	0.07377	9.880	0.0000
2	5	2.1702	0.07377	29.416	0.0000

Wheel = 2
Surface = 4 subtracted from:

Wheel	Surface	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	5	1.441	0.07377	19.54	0.0000

Appendix C: ANOVA Analysis for Obstacle Sets

Descriptive Statistics: Health

Results for Tires = 1

Variable	Obstacle	Mean	StDev	Minimum	Median	Maximum
Health	6	1.8353	0.0493	1.7656	1.8486	1.8782
	7	1.8902	0.0242	1.8583	1.8940	1.9144
	8	2.2586	0.0203	2.2332	2.2591	2.2828

Results for Tires = 2

Variable	Obstacle	Mean	StDev	Minimum	Median	Maximum
Health	6	1.9529	0.0240	1.9242	1.9539	1.9795
	7	1.9395	0.0653	1.8712	1.9419	2.0028
	8	2.1532	0.0313	2.1219	2.1510	2.1890

Descriptive Statistics: Comfort

Results for Tires = 1

Variable	Obstacle	Mean	StDev	Minimum	Median	Maximum
Comfort	6	1.7851	0.0425	1.7238	1.7993	1.8181
	7	1.8214	0.0249	1.7915	1.8252	1.8439
	8	2.1665	0.0147	2.1471	2.1694	2.1802

Results for Tires = 2

Variable	Obstacle	Mean	StDev	Minimum	Median	Maximum
Comfort	6	1.9018	0.0279	1.8669	1.9032	1.9339
	7	1.8727	0.0715	1.7976	1.8797	1.9338
	8	2.0797	0.0226	2.0583	2.0774	2.1057

General Linear Model: Health, Comfort versus Tires, Obstacle

Factor	Type	Levels	Values
Tires	fixed	2	1, 2
Obstacle	fixed	3	6, 7, 8

Analysis of Variance for Health, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tires	1	0.00253	0.00253	0.00253	1.64	0.217
Obstacle	2	0.48633	0.48633	0.24317	157.87	0.000
Tires*Obstacle	2	0.05220	0.05220	0.02610	16.94	0.000
Error	18	0.02773	0.02773	0.00154		
Total	23	0.56878				

S = 0.0392465 R-Sq = 95.13% R-Sq(adj) = 93.77%

Unusual Observations for Health

Obs	Health	Fit	SE Fit	Residual	St Resid	
3	1.76560	1.83525	0.01962	-0.06965	-2.05	R
17	1.87120	1.93945	0.01962	-0.06825	-2.01	R

R denotes an observation with a large standardized residual.

Analysis of Variance for Comfort, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Tires	1	0.004388	0.004388	0.004388	2.91	0.105
Obstacle	2	0.411770	0.411770	0.205885	136.60	0.000
Tires*Obstacle	2	0.043160	0.043160	0.021580	14.32	0.000
Error	18	0.027129	0.027129	0.001507		
Total	23	0.486446				

S = 0.0388222 R-Sq = 94.42% R-Sq(adj) = 92.87%

Unusual Observations for Comfort

Obs	Comfort	Fit	SE Fit	Residual	St Resid
17	1.79760	1.87268	0.01941	-0.07508	-2.23 R

R denotes an observation with a large standardized residual.

Tukey Simultaneous Tests
Response Variable Health
All Pairwise Comparisons among Levels of Obstacle
Obstacle = 6 subtracted from:

Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
7	0.02075	0.01962	1.057	0.5516
8	0.31181	0.01962	15.890	0.0000

Obstacle = 7 subtracted from:

Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
8	0.2911	0.01962	14.83	0.0000

Tukey Simultaneous Tests
Response Variable Health
All Pairwise Comparisons among Levels of Tires*Obstacle
Tires = 1
Obstacle = 6 subtracted from:

Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	7	0.05492	0.02775	1.979	0.3906
1	8	0.42330	0.02775	15.253	0.0000
2	6	0.11762	0.02775	4.239	0.0056
2	7	0.10420	0.02775	3.755	0.0154
2	8	0.31795	0.02775	11.457	0.0000

Tires = 1
Obstacle = 7 subtracted from:

Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	8	0.36838	0.02775	13.274	0.0000
2	6	0.06270	0.02775	2.259	0.2602
2	7	0.04928	0.02775	1.776	0.5041
2	8	0.26303	0.02775	9.478	0.0000

Tires = 1
Obstacle = 8 subtracted from:

Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	6	-0.3057	0.02775	-11.01	0.0000
2	7	-0.3191	0.02775	-11.50	0.0000
2	8	-0.1053	0.02775	-3.80	0.0142

Tires = 2
Obstacle = 6 subtracted from:

Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	7	-0.01342	0.02775	-0.4838	0.9962
2	8	0.20033	0.02775	7.2185	0.0000

Tires = 2
Obstacle = 7 subtracted from:

Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	8	0.2138	0.02775	7.702	0.0000

Tukey Simultaneous Tests
Response Variable Comfort
All Pairwise Comparisons among Levels of Obstacle
Obstacle = 6 subtracted from:

Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
7	0.003587	0.01941	0.1848	0.9814
8	0.279637	0.01941	14.4060	0.0000

Obstacle = 7 subtracted from:

Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
8	0.2761	0.01941	14.22	0.0000

Tukey Simultaneous Tests
Response Variable Comfort
All Pairwise Comparisons among Levels of Tires*Obstacle
Tires = 1
Obstacle = 6 subtracted from:

Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	7	0.03630	0.02745	1.322	0.7695
1	8	0.38137	0.02745	13.893	0.0000
2	6	0.11668	0.02745	4.250	0.0054
2	7	0.08755	0.02745	3.189	0.0489
2	8	0.29457	0.02745	10.731	0.0000

Tires = 1
Obstacle = 7 subtracted from:

Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
1	8	0.34508	0.02745	12.570	0.0000
2	6	0.08038	0.02745	2.928	0.0812
2	7	0.05125	0.02745	1.867	0.4516
2	8	0.25828	0.02745	9.408	0.0000

Tires = 1
Obstacle = 8 subtracted from:

Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	6	-0.2647	0.02745	-9.64	0.0000
2	7	-0.2938	0.02745	-10.70	0.0000
2	8	-0.0868	0.02745	-3.16	0.0516

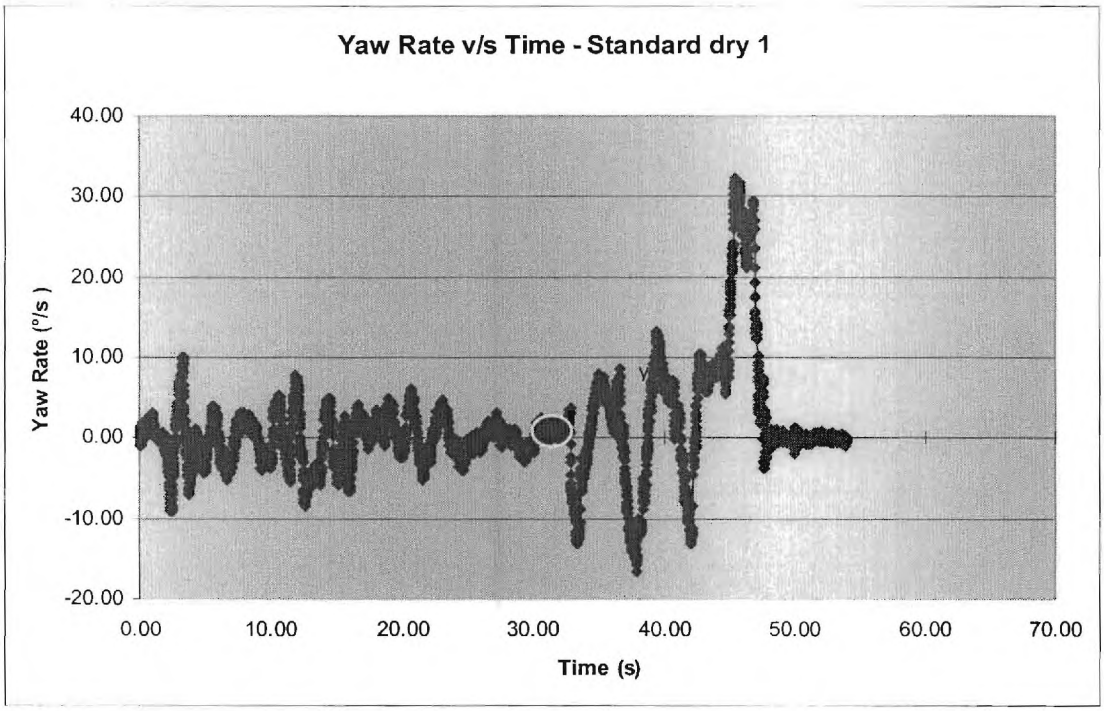
Tires = 2
Obstacle = 6 subtracted from:

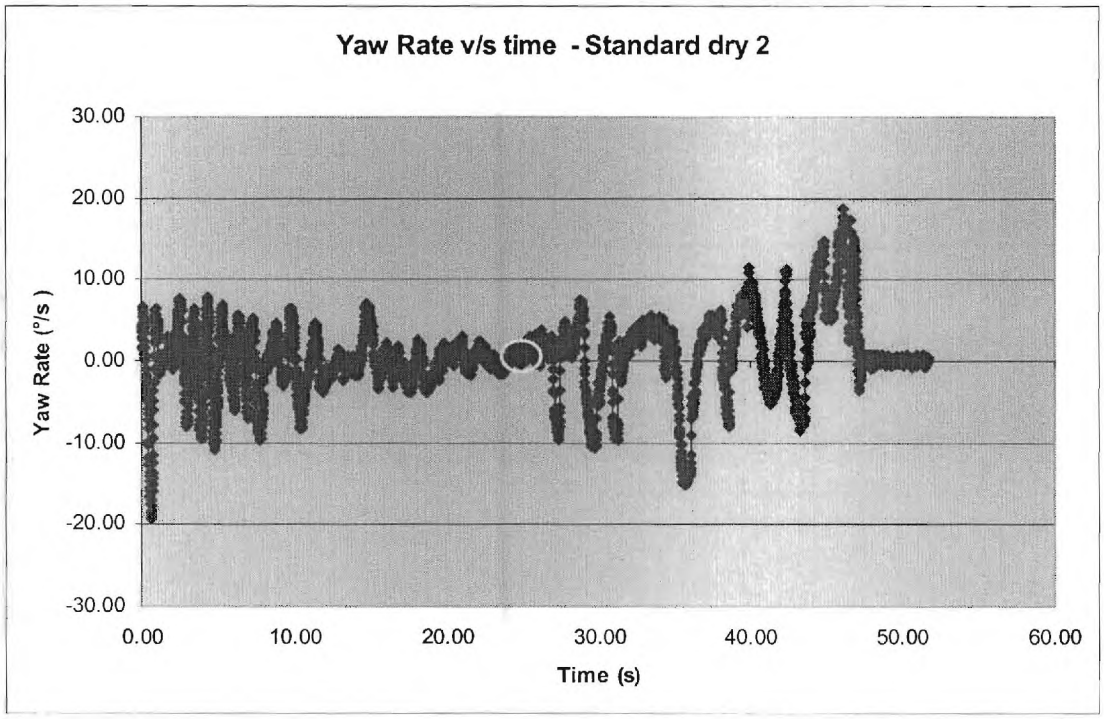
Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	7	-0.02913	0.02745	-1.061	0.8903
2	8	0.17790	0.02745	6.481	0.0001

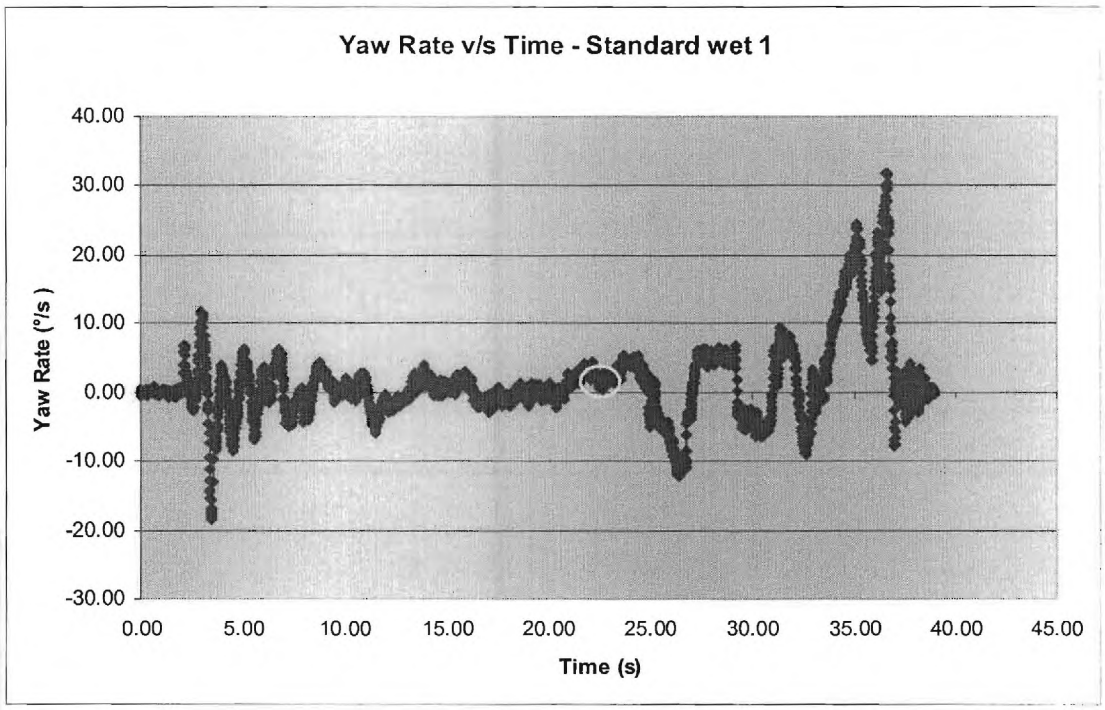
Tires = 2
Obstacle = 7 subtracted from:

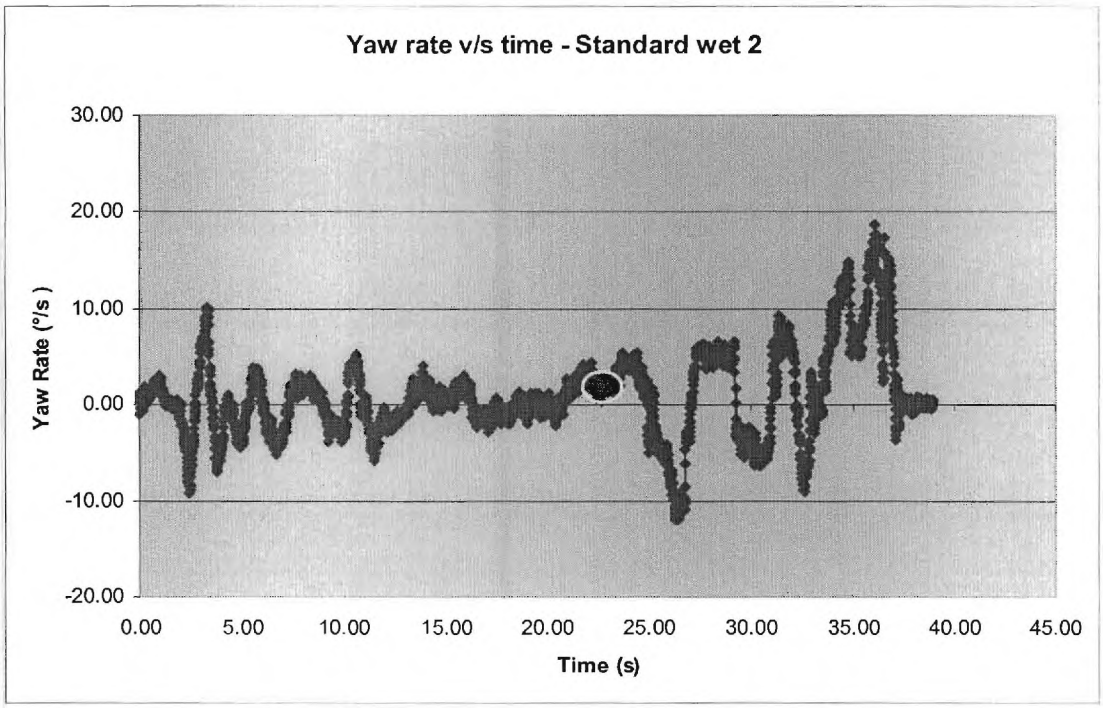
Tires	Obstacle	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	8	0.2070	0.02745	7.541	0.0000

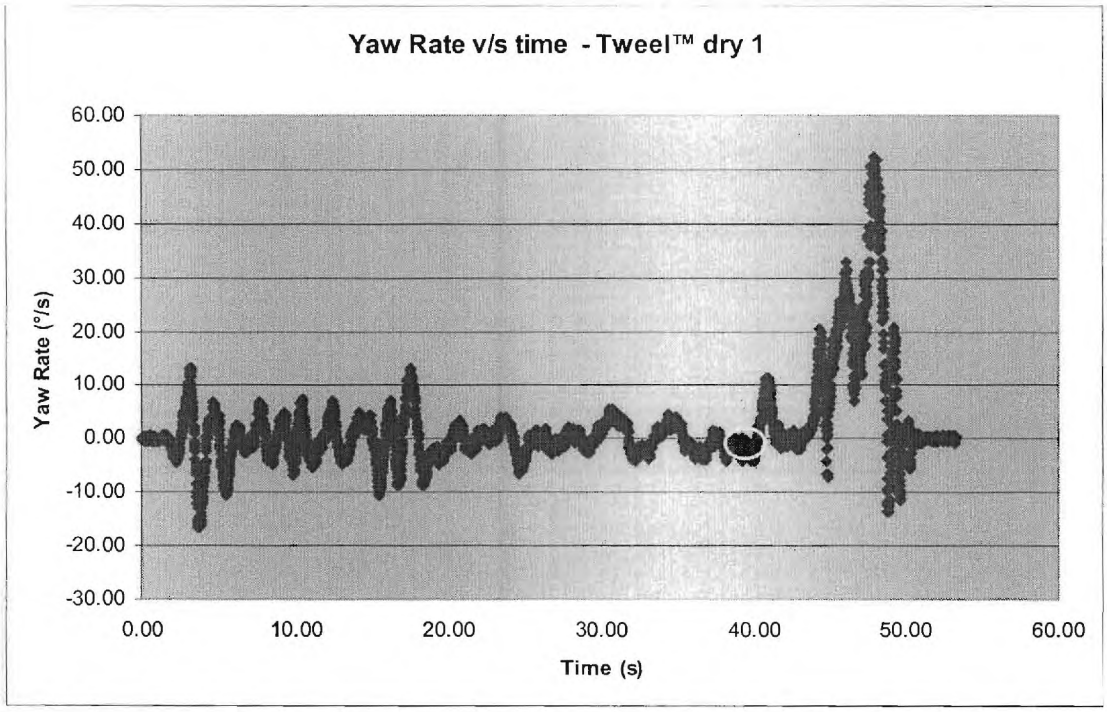
Appendix D : Traction Angle Calculation Graphs

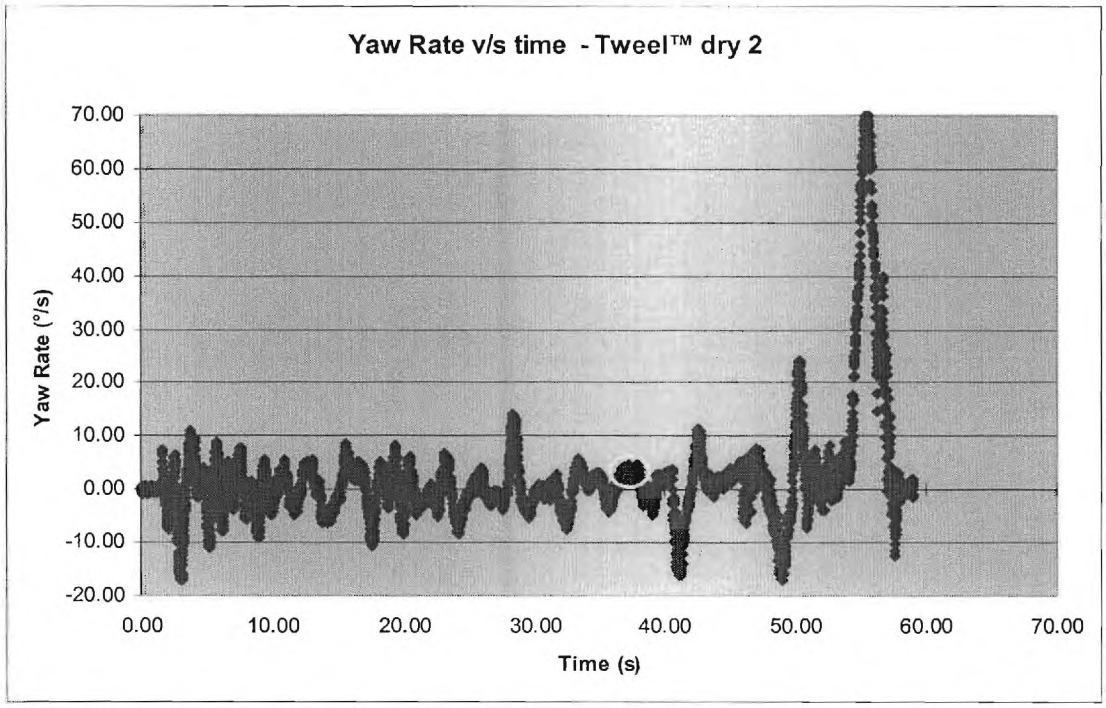


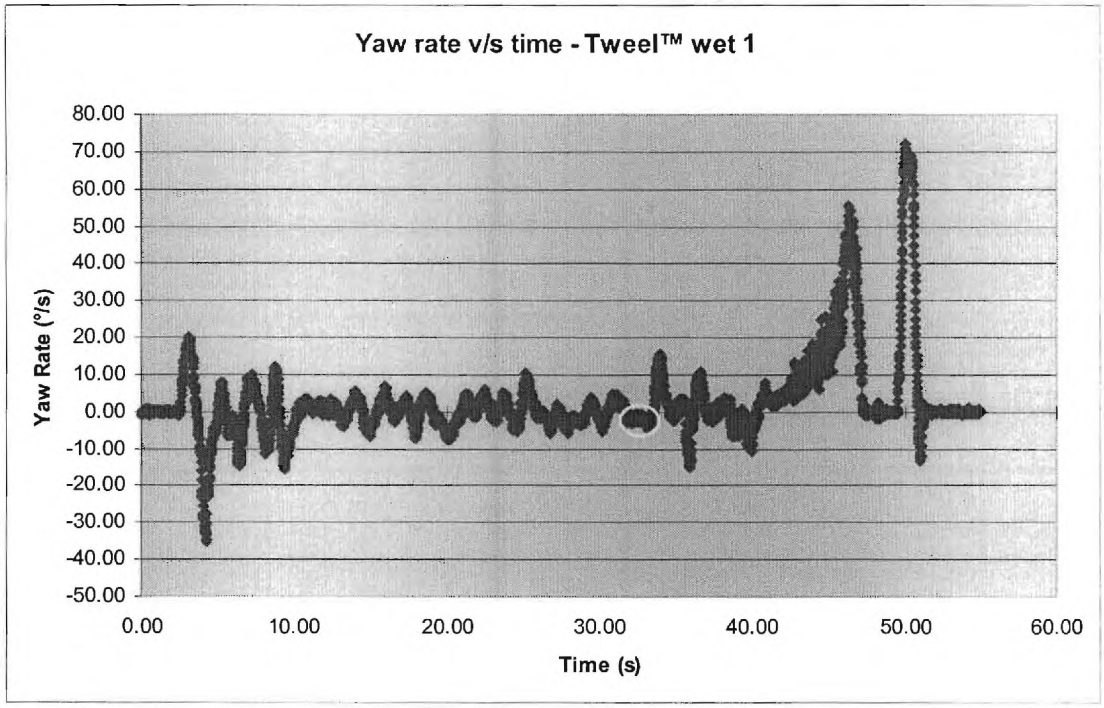


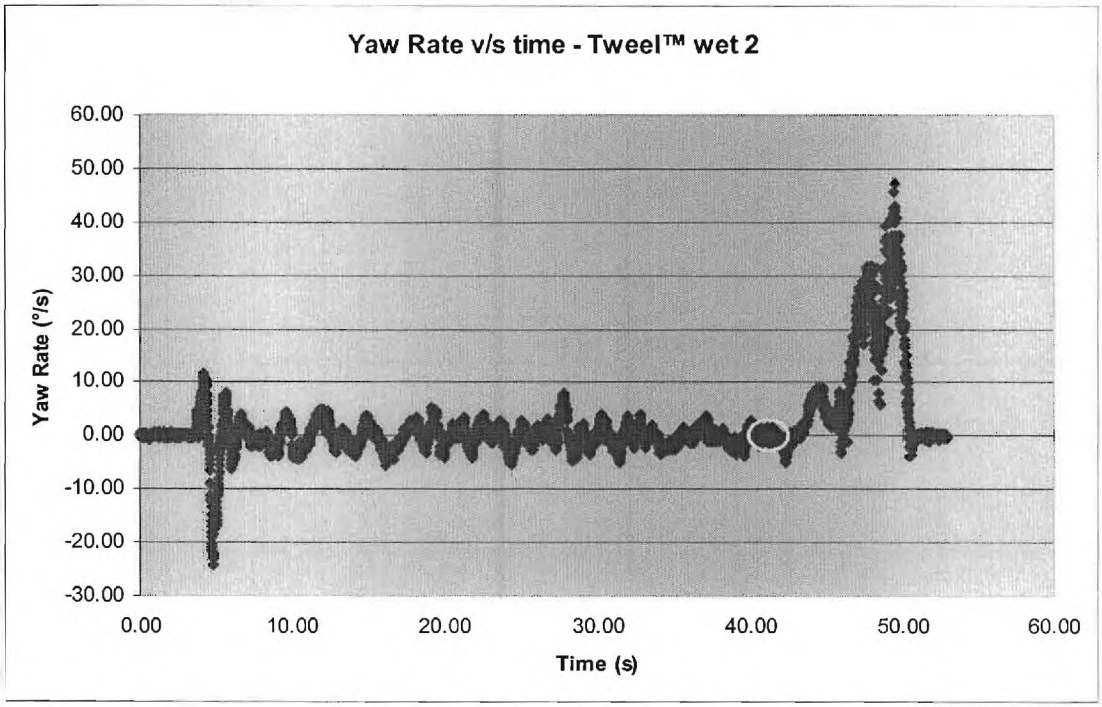

Yaw Rate v/s Time - Standard wet 1
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
Yaw Rate (°/s)
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
Time (s)


Yaw rate v/s time - Standard wet 2
30.00
20.00
10.00
0.00
-10.00
-20.00
Yaw Rate (°/s)
0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
Time (s)


Yaw Rate v/s time - Tweel™ dry 1
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
Yaw Rate (°/s)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
Time (s)


Yaw Rate v/s time - Tweel™ dry 2
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
Yaw Rate (°/s)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
Time (s)


Yaw rate v/s time - Tweel™ wet 1
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
-40.00
-50.00
Yaw Rate (°/s)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
Time (s)


Yaw Rate v/s time - Tweel™ wet 2
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
-20.00
-30.00
Yaw Rate (°/s)
0.00
10.00
20.00
30.00
40.00
50.00
60.00
Time (s)

Force loss and damage in Tweel™ casters and drive wheels after a field trial

Abstract:

The purpose of this study was to measure the Force-Deflection properties of Tweel™ technology tires before and after field trials to determine deterioration in material properties after use. Nine power wheelchairs were fit with Tweel™ casters and/or drive wheels for a month-long trial. One additional subject used the Tweel™ tires for 3 months. A total of 22 casters and 10 drive wheels were evaluated. The Tweel™ tires showed significant deterioration in material properties; the force required to induce 5% and 10% deflections was reduced by an average of 11%. Visual inspection before and after the field trial documented visible damage, particularly on the drive wheels. One caster was rendered unusable due to a flat spot.

Methods:

Apparatus

A Zwick/Roell Z005 testing machine was used to measure force-deflection response of the Tweel™ casters and drive wheels. The Zwick can apply a maximum load of 5000N (AST load cell) at a maximum speed of 500mm/min which far exceeded the requirements for this study. The Tweel™ tires were attached by a rod passing through the center, such that they were free to rotate about the rod (Fig 1). However the fixture prevented any lateral movements of the Tweel™ wheels.

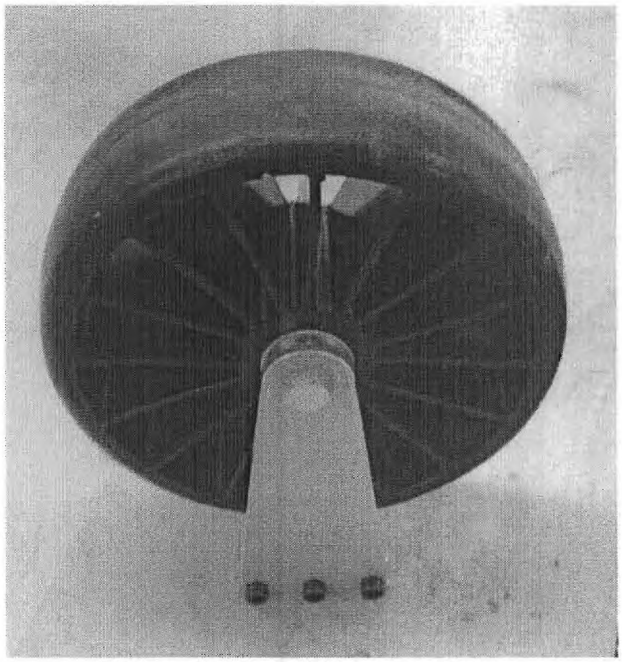


Figure 1: Tweel™ caster fixture.

Test

The Tweel™ tires were marked with a number to keep a record for future references. The casters were labeled on the inner surface of the urethane ring with a soldering iron, while the metal hubs of the drive wheels were embossed with the respective part number. Two locations on each caster and drive wheel were noted where the load was applied during testing. For this purpose the markings etched into the product during manufacturing were used (Table 1)

Table 1: Location of numbering and Testing Locations

Tweel™ Type	Numbering Location	Testing locations
Caster	On side A, underneath the point which is marked with "Michelin Tweel"	At the point where it was numbered and 90 deg from it where it states "max load".
Drive Wheel	Embossed on the hub with a metal stamp	At the point where it's marked "Michelin Tweel" and 90 deg from this point where it's marked "6202-1"

The test was conducted at standard room temperature and humidity. The test specimen was pre-loaded with 5N and the initial radius was measured. This radius was used to determine the percent deflection required for load-deflection testing. The Tweel™ was then pre-conditioned by compressing it by 15% of the deformable material thickness. The load was applied at 50mm/min and then removed at the same rate. The process was repeated 3 times with no pause between the cycles.

The Tweel™ tire was allowed to rest for 1 min before the compressive force was applied at 50mm/min. The Tweel™ tire was deflected by 10% of the initial radial distance for the casters and 10% of the urethane height for the drive wheel. The load was then removed at the same rate at which it was applied. The force values at 5% and 10% deformation were recorded for future calculations. The test was repeated at 90 degrees from the spot of the original test to check for discrepancies in material properties.

Data analysis and results:

Statistical tests were run to determine the difference in material properties at the 2 test locations, differences between pre and post field trial use and the relationship between material properties and distance traveled. Differences are reported for all tests having a $p < 0.1$ significance level.

A paired t-test was conducted to determine whether the order of testing the two locations had any effect on the results. The mean force required to deflect the material by 5% or 10% was lower at Location 2 than Location 1. T-test analysis showed significance at the $p<0.1$ level for the pre- and post-test at 5% deflection and the 10% deflection during the pre-test (Table 2). Significance differences were not found with the drive wheels (Table 3). These results indicate that an order effect might have influenced the results of testing the 2 locations but these differences were minor (non-significant and <1%) for the drive wheels and fairly small (approximately 1%) for the casters. Because testing was conducted in the same order before and after the field trial and the down time between the testing of the locations was the same in both

cases, any residual effect would have been approximately the same during pre- and post-testing. Therefore both the locations were used for subsequent analyses.

Table 2: Pre- and Post-test force values at 5% and 10% for casters

Casters	**Pre 5%**			**Pre 10 %**		
	Location 1	**Location2**	**P val.**	**Location 1**	**Location 2**	**P val.**
mean	385.16	381.30	0.057	599.05	594.02	0.088
Stdev.	38.69	40.33		59.57	60.06	
	Post 5%			**Post 10 %**		**Pre 5%**
	Location 1	**Location2**	**P val.**	**Location 1**	**Location2**	**P val.**
Mean	338.45	335.59	0.099	529.65	525.83	0.252
Stdev.	47.08	47.44		63.56	65.59	

Table 3: Pre- and Post-test force values at 5% and 10% for drive wheels

Drive Wheel	**Pre 5%**			**Pre 10 %**		
	Location 1	**Location2**	**P val.**	**Location 1**	**Location 2**	**P val.**
Mean	710.73	708.63	0.688	1125.11	1119.13	0.474
Stdev.	30.46	25.56		46.11	39.06	
	Post 5%			**Post 10 %**		**Pre 5%**
	Location 1	**Location2**	**P val.**	**Location 1**	**Location2**	**P val.**
Mean	625.79	620.26	0.219	1005.82	996.29	0.127
Stdev.	28.91	27.43		48.54	42.04	

The mean, standard deviation and coefficient of variation of the force required to compress the Tweel™ technology tires by 5% and 10% was calculated (Table 4 and 5). For Tweel™ casters, the coefficient of variation before the field trial was about 10% indicating some variance across casters. The coefficient of variation for Tweel™ drive wheels was much lower at 3%, suggesting better uniformity in material properties over the set.

The post field trial data shows that the mean force had fallen in all cases by an average of more than 10% at both 5% and 10% deflection levels. Force loss in casters ranged from about 1% to 50%. A paired t-test comparing the caster pre- and post- force values was significant at $p<0.001$ for both 5% and 10% deflections. Force loss in drive wheels ranged from 9% to 14% at 5% deflection and from 8% to 14% at 10% deflection. A paired t-test comparing the drive wheel pre- and post- force values was significant at $p<0.001$ for both 5% and 10% deflections This force loss can be considered a significant change since the field trial was only conducted over a 30 day period. The coefficient of variation in all of the cases increased in the post field trial testing showing that the wear differed across Tweels™, which was expected as they were driven under different conditions and distance. A Complete set of the data is tabulated in Appendix A.

Table 4: Force required to deform casters by 5 and 10%

Casters	Mean force (N) 5%	Std. 5%	Coefficient of variation	Mean Force (N) 10%	Std. 10%	Coefficient of variation
Pre	383.2301	39.08186	0.101	596.5334	59.13839	0.099
Post	337.0206	46.70509	0.138	527.7394	63.81765	0.120
Difference	46.20955			68.794		
% Difference	12.1 %			11.5 %		

Table 5: Force required to deform Drive wheels by 5 and 10%

Drive Wheels	Mean force (N) 5%	Std. 5%	Coefficient of variation	Mean Force (N) 10%	Std. 10%	coefficient of variation
Pre	709.6787	27.38848545	0.0385	1122.1205	41.70389941	0.0371
Post	623.0274	27.57405788	0.0442	1001.05515	44.46423255	0.0444
Difference	86.6513			121.06535		
% Difference	12.2%			10.78%		

The relationship between force loss and distance traveled was investigated using linear regression. Caster data, shown in Figure 2, illustrates most distance distributed around 40 miles, thereby offering a poor distribution for analysis. In addition, one set of casters experienced significant force loss resulting in a very poor R^2 value of 0.11. This infers that distance is not the only factor that contributed to force loss in casters and other variables, such as environment of use may have influenced the results. In fact, the subject whose casters experienced the highest force loss regularly used his wheelchair at construction sites.

Drive wheel data showed a much stronger relationship between force loss and distance traveled (R^2 =0.635). In contradistinction to the caster data, this relationship illustrates a stronger influence of distance traveled on the force loss of drive wheels.

The average force loss in casters traveling 40 miles or less was about 7% and the force loss of drive wheels traveling less than 40 miles was 9%. This early loss in stiffness accounts for a high percentage of overall force loss, i.e., the average force loss for all drive wheels was 11%. This result is consistent with a settling-in period which must be considered during design. Tweel™ tires should settle into their ideal operating performance after this initial drop in stiffness.

While the data set is limited, the differences in the regression analysis illustrate the different roles of casters and drive wheels. Casters are exposed to many different types of forces and stressors since they are of smaller diameter and impact obstacles during everyday mobility. Drive wheels are better equipped to negotiate barriers so fatigue is more related to distance.

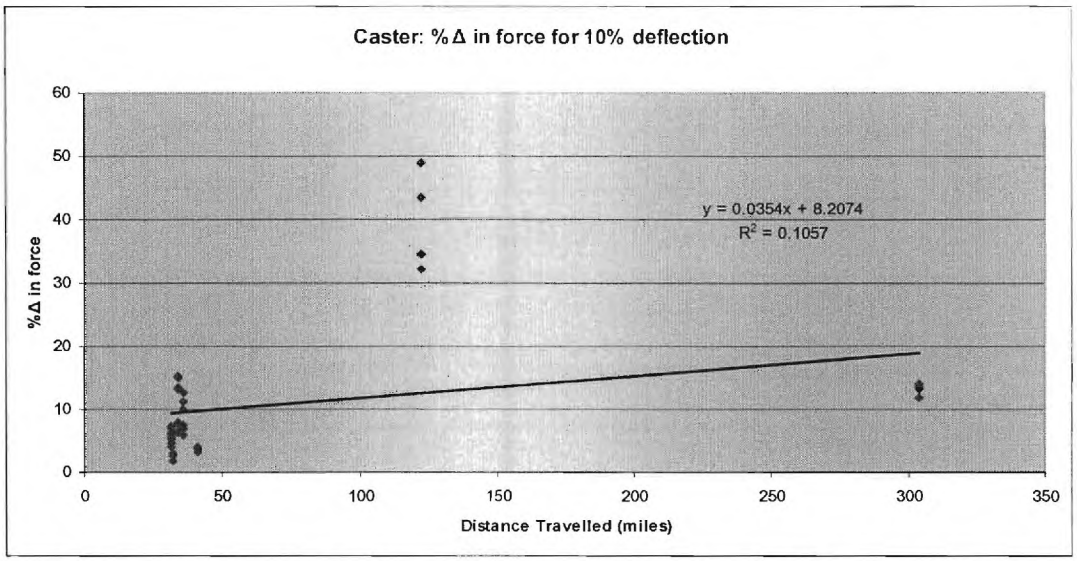


Figure 2: Percent reduction in force required at 10% deflection in casters with respect to distance traveled

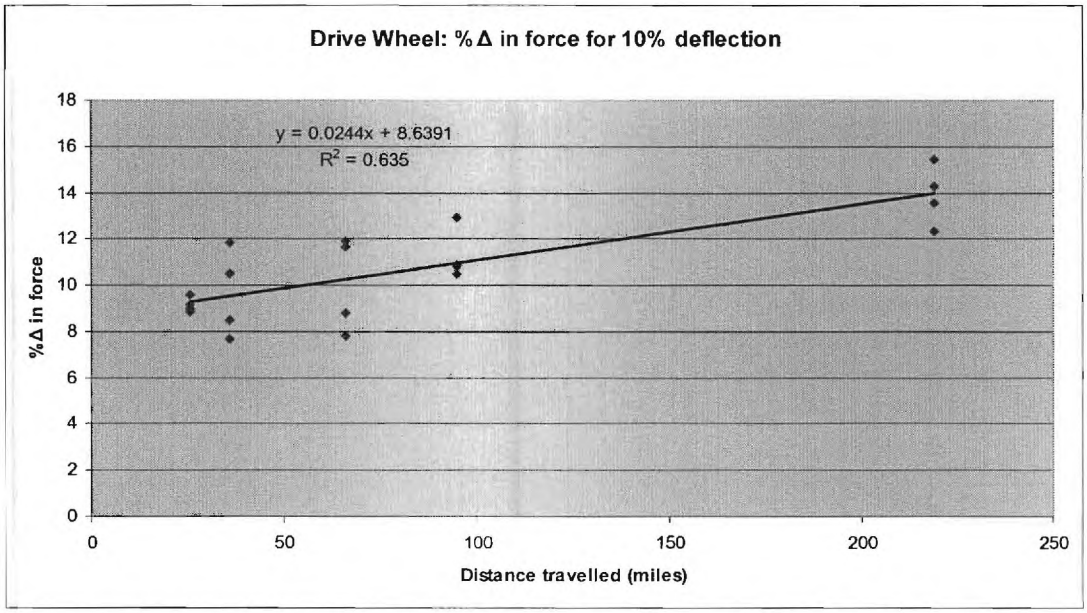


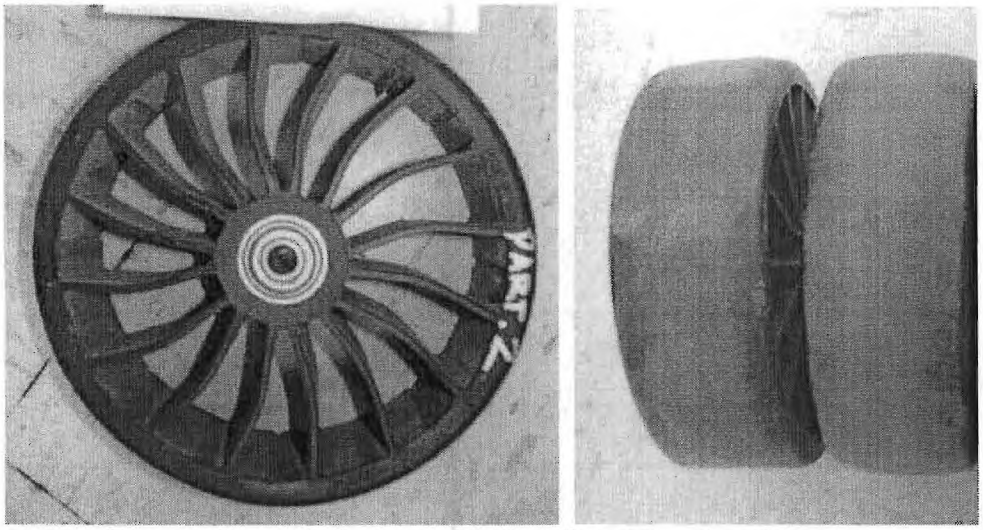
Figure 3: Percent reduction in force required at 10% deflection in drive wheels with respect to distance traveled

Visible wear and damage inspection:

Most of the drive wheels and casters did not show significant visual damages. However all of the Tweel™ drive wheels had lost some parts of the tread. In most cases it was on the outer edge of the wheel as shown in figure 4. Some of the drive wheels also lost tread in the middle of the tire. This could affect the long term use of the tire as it would lead to lower traction.

Figure 4: Extensive tread damage to a drive wheel

The Tweel™ casters showed less physical damage after the field trials but noticeable wear could be seen. In two cases in which casters were subjected to high usage, significant degradation to the materials was visualized. The fins on two casters were bent, one caster had a broken fin, and one of the casters developed a flat spot as can be seen in figures 5 and 6. A Complete set of visual damage report along with user information is attached in Appendix B



Figures 5 and 6: Casters with significant structural damage

Conclusion:

The Tweel™ tires did not perform to the expectations that users have of casters and drive wheels. On average, users replace their casters every 2-3 years with drive wheels being replaced a bit more frequently due to tread wear. The Tweel™ drive wheels and casters showed significant deterioration in material properties (average 10% reduction in force) over the short field trial. This issue needs to be addressed as durability and life span is an important criterion in choosing replacements wheels for wheelchairs; one of the key reasons why users don't use pneumatic tires.

The Tweel™ tires showed a drop in material stiffness over the first 40 miles of use. This loss of stiffness may indicate a settling or break-in time for Tweel™ casters and drive wheels. However a longer study needs to be conducted to better relate the deterioration in material properties to usage.

The Tweel™ casters showed relatively lower signs of visual damages at the end of the trial, but one of the casters had to be replaced due to a flat spot. Although none of the Tweel™ Drive wheels had to be replaced they showed significant loss of tread. This could prove to be important as the tread provides the traction for the wheelchairs. In conclusion, the life span of both the Tweel™ drive wheels and casters needs to be improved before it can be sold to most wheelchair users.

Appendix A: Force Deflection Data

Table 1: Force required for 5% and 10% deflection and distance traveled for Casters

Subject #	Caster#	Distance Traveled	Pre 5% Force (N)	Post 5% Force (N)	Pre 10% Force (N)	Post 10% Force (N)	Location
2	24	122	398.257	193.996	624.406	352.008	1
2	24	122	402.96	182.801	631.709	322.7	2
2	25	122	480.798	285.715	747.614	489.558	1
2	25	122	498.621	299.471	765.288	519.037	2
3	26	41	334.515	329.017	524.086	506.875	1
3	26	41	335.317	327.878	528.541	509.136	2
3	27	41	338.975	329.303	527.258	506.223	1
3	27	41	345.384	334.539	535.521	515.344	2
9	5	34	370.582	339.728	574.029	528.017	1
9	5	34	352.082	324.816	552.237	509.603	2
9	7	34	372.283	311.837	579.088	492.036	1
9	7	34	372.086	312.069	584.407	495.025	2
9	8	34	375.373	320.778	582.791	504.247	1
9	8	34	366.068	312.701	568.137	493.183	2
9	9	34	346.591	331.811	543.527	507.709	1
9	9	34	348.48	327.724	543.167	508.817	2
11	6	31.61	423.329	397.738	652.157	615.449	1
11	6	31.61	415.417	392.998	648.397	614.209	2
11	10	31.61	417.616	398.79	641.304	610.783	1
11	10	31.61	424.431	404.744	652.665	625.759	2
11	11	31.61	433.642	403.106	681.785	631.505	1
11	11	31.61	410.246	387.612	640.204	601.255	2
11	12	31.61	357.116	333.193	557.578	518.491	1
11	12	31.61	356.546	335.825	557.789	522.499	2
12	2	304	368.452	325.264	573.548	505.669	1
12	2	304	360.777	319.142	564.572	497.974	2
12	3	304	356.715	309.828	557.791	481.563	1
12	3	304	345.707	299.633	538.581	463.3	2
12	4	304	353.335	307.535	549.725	473.134	1
12	4	304	351.45	308.851	550.398	477.329	2
13	21	32	337.216	332.559	527.937	514.342	1
13	21	32	337.904	335.614	533.771	523.524	2
13	22	32	372.875	364.655	571.351	556.357	1
13	22	32	361.965	352.773	558.88	542.385	2
15	14	36	418.7	376.776	652.082	587.494	1
15	14	36	408.272	369.828	633.697	571.183	2
15	15	36	422.018	391.446	656.574	610.557	1
15	15	36	417.351	388.515	646.005	597.421	2
15	16	36	420.743	361.181	655.7	572.859	1
15	16	36	417.271	366.327	654.828	581.919	2
15	17	36	389.313	363.296	599.755	557.708	1
15	17	36	378.886	363.451	585.523	550.869	2
Mean		**81.35**	**383.23**	**337.02**	**596.53**	**527.74**	

Table 2: Reduction in force required for 5% and 10% deflection and distance traveled for Casters

Subject #	Caster#	Distance Traveled	Reduction in 5% Force (N)	%Δ in 5% force	Reduction in 10% Force (N)	%Δ in 10% force	Location
2	24	122	204.261	51.3	272.398	43.6	1
2	24	122	220.159	54.6	309.009	48.9	2
2	25	122	195.083	40.6	258.056	34.5	1
2	25	122	199.15	39.9	246.251	32.2	2
3	26	41	5.498	1.6	17.211	3.3	1
3	26	41	7.439	2.2	19.405	3.7	2
3	27	41	9.672	2.9	21.035	4.0	1
3	27	41	10.845	3.1	20.177	3.8	2
9	5	34	30.854	8.3	46.012	8.0	1
9	5	34	27.266	7.7	42.634	7.7	2
9	7	34	60.446	16.2	87.052	15.0	1
9	7	34	60.017	16.1	89.382	15.3	2
9	8	34	54.595	14.5	78.544	13.5	1
9	8	34	53.367	14.6	74.954	13.2	2
9	9	34	14.78	4.3	35.818	6.6	1
9	9	34	20.756	6.0	34.35	6.3	2
11	6	31.61	25.591	6.0	36.708	5.6	1
11	6	31.61	22.419	5.4	34.188	5.3	2
11	10	31.61	18.826	4.5	30.521	4.8	1
11	10	31.61	19.687	4.6	26.906	4.1	2
11	11	31.61	30.536	7.0	50.28	7.4	1
11	11	31.61	22.634	5.5	38.949	6.1	2
11	12	31.61	23.923	6.7	39.087	7.0	1
11	12	31.61	20.721	5.8	35.29	6.3	2
12	2	304	43.188	11.7	67.879	11.8	1
12	2	304	41.635	11.5	66.598	11.8	2
12	3	304	46.887	13.1	76.228	13.7	1
12	3	304	46.074	13.3	75.281	14.0	2
12	4	304	45.8	13.0	76.591	13.9	1
12	4	304	42.599	12.1	73.069	13.3	2
13	21	32	4.657	1.4	13.595	2.6	1
13	21	32	2.29	0.7	10.247	1.9	2
13	22	32	8.22	2.2	14.994	2.6	1
13	22	32	9.192	2.5	16.495	3.0	2
15	14	36	41.924	10.0	64.588	9.9	1
15	14	36	38.444	9.4	62.514	9.9	2
15	15	36	30.572	7.2	46.017	7.0	1
15	15	36	28.836	6.9	48.584	7.5	2
15	16	36	59.562	14.2	82.841	12.6	1
15	16	36	50.944	12.2	72.909	11.1	2
15	17	36	26.017	6.7	42.047	7.0	1
15	17	36	15.435	4.1	34.654	5.9	2
Mean		**81.35**	**46.21**	**11.48**	**68.79**	**11.09**	

Table 3: Force required for 5% and 10% deflection and distance traveled for Drive Wheels

Subject #	Drive Wheel#	Distance Traveled	Pre 5% Force (N)	Post 5% Force (N)	Pre 10% Force (N)	Post 10% Force (N)	Loc.
4	6	94.5	719.251	634.717	1141.63	1022.08	1
4	6	94.5	707.923	614.371	1117.36	996.825	2
4	7	94.5	712.636	619.651	1113.25	992.114	1
4	7	94.5	695.546	597.734	1098.93	957.015	2
5	14	25.45	679.859	614.931	1070.35	972.264	1
5	14	25.45	680.13	610.143	1082.38	978.882	2
5	15	25.45	777.771	686.843	1223.95	1115.71	1
5	15	25.45	755.418	666.591	1186.9	1080.68	2
8	8	66	702.759	633.132	1109.24	1011.48	1
8	8	66	693.848	628.711	1089.91	1005.11	2
8	9	66	720.02	637.288	1144.26	1008.2	1
8	9	66	716.836	628.82	1135.68	1003.34	2
12	4	219	687.515	591.869	1103.52	953.738	1
12	4	219	709.344	593.72	1131.94	957.355	2
12	5	219	692.191	583.031	1108.32	950.29	1
12	5	219	678.382	577.212	1069.6	937.625	2
15	11	36	677.845	614.399	1070.91	988.725	1
15	11	36	702.007	630.946	1101.74	1008.55	2
15	12	36	737.434	642.078	1165.69	1043.6	1
15	12	36	746.859	654.361	1176.85	1037.52	2
Mean		**88.2**	**709.68**	**623.03**	**1122.12**	**1001.06**	

Table 4: Reduction in force required for 5% and 10% deflection Drive wheels

Subject #	Drive Wheel#	Distance Traveled	Reduction in 5% Force (N)	%Δ in 5% force	Reduction in 10% Force (N)	%Δ in 10% force	Loc.
4	6	94.5	84.534	11.8	119.55	10.5	1
4	6	94.5	93.552	13.2	120.535	10.8	2
4	7	94.5	92.985	13.0	121.136	10.9	1
4	7	94.5	97.812	14.1	141.915	12.9	2
5	14	25.45	64.928	9.6	98.086	9.2	1
5	14	25.45	69.987	10.3	103.498	9.6	2
5	15	25.45	90.928	11.7	108.24	8.8	1
5	15	25.45	88.827	11.8	106.22	8.9	2
8	8	66	69.627	9.9	97.76	8.8	1
8	8	66	65.137	9.4	84.8	7.8	2
8	9	66	82.732	11.5	136.06	11.9	1
8	9	66	88.016	12.3	132.34	11.7	2
12	4	219	95.646	13.9	149.782	13.6	1
12	4	219	115.624	16.3	174.585	15.4	2
12	5	219	109.16	15.8	158.03	14.3	1
12	5	219	101.17	14.9	131.975	12.3	2
15	11	36	63.446	9.4	82.185	7.7	1
15	11	36	71.061	10.1	93.19	8.5	2
15	12	36	95.356	12.9	122.09	10.5	1
15	12	36	92.498	12.4	139.33	11.8	2
Mean		**88.2**	**86.65**	**12.21**	**121.07**	**10.79**	

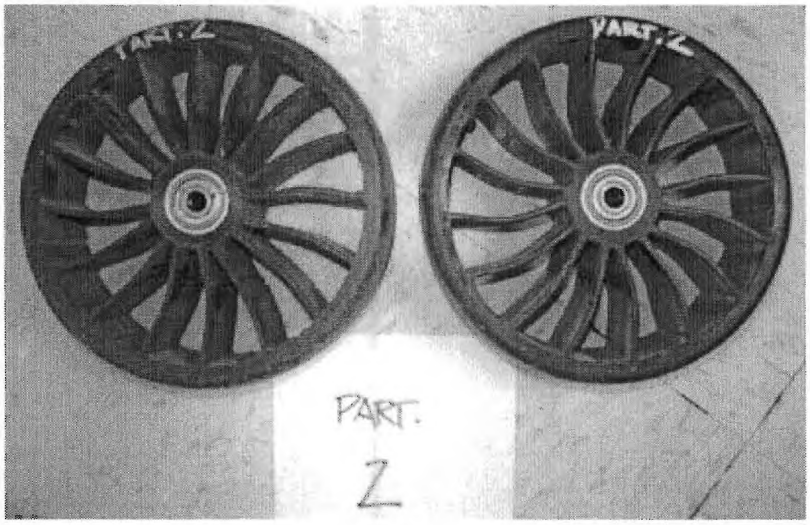
Appendix B: Visual Inspection of Wear and Damage

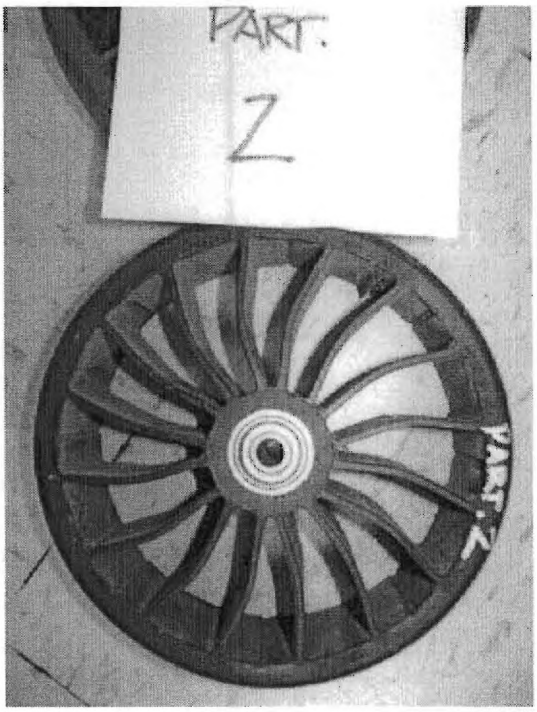
The following documentation has been broken down by subject and the specific Tweel™ technology tires they had installed on their power wheelchairs. The information for each field trial subject includes: Tweel™ type, Wheelchair type, self-reported weight of participant, odometer reading, photographs of and any damage to the Tweel™ tires, a written description of the condition of wheels, pre/post force deflection results. All Tweel™ tires were used for approximately 4-5 weeks.

Subject 2
Tweel™ Used: 2 Tweel™ casters, front wheels.
Wheelchair Type: Invacare Action Ranger
Approximate weight of user: 225 lbs.
Odometer Reading: 122 miles.
Usage Dates: 3/31/2006 – 5/16/2006 (46 days)

C #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
24	398.257	193.996	624.406	352.008	204.261	272.398
24	402.96	182.801	631.709	322.7	220.159	309.009
25	480.798	285.715	747.614	489.558	195.083	258.056
25	498.621	299.471	765.288	519.037	199.15	246.251

There was significant deformation of the caster spokes. There was no visible damage but there was excessive wear to the casters.

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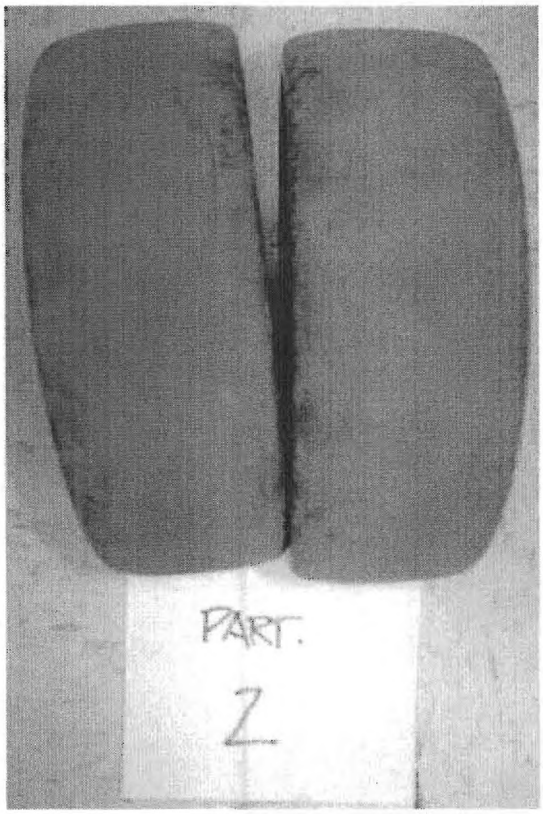
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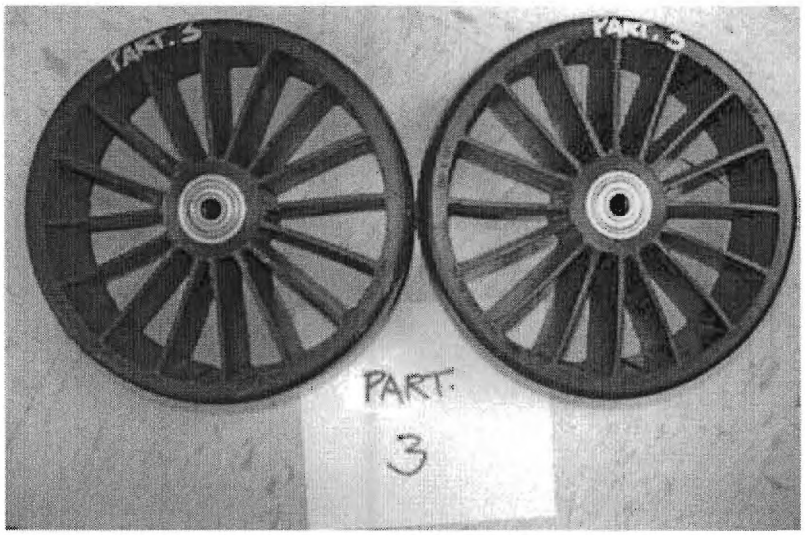
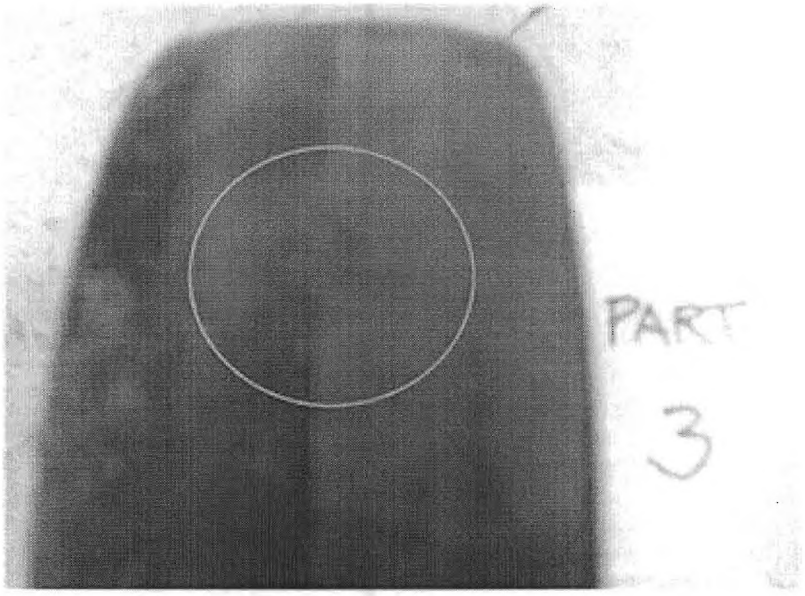
Subject 3
Tweel™ Used: 2 Tweel™ caters, front wheels
Wheelchair Type: Quickie V-121
Approximate weight of user: 200 lbs.
Odometer Reading: 41 miles.
Usage Dates: 4/07/2006 – 5/09/2006 (32 days)

C #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
26	334.515	329.017	524.086	506.875	5.498	17.211
26	335.317	327.878	528.541	509.136	7.439	19.405
27	338.975	329.303	527.258	506.223	9.672	21.035
27	345.384	334.539	535.521	515.344	10.845	20.177

The casters had wear but the most noticeable issue was a small pit in the center of one of the caster wheels.

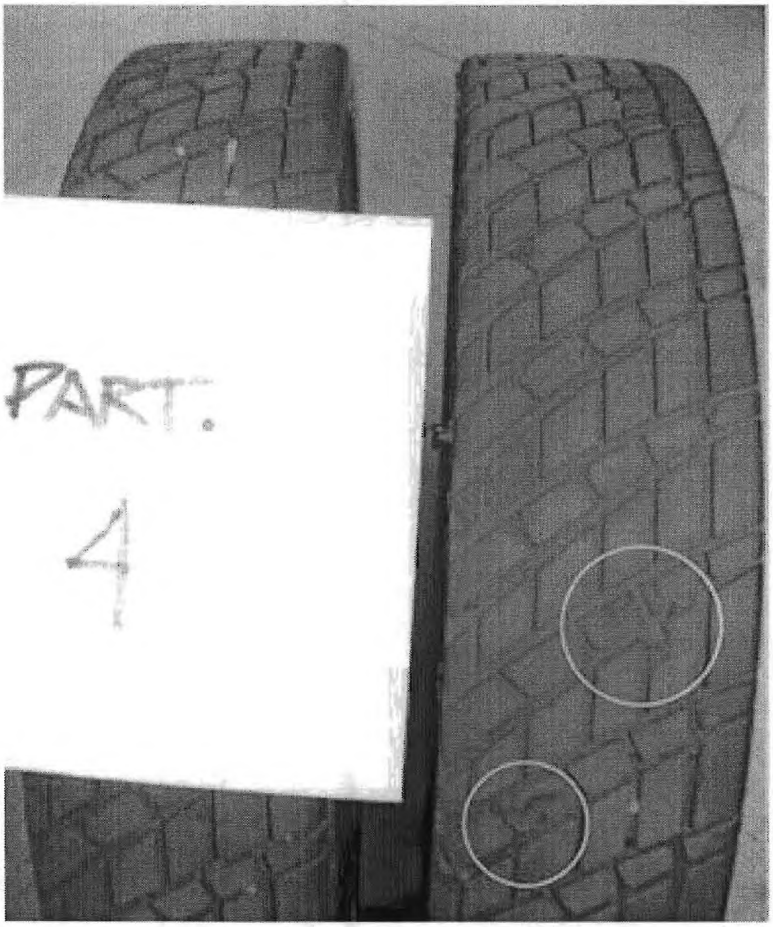




Subject 4
Tweel™ Used: 2 Tweel™ drive wheels.
Wheelchair Type: Quickie P-222
Approximate weight of user: 240 lbs.
Odometer Reading: 94.5 miles.
Usage Dates: 3/29/2006 – 5/05/2006 (37 days)

D #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
6	719.251	634.717	1141.63	1022.08	84.534	119.55
6	707.923	614.371	1117.36	996.825	93.552	120.535
7	712.636	619.651	1113.25	992.114	92.985	121.136
7	695.546	597.734	1098.93	957.015	97.812	141.915

There was minimal damage to the Tweel™drive wheel. Only a few areas where the tread, on both drive Tweels, where some damage occurred.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Subject 5
Tweel™ Used: 2 Tweel™ drive wheels.
Wheelchair Type: Invacare Torque
Approximate weight of user: 150 lbs.
Odometer Reading: 25.5 miles.
Usage Dates: 4/05/2006 – 5/05/2006 (30 days)

D #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
14	679.859	614.931	1070.35	972.264	64.928	98.086
14	680.13	610.143	1082.38	978.882	69.987	103.498
15	777.771	686.843	1223.95	1115.71	90.928	108.24
15	755.418	666.591	1186.9	1080.68	88.827	106.22

There was significant damage to outside edge of the right side Tweel™ drive wheel Most of the outside edge has been torn off, probably because of a metal ramp. There were a few pits removed from the tread. There was some outside edge damage to the Tweel™ tireon the left side of the wheelchair.

Subject 8
Tweel™ Used: 2 Tweel™ drive wheels.
Wheelchair Type: Jazzy 1122
Approximate weight of user: 145 lbs.
Odometer Reading: 66 miles.
Usage Dates: 3/28/2006 – 5/01/2006 (34 days)

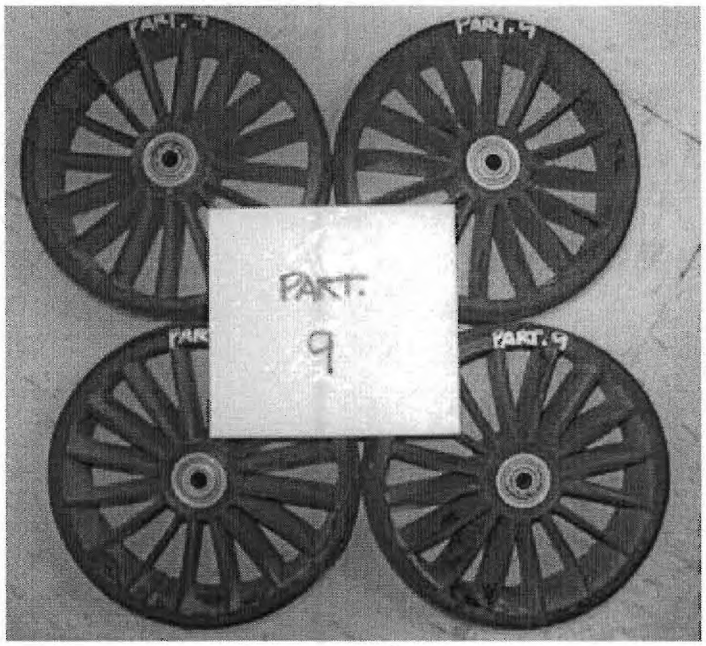
D #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
8	702.759	633.132	1109.24	1011.48	69.627	97.76
8	693.848	628.711	1089.91	1005.11	65.137	84.8
9	720.02	637.288	1144.26	1008.2	82.732	136.06
9	716.836	628.82	1135.68	1003.34	88.016	132.34

There was only minor edge damage to the Tweel™ drive wheel.

Subject 9
Tweel™ Used: 4 Tweel™ casters.
Wheelchair Type: Invacare Storm TDX 5.
Approximate weight of user: 250 lbs.
Odometer Reading: 34 miles.
Usage Dates: 3/03/2006 – 4/14/2006 (41 days)

C #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
5	370.582	339.728	574.029	528.017	30.854	46.012
5	352.082	324.816	552.237	509.603	27.266	42.634
7	372.283	311.837	579.088	492.036	60.446	87.052
7	372.086	312.069	584.407	495.025	60.017	89.382
8	375.373	320.778	582.791	504.247	54.595	78.544
8	366.068	312.701	568.137	493.183	53.367	74.954
9	346.591	331.811	543.527	507.709	14.78	35.818
9	348.48	327.724	543.167	508.817	20.756	34.35

There was damage to only one of the Tweel™ casters. The removal of the urethane tread was over the entire tread area. There was no damage to any of the other casters.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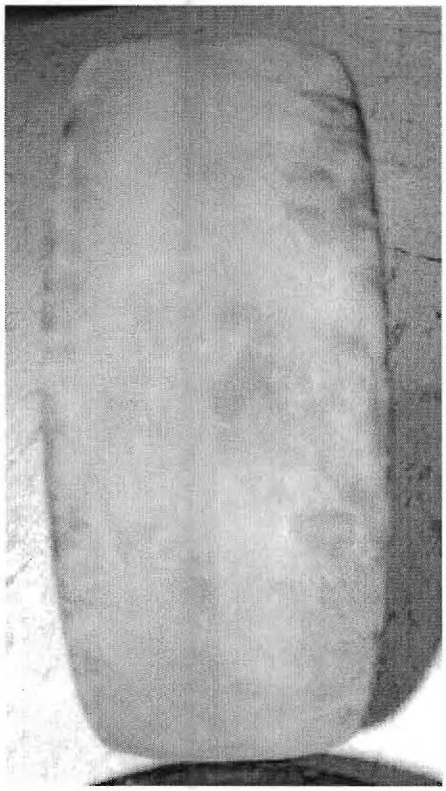
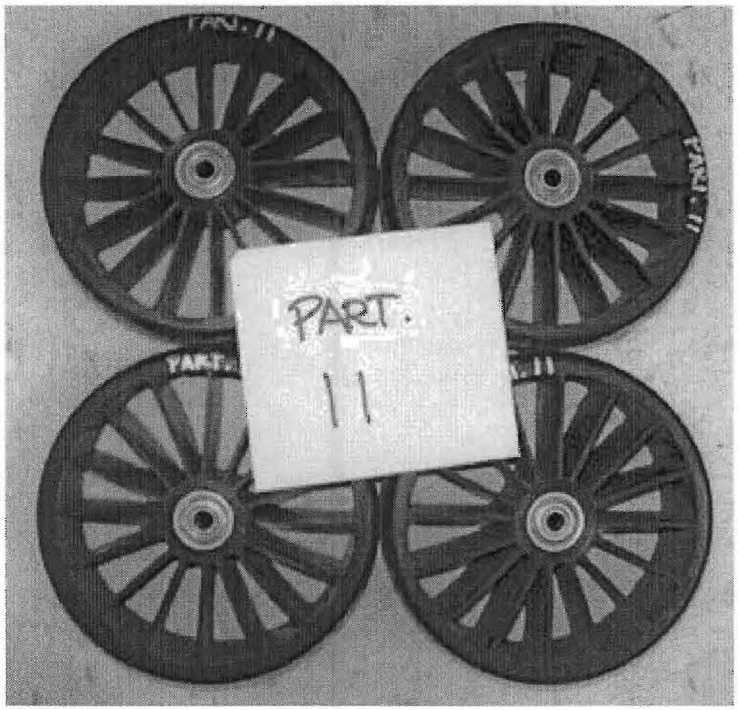


Subject 11
Tweel™ Used: 4 Tweel™ casters.
Wheelchair Type: Invacare TDX 3
Approximate weight of user: 175 lbs.
Odometer Reading: 31.5 miles.
Usage Dates: 3/06/2006 -4/21/2006 (46 days)

C #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
6	423.329	397.738	652.157	615.449	25.591	36.708
6	415.417	392.998	648.397	614.209	22.419	34.188
10	417.616	398.79	641.304	610.783	18.826	30.521
10	424.431	404.744	652.665	625.759	19.687	26.906
11	433.642	403.106	681.785	631.505	30.536	50.28
11	410.246	387.612	640.204	601.255	22.634	38.949
12	357.116	333.193	557.578	518.491	23.923	39.087
12	356.546	335.825	557.789	522.499	20.721	35.29

There was no visible damage to the Tweel™ casters. There was wear but the parting line was still visible.



Subject 12

Tweel™ Used: 4 Tweel™ casters, 2 Tweel™ drive wheels.
Wheelchair Type: Invacare TDX 4
Approximate weight of user: 125 lbs.
Odometer Reading: 304 miles (casters) 219 miles (drive wheels).
Usage Dates: 3/01/2006 – 5/20/2006 (80days) (Casters)
3/24/2006 – 5/20/2006 (57 days) (Drive Wheels)

C. #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
1*	358.03	264.973	560.598	443.118	93.057	117.48
1*	354.102	242.068	553.22	390.659	112.034	162.561
2	368.452	325.264	573.548	505.669	43.188	67.879
2	360.777	319.142	564.572	497.974	41.635	66.598
3	356.715	309.828	557.791	481.563	46.887	76.228
3	345.707	299.633	538.581	463.3	46.074	75.281
3**		303.621		475.837		
4	353.335	307.535	549.725	473.134	45.8	76.591
4	351.45	308.851	550.398	477.329	42.599	73.069

*The values were not used for other calculations as the casters were removed before the end of the experiment

**At the location of the torn fin

D #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
4	687.515	591.869	1103.52	953.738	95.646	149.782
4	709.344	593.72	1131.94	957.355	115.624	174.585
5	692.191	583.031	1108.32	950.29	109.16	158.03
5	678.382	577.212	1069.6	937.625	101.17	131.975

There was some visible damage to the tread of the drive wheels, particularly on the outside edges. Tread wear was noticed on all of the Casters and 2 of them had significant damages. One of the casters (1) developed visible flat spots probably from getting stuck and being dragged along and had to be replaced. One of the urethane fins on a casters (3) was torn on the inside edge.

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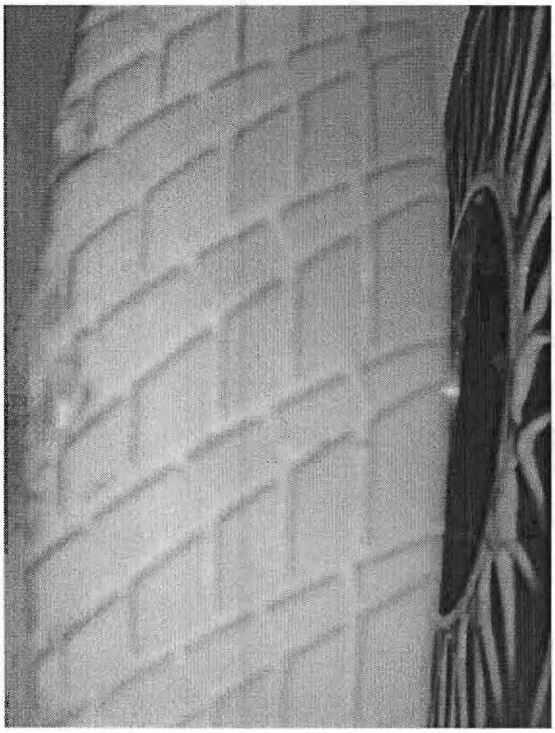

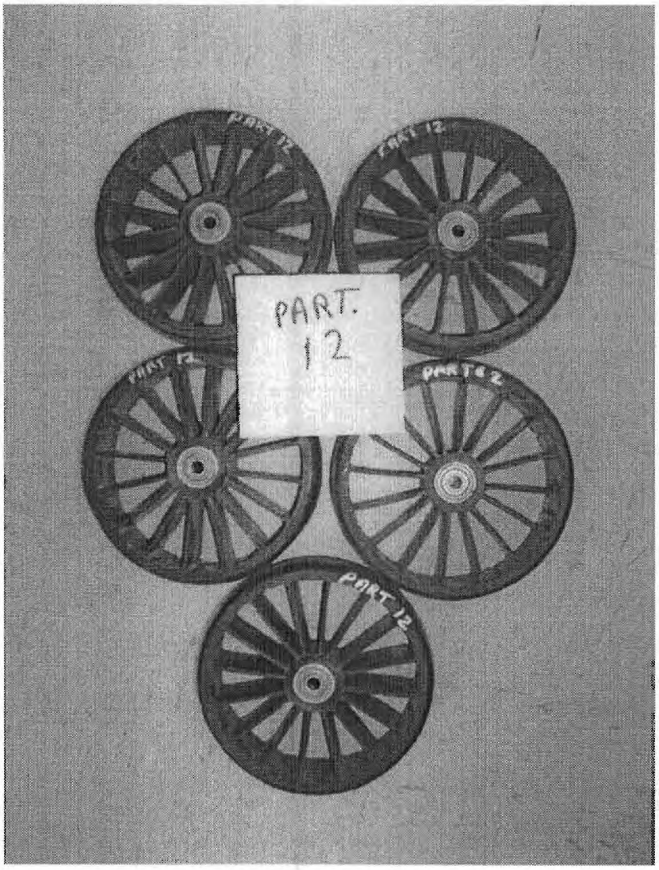
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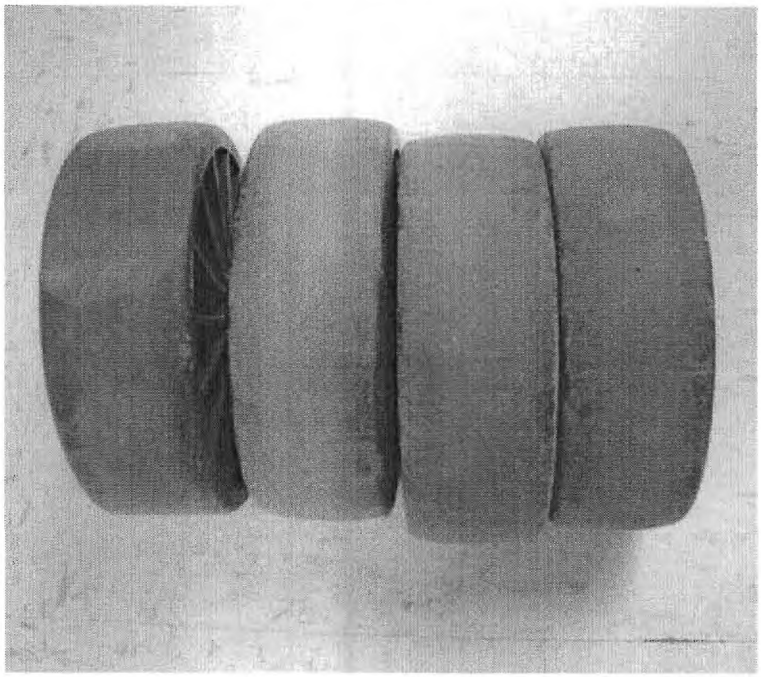
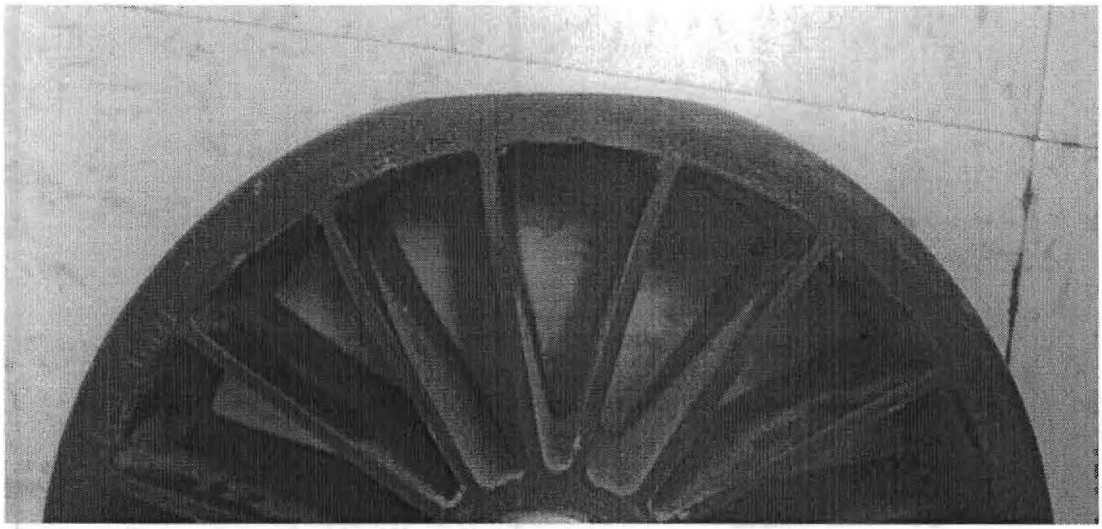
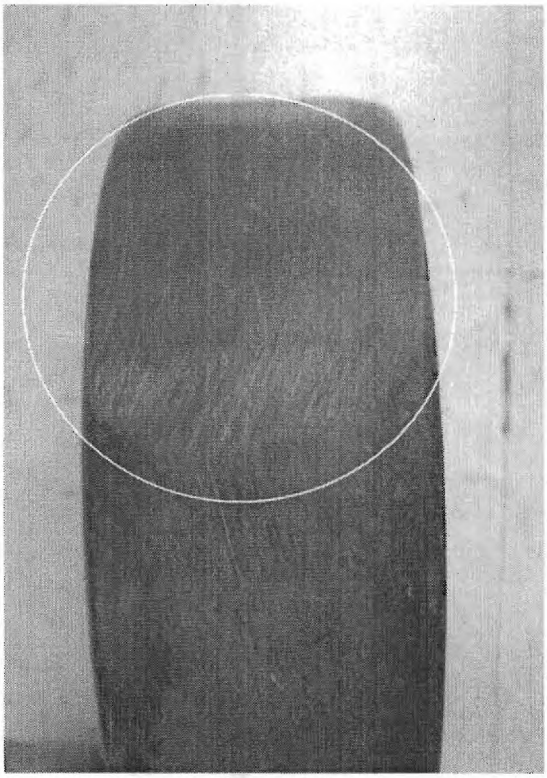
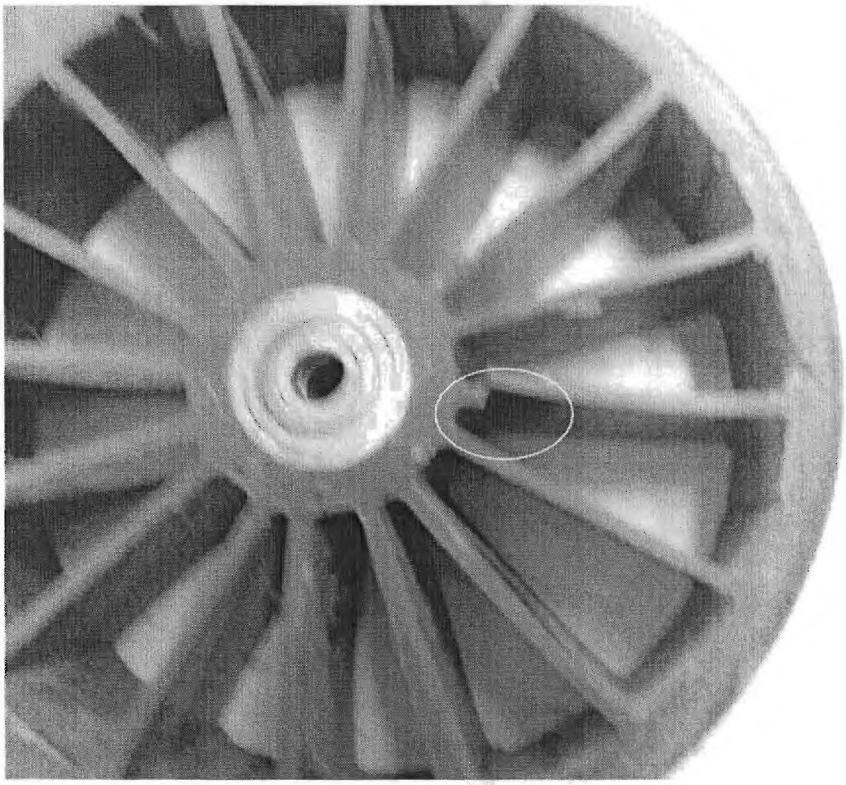






Caster# 1

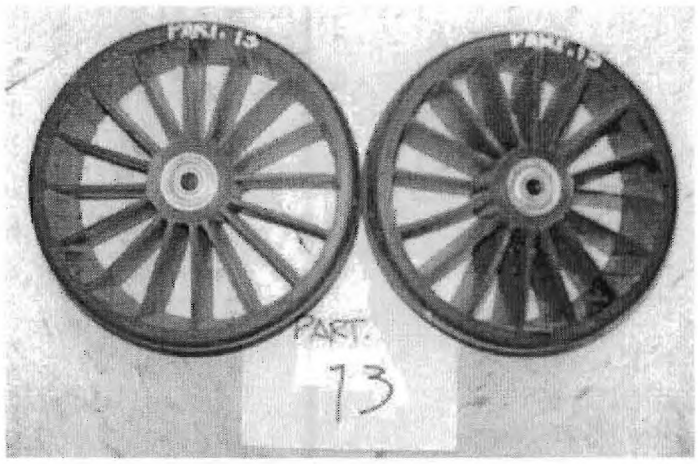


Caster #3

Subject 13
Tweel™ Used: 2 Tweel™ casters, rear wheels.
Wheelchair Type: Invacare X-Terra GT
Approximate weight of user: 250 lbs.
Odometer Reading: 32 miles.
Usage Dates: 3/24/2006 – 4/24/2006 (31 days)

C #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
21	337.216	332.559	527.937	514.342	4.657	13.595
21	337.904	335.614	533.771	523.524	2.29	10.247
22	372.875	364.655	571.351	556.357	8.22	14.994
22	361.965	352.773	558.88	542.385	9.192	16.495

No damage to casters and only minimal wear to tread.

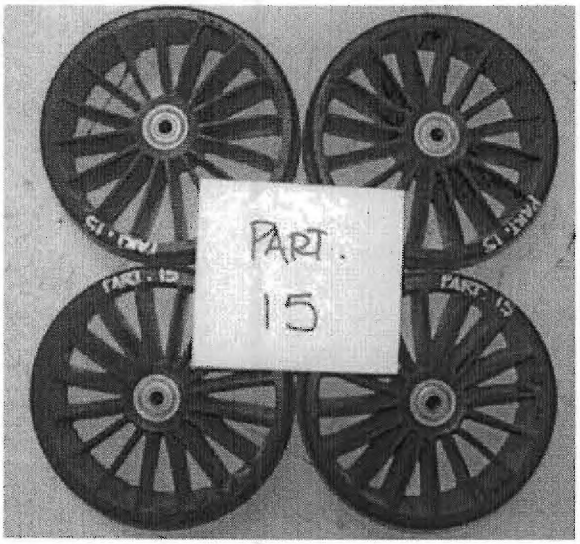


Subject 15
Tweel™ Used: 4 Tweel™ casters, 2 Tweel™ drive wheels.
Wheelchair Type: Invacare TDX 3
Approximate weight of user: 140 lbs.
Odometer Reading: 36 miles.
Usage Dates: 3/28/2006 – 5/9/2006 (42 days)

C. #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
14	418.7	376.776	652.082	587.494	41.924	64.588
14	408.272	369.828	633.697	571.183	38.444	62.514
15	422.018	391.446	656.574	610.557	30.572	46.017
15	417.351	388.515	646.005	597.421	28.836	48.584
16	420.743	361.181	655.7	572.859	59.562	82.841
16	417.271	366.327	654.828	581.919	50.944	72.909
17	389.313	363.296	599.755	557.708	26.017	42.047
17	378.886	363.451	585.523	550.869	15.435	34.654

D #	Pre 5% (N)	Post 5% (N)	Pre 10% (N)	Post 10% (N)	Diff. 5% (N)	Diff. 10% (N)
11	677.845	614.399	1070.91	988.725	63.446	82.185
11	702.007	630.946	1101.74	1008.55	71.061	93.19
12	737.434	642.078	1165.69	1043.6	95.356	122.09
12	746.859	654.361	1176.85	1037.52	92.498	139.33

There was no visible damage to the Tweel™ casters but some wear noticed. The Tweel™ drive wheels had some damage to the outside edge of the right Tweel™ drive wheel. There was a lot of debris caught in the tread.


PART.
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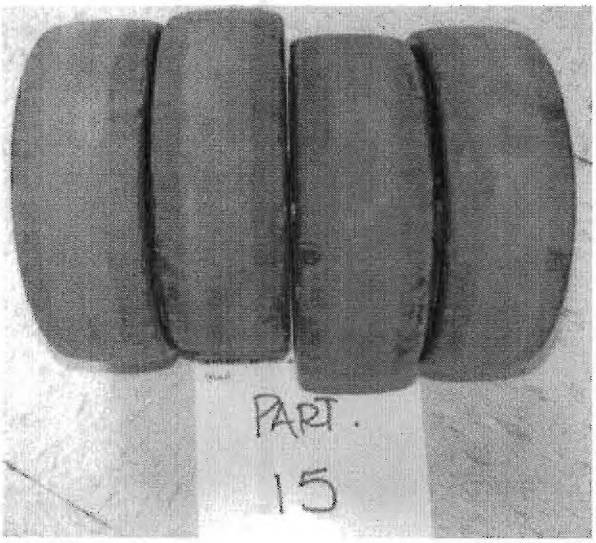
PART.
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PART
15