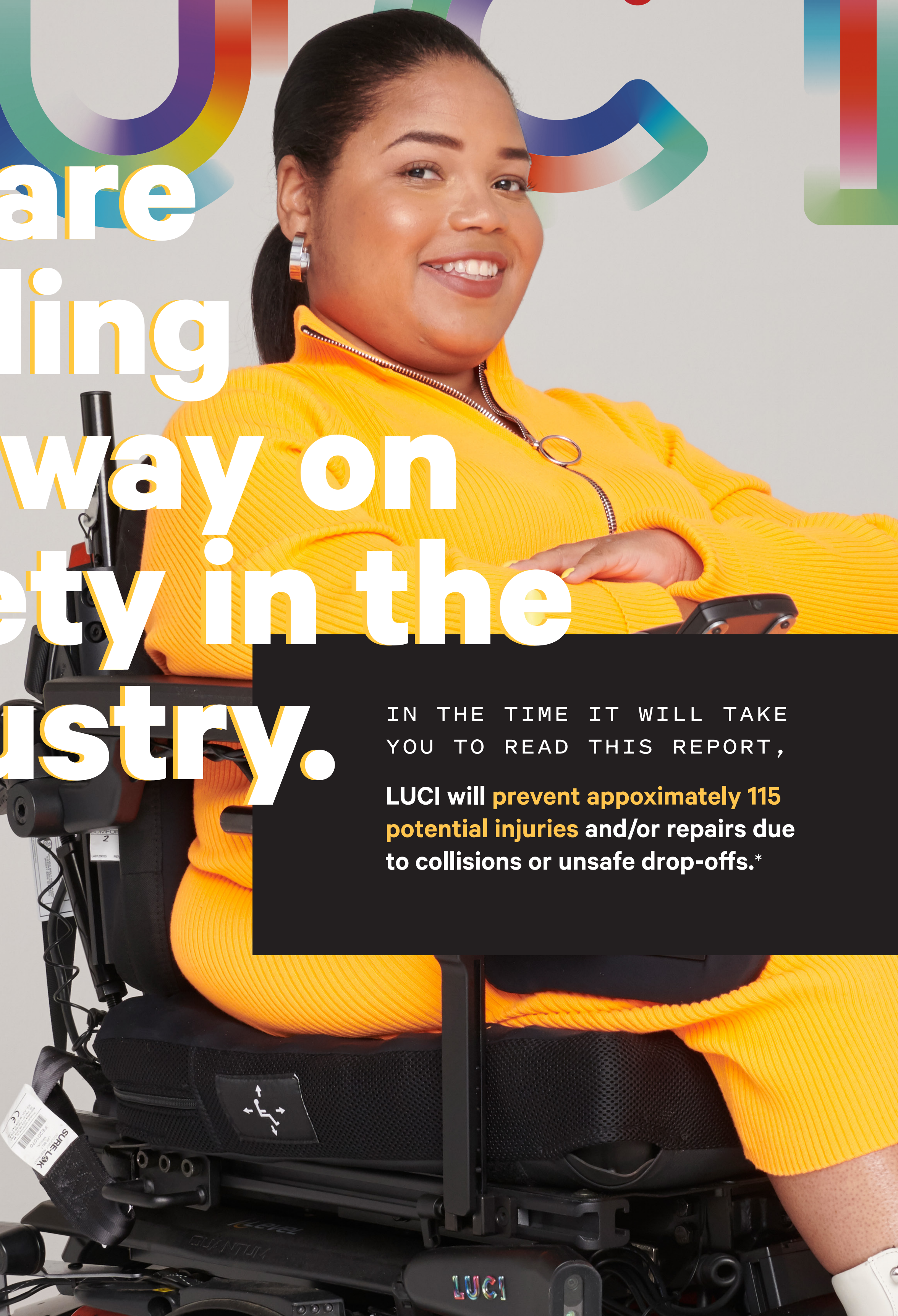
Safety Report 2022

LUCI

We are leading the way on safety in the industry.



IN THE TIME IT WILL TAKE YOU TO READ THIS REPORT,

LUCI will prevent appoximately 115 potential injuries and/or repairs due to collisions or unsafe drop-offs.*

WHAT'S INSIDE

Our 2nd Annual Report with **new brands and models** of chairs tested.

Improvements in our award-winning performance!

Behind the scenes look at some of our **state-of-the-art testing procedures**


LUCI gets safer
and easier to
use with every
free, over the air
software update!

On an average day, LUCI prevents over a dozen potential collisions and injuries per user.

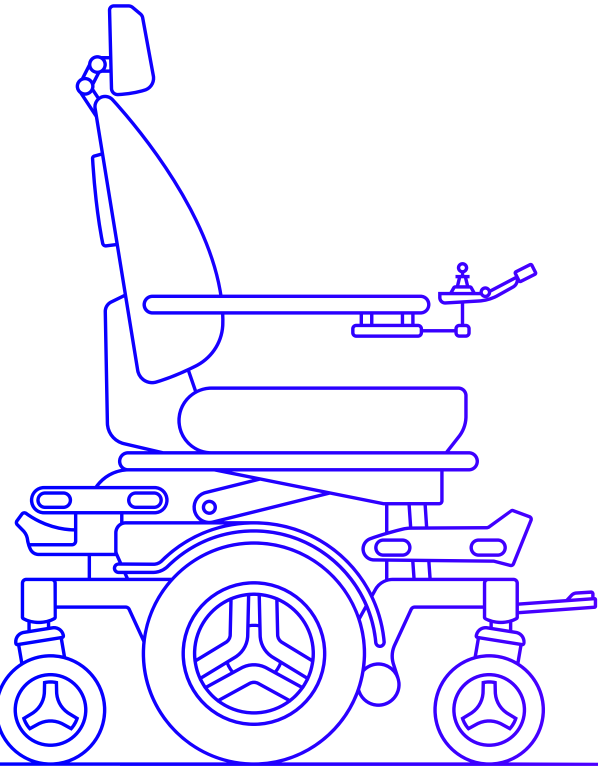
At LUCI, user safety and independence are at the heart of everything we do. We invented the first and only active driver assistance system for power wheelchairs and in doing so are redefining safety for the entire industry. LUCI's technology is in use in homes and clinics nationwide and has a proven track record of safety and effectiveness in the home and in the community. The LUCI team has completed more than 46,000 hours of testing since 2018. In that time, we have built a comprehensive safety program to guide our testing and development of power wheelchair driving technology.

Testing shows that our proven technology is safe and effective:

LUCI checks **10X every second, to avoid collisions, drop-offs, and potential injuries**, which is two times faster than a human can.

LUCI's **collision avoidance is 99% effective** at slowing the chair before a collision with detected stationary object and is approximately 97% effective at stopping the wheelchair completely before contact based on our extensive testing methods.

LUCI's **drop-off protection is more than 99% effective** based on our actual curb drop-off protection testing.



OUR MISSION

At LUCI we exist to reimagine mobility.

Our mission is to provide security, stability, and connectivity for power wheelchair users.

LUCI may be small, but we believe in leading. To this end we released Judging Smart[1], a framework for thinking about what "smart" should mean in power mobility products, and we have industry-leading transparency around product data and security practices[2]. Leading also requires that we release this annual report outlining our efficacy and our approach to ensuring safety for LUCI and wheelchair users everywhere.

Riders' capabilities, needs, wants and desires vary widely, and all are important to us. We are taking on the challenge of creating a new norm for the industry. And we challenge others in the power mobility industry to join us in detailing their dedication to safety as smart technologies inevitably become the future of powered mobility.

THE CHALLENGE

Safety in the power wheelchair industry today is stuck in the past. The only real safety technology for wheelchair falls and collisions is a seatbelt. Many users we have talked to choose not to use the seatbelt so that they can better move away from their chair when it tips.

Based on our testing, the possibility for injury to a user in both collision and tip events can be extreme without LUCI.[3] In a head-on collision with a wall, a power wheelchair user experienced maximum forces in the femur that exceeded the limits prescribed in federal motor vehicle safety standards. Had these results for lower extremity injury been measured in a motor vehicle, that car would not be allowed to be sold in the United States. Similarly, in a tip-over event where a power wheelchair drove off a curb, the angular velocities seen on the user's head corresponded to a significant (30%) risk of mild to severe concussion including loss of consciousness for up to six hours. The fact is that...

A wheelchair, without LUCI, has a high likelihood of the collision and tipping hazards that LUCI mitigates.

No technology can avoid all accidents and dangerous situations; however, LUCI has proven that we can do better as an industry by using modern technology to reduce the risk of injury to wheelchair users.

[1]https://luci.com/smart/
[2]https://luci.com/data/
[3]https://luci.com/2020/09/power-wheelchair-qa-with-dr-matt-maltese-a-leading-expert-in-crashing-things/

Collision Avoidance

Starting this year (2022) twenty of the largest automakers have agreed to equip all new vehicles with automated emergency braking (AEB). In addition to AEB, there are many options for collision avoidance, automation, and safety in the automotive market ranging from Cadillac Super Cruise to the pedestrian crash prevention technologies on a Nissan Altima. These technologies are active, amazing, and helpful. Any life saved or collision avoided is considered a major victory, but they are far from perfect. In fact, pedestrian crash prevention systems may only be effective about 40% of the time[4] and automated emergency braking systems are almost completely ineffective outside of extremely controlled scenarios.[5] The required level of performance for these systems has been developed and agreed upon by regulatory bodies, and car manufacturers have little incentive to push for higher levels of safety because consumers have consistently complained at any false-positive braking events by the car.[5] So balancing more effective, active collision avoidance against the annoyance of false positives that stop the vehicle is a challenge. However...

The automotive industry has proven that active intervention is key for safety.

Passive collision avoidance systems such as backup cameras and beeper systems aren't enough for effective safety in cars otherwise automotive manufacturers would have stopped at backup cameras long ago. Backup cameras are convenient, but the automotive industry has known for years that they aren't very effective at actually preventing accidents. The most positive results for backup camera effectiveness showed a 16-percent reduction in collisions between cars with and without backup cameras.[6] However, according to the National Highway Traffic Safety Administration (NHTSA) over a three-year period, from 2008 to 2011 when backup cameras in vehicles went from 32 to 68-percent, back-up injuries decreased by less than 8-percent.[7] These same studies found an inconclusive or non-existent impact of beeper warning systems on actual collision avoidance.[8] Attempts to use beeper warning systems with wheelchairs, which have been available in the market for over a decade,[9] have found similar limitations with users and clinicians reporting a lack of perceived effectiveness and general annoyance.

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https://newsroom.aaa.com/2019/10/aaa-warns-pedestrian-detection-systems-dont-work-when-needed-most/
https://www.caranddriver.com/features/a24511826/safety-features-automatic-braking-system-tested-explained/
https://www.iihs.org/news/detail/rearview-cameras-reduce-police-reported-backing-crashes
https://www.latimes.com/business/la-fi-hy-back-up-cameras-20160617-snap-story.html
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https://www.asl-inc.com/products/product_detail.php?prod=42

In many ways, applying collision avoidance technology to power wheelchairs is more complex than in the automotive field. Some of the major challenges of effective collision avoidance in power wheelchairs include:

- The boundaries of the vehicle are constantly changing as the seating system moves, legs elevate, the seat back reclines.
- There is no exterior surface, bumper, or roof to place sensors on, so you must place sensors around the user and design the system to look past the user's lower extremities. When the driver inevitably moves his/her foot or leg, the sensors may see 'the obstacle', which can lead to more false positive slowing events.
- Users need to maneuver in extremely tight places, often wanting to touch obstacles with the wheelchair footrests or align the seat to another surface for a transfer, which makes it difficult to tell the difference between a desired contact and a non-desirable "collision."
- Unpredictable caster rotation (the "caster flip problem") can cause several centimeters of unexpected/uncontrolled movement at any moment when turning.
- The system must be able to rapidly decelerate the wheelchair:
  - Which can move at a high rate of speed (6+mph) relative to the proximity of surrounding objects.
  - Without throwing the user out of the seat or causing discomfort to users with poor trunk control. You can't assume there is a harness or seatbelt in use.
  - When the vehicle itself is inherently unstable under many conditions.
- Current motor controllers for power wheelchairs do not have encoders and therefore do not provide accurate information about the movement of the wheelchair. When the wheelchair doesn't know what it is doing accurately it is hard to take any precision action.[10]

All these challenges make the physics modeling of the wheelchair challenging. In addition, the question "what are standard collision obstacles?", has not been defined in any wheelchair test methods until now.

For wheelchairs there are an infinite number of possible collision objects and scenarios out there. While the challenge is difficult, life in a power wheelchair is a life of bumps and bruises and even collisions. Every collision avoided is one less injury, one less repair, or one less stressful situation.

[10]Current wheelchair "tracking" technology is an attempt to correct for this so that a wheelchair drives straight ahead when the joystick is pointed straight ahead. On most other devices this is assumed behavior instead of an option.


LUCI
LUCI

Drop-off Protection

Every power wheelchair manufacturer publishes a safe step threshold for their wheelchair. This safe step limit is typically in the range of 2-3.5 inches but varies by wheelchair make and model and represents the drop-off that would likely cause the wheelchair to tip over. It is the best rule-of-thumb value based on ANSI/RESNA testing and is useful; but it is based on strict test methodologies in test lab conditions; not in real world driving. In the real world...

Physics tells us that there are an infinite number of combinations of seating assembly positions, accessories and attachments, user weight, user positioning, ground slopes, and drop-offs that could cause a power wheelchair to tip over.

In the future, intelligent seating assemblies will improve the safety of wheelchairs. But for now, since most current power wheelchairs on the market do not actively track the actual center of gravity of the chair, the safe step threshold is the best information we currently have to work with. By keeping a wheelchair from driving off steps larger than its safe step threshold (drop-off protection) many wheelchair injuries can be avoided.

LUCI has developed predictive drop-off protection, which is an active safety technology unique to wheelchairs. Predictive drop-off protection requires monitoring the slope the wheelchair is driving on and mapping the ground several meters around the chair to confirm it is safe. All the previously discussed challenges of developing safety technology for collision avoidance apply to drop-off protection, with the added challenges of:

- Unlike automobiles, wheelchairs go everywhere; there is no mapped road with a nice stripe down the middle and road signs.
- Many carpet patterns, tile patterns, surface textures and light to dark shadows mimic the look of an unsafe curb or edge.
- The clinical and industrial environment often use highly polished reflective flooring that can make detection of the ground difficult, due to glare..

While the challenge is difficult, tips and falls in power wheelchairs can be extremely dangerous. Every tip avoided is one less potentially catastrophic injury.

Challenge Accepted

These are tough problems, but LUCI's team is leading the way.

From a safety standpoint, LUCI introduces collision avoidance safety features that are simply expected on other motorized vehicles and is adding drop-off protection to the list of safety features that exist in the world. Our outside research found that a power wheelchair collision can create forces greater than those allowed by law in cars and can cause more trauma than an NFL helmet-to-helmet tackle.3 LUCI's collision avoidance protects riders while allowing them greater independence with fewer accidents and fewer costly chair and home repairs.

LUCI has changed the industry's discussions around innovation and safety and offers a platform for progress. Ultimately, we hope the experience and information LUCI provides leads to real improvements in riders' experience, health, independence, and quality of life.

SAFETY AS A PROCESS

As the first company to produce a Level 2 driver assistance system for wheelchair users, we are leading the way on safety in the industry.[1]

Current wheelchair standards are primarily written to deal with physical durability and electrical safety for the power base of the wheelchair. Meeting these defined minimums is important for the wheelchair industry, but safety at LUCI goes much further.

From the beginning, LUCI established our quality system, with documented practices that ensure safety is always considered in the development of our technology. We leaned on our experienced employees and advisors to take best practices from the medical device, automotive, and aerospace worlds to embed safety into how we work every day. Over time, these practices have evolved into the first comprehensive and robust system for evaluating wheelchair driver assistance devices.

It is impossible to develop a perfect collision avoidance or drop-off protection system that will work in all environments and all settings. However, our process includes identifying hazards to the wheelchair user and potential mitigations that can be implemented to reduce risks that are in line with ISO 14971 risk management for medical device best practices. These mitigations take various forms such as software or hardware requirements, hardware or software design elements, training, or disclosures. We use a variety of hazard identification methods such as Hazard Analysis and Design Failure Modes and Effects Analyses (DFMEA). This continuous process goes together with ongoing engineering and test activities to continually improve the capabilities of LUCI and increase user safety.

HOW LUCI WORKS

LUCI adds smart technology to an existing power wheelchair for stability, security, and connectivity. For LUCI to do the amazing things that it does, three elements must work together with the user:

1. The base wheelchair, as certified by the wheelchair manufacturer,
2. The LUCI hardware, and,
3. LuciCore software.

Each of these subsystems is then combined to form a LUCI enabled wheelchair. Individually and collectively testing the hardware and software ensures that our collision avoidance and drop-off protection system meets the safety requirements that we establish for our system.

The Base Wheelchair

LUCI's current generation of collision avoidance and drop-off protection systems mount to the power base of existing power wheelchair assemblies (PWA) made by Permobil, Quickie, and ROVI. These power wheelchairs have been certified by the manufacturer as compliant with all applicable ANSI/RESNA/ISO standards that regulate the safety performance requirements for wheelchairs in the US.

Every wheelchair manufacturer is required by ISO standards to meet a minimum braking distance from full speed. These distances are how long it takes the chair to come to a stop if the user is traveling on flat ground, recognizes an obstacle ahead, lets go of the joystick and waits for the chair to stop moving. It takes a wheelchair a lot longer to slow down than most people think!

This is what LUCI starts with.

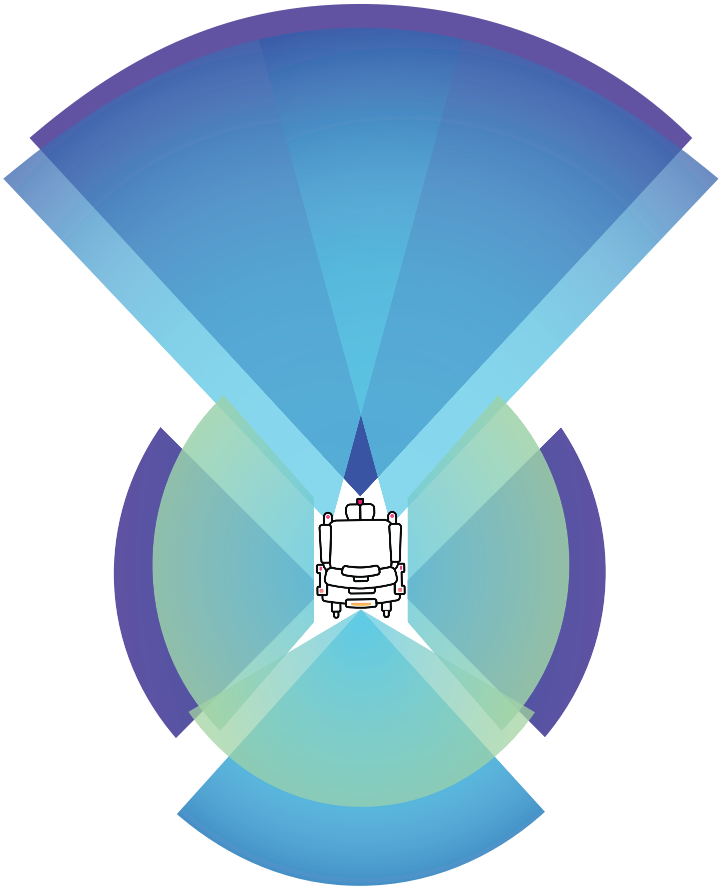
Chair Type	Model	Minimum Braking Distance[11]
Group III	Permobil M3, Permobil F3, Quickie Q300 M, Quickie Q500 M, Quickie Q700 M, ROVI X3	6.6 feet
Group IV	Permobil M5, Permobil F5	9.2 feet

[11] Obtained from manufacturer based on testing to ISO Standard 7176-3.

LUCI Hardware: SmartFrame, a System of Sensors and a Brain

LUCI is an accessory for specific power wheelchair models. LUCI interfaces with the existing power wheelchair and uses existing mounting locations on the wheelchair base. LUCI is intended for use in the home and/or community environments. LUCI consists of wheelchair mounted hardware (SmartFrame, Scout, Dashboard, and LuciLink Hub), LuciLink Wheelchair Key, and the MyLUCI App. LUCI is intended to be installed on a power wheelchair by a trained technician and proper installation and setup of the hardware is an important part of making LUCI safe.

After proper installation and setup, LUCI begins working as soon as the user turns the wheelchair on. It connects to the wheelchair's power system and assists the driver in maneuvering their environment safely. LUCI is suitable for continuous operation.



To meet the complex demands of collision avoidance and drop-off protection for power wheelchairs, LUCI has developed an array of sensors that provide 360-degree coverage, both in daytime and at night.

LUCI's patented system combines stereo vision, infrared projector, inertial measurement unit (IMU), ultrasonic and radar data into a single view of the world, enabling never-before-seen possibilities for power wheelchair riders. The sensor coverage is best illustrated from a bird's-eye view. In the image:

- **light blue** represents coverage by the stereo vision cameras,
- **purple** represents radar coverage and
- **green** represents ultrasonic sensor coverage.

One type of sensor isn't enough.[12] The combination of sensors, fused into one map of the world maximizes coverage and mitigates interference sources to give LUCI the best chance of avoiding the highest number of collisions and drop-offs possible.

We developed a cutting-edge mmWave radar and multiple custom ultrasonic sensors to keep users safe.

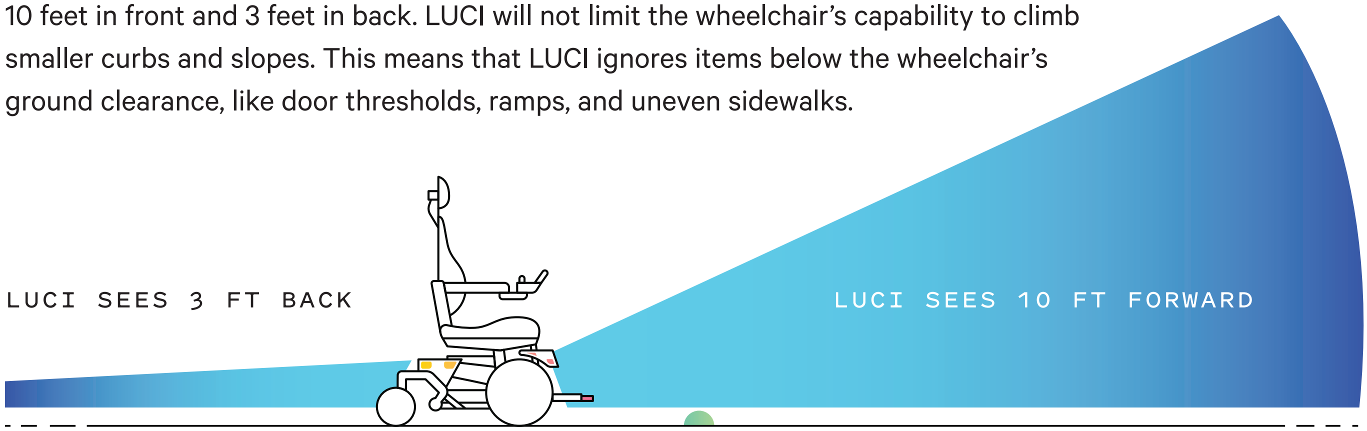
Sensor	Why it is cool
Stereo vision camera with infrared projector	These sensors perceive depth like your eyes do. They give LUCI a depth value to every pixel in the image. Thanks to the infrared projectors (which LUCI controls intelligently) LUCI can still see in the dark! LUCI uses these sensors to map the ground and look for potential collisions.
mmWave Radar	This was the first FCC-certified mmWave radar of its type used outside of military or automotive environments. Radar uses electromagnetic waves to perceive objects and movement. Radar remains effective in rain, fog, and operates equally well day or night. It is the size of a business card but can see things over 6-meters away!
Custom Ultrasonic	Our ultrasonic sensors see things that a typical ultrasonic sensor can't, and they do it in environments with other ultrasonic noise too.
IMU	LUCI's IMU modules use accelerometers and gyroscopes to figure out how the wheelchair is moving. Since current power wheelchairs don't really have modern control systems, we use our own IMU's to do amazing things anyway.

Collision Avoidance

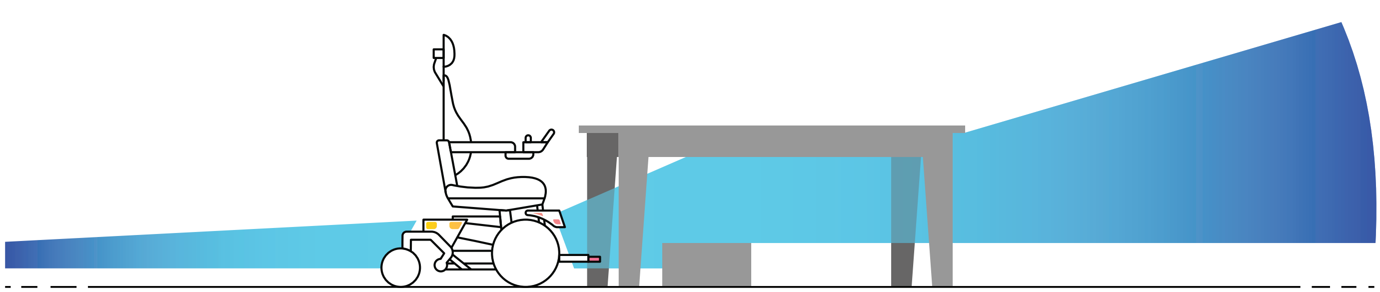
LUCI uses multiple types of sensors to identify and cross-check potential obstacles. The data from these sources is fused and analyzed to ensure the safety of the surroundings. LUCI obstacle detection has the following capabilities.

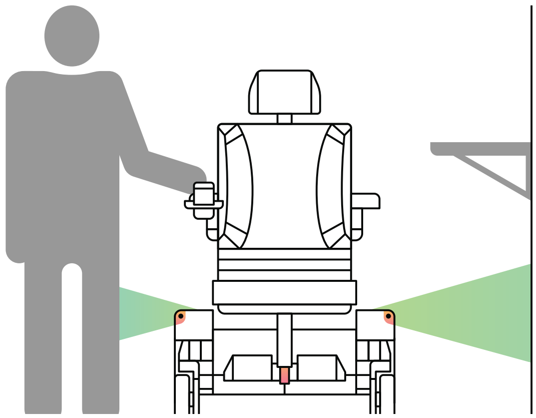
MINIMUM DETECTION RANGE	Objects closer than 3 cm (1.2 in) to the wheelchair may not be registered accurately	Measured from the edge of the wheelchair
MAXIMUM DETECTION RANGE	Forward: up to 4.5 m (14.8 ft) Backward: up to 1.2 m (3.9 ft) Sides: up to 1.3 m (4.2 ft)	Measured from the edge of the wheelchair
MINIMUM OBJECT DETECTION	Hard objects: 3 cm (1.2 in) Soft objects: 6 cm (2.4 in)	Measured as the cross section of the object facing the wheelchair
LIMITATIONS	Fast moving objects traveling across your path or directly at you may not be detected in time to be avoided. Objects smaller than the above minimums, such as cables, may not be detected by LUCI.	

Looking at LUCI's collision avoidance coverage from the side: LUCI can see more than 10 feet in front and 3 feet in back. LUCI will not limit the wheelchair's capability to climb smaller curbs and slopes. This means that LUCI ignores items below the wheelchair's ground clearance, like door thresholds, ramps, and uneven sidewalks.



LUCI's collision avoidance intentionally does not limit the chair navigation for obstacles above the power base of the chair. This allows LUCI to still pull into open spaces like tables or desks. However, if you want LUCI to stop your chair at the same spot under a table every time then you can place an object under the table (like a box).

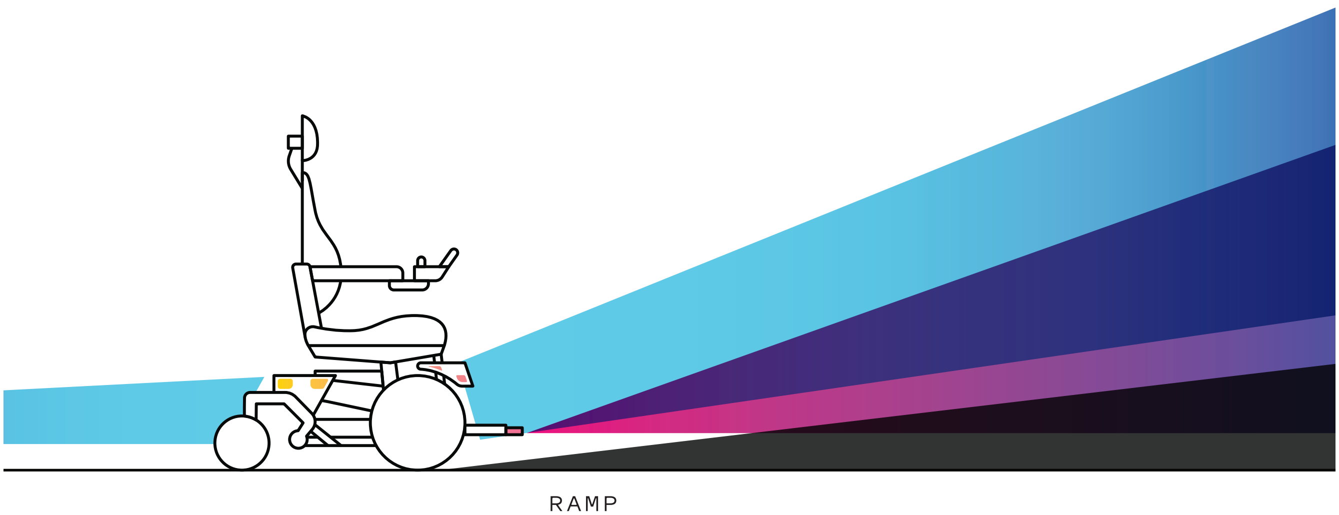




Side sensor coverage is like the front-back coverage. LUCI will see a person's leg but not their toes. LUCI will see a wall but not an overhanging object like a wall shelf, doorknob, or handrail. It is important to know that based on user feedback, LUCI is tuned to get close to things on the side, even sometimes lightly scraping the arm rest, depending on how wide the seating assembly is set.

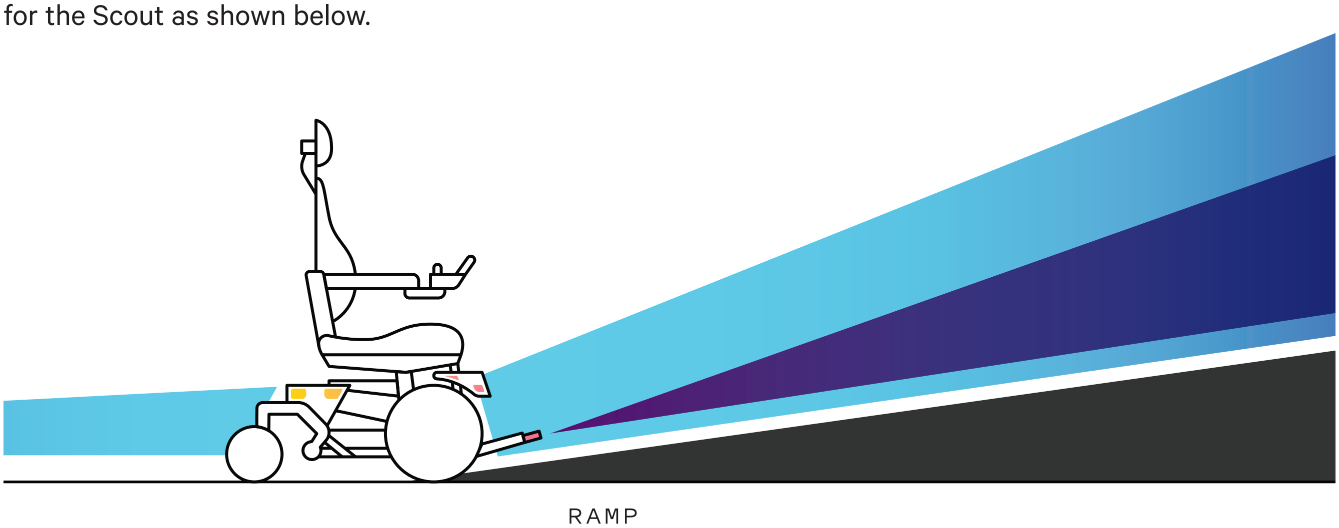
LUCI's front sensor coverage changes with the seating assembly position, specifically with the height and angle of the Scout. The Scout is LUCI's forward facing radar.

The fact that the Scout moves with the seating assembly is a good thing!

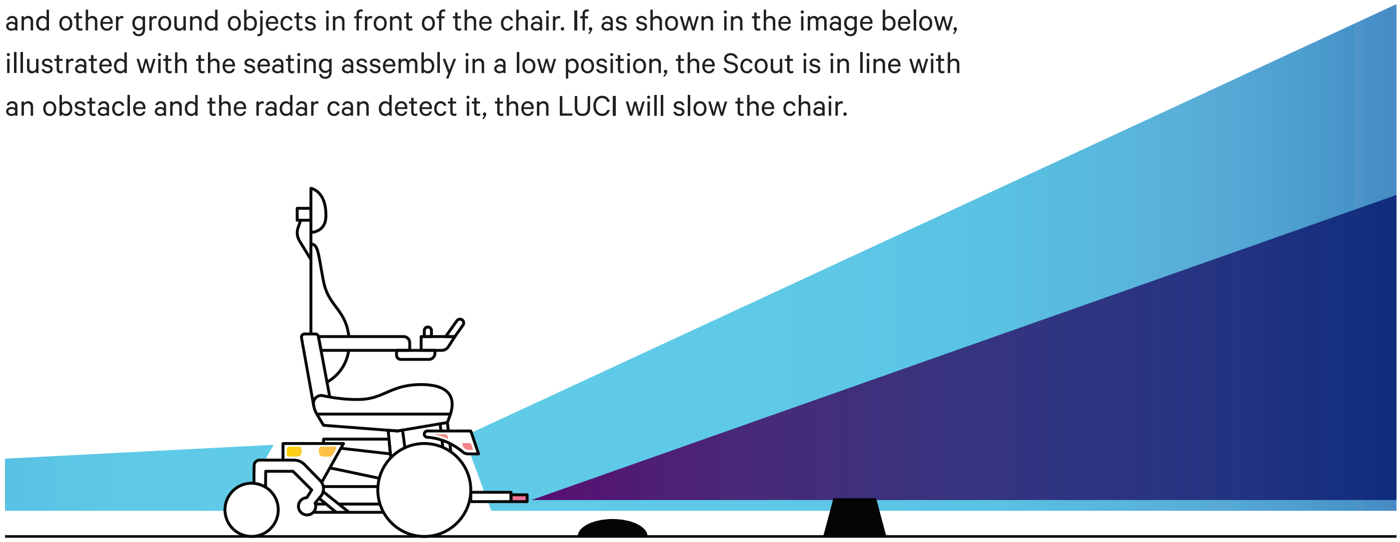


The picture above shows a wheelchair with the Scout low and pointed straight at a ramp. The blue indicates camera collision coverage; notice that it is limited so that LUCI's cameras won't see the ramp as an obstacle and stop you from going up it. The pink indicates the Scout collision coverage which may identify the ramp as an obstacle in some situations.

If you tilt the seating assembly or elevate the footrest, the ramp will no longer register as an obstacle for the Scout as shown below.

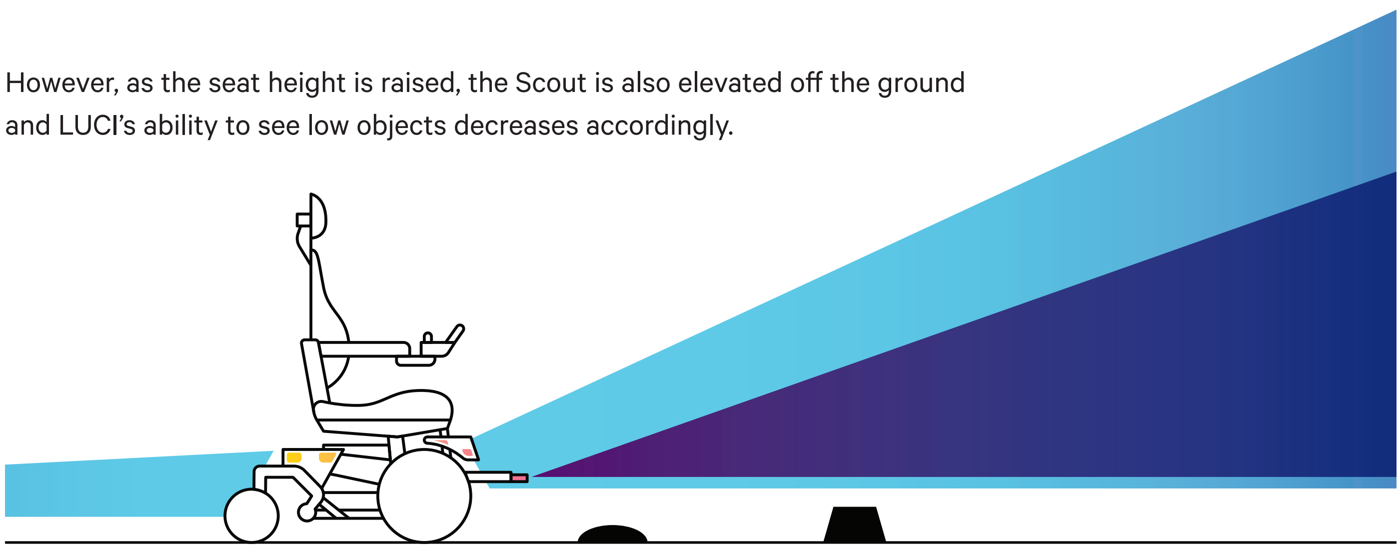


This same behavior impacts LUCI's ability to see speed bumps, parking blocks, and other ground objects in front of the chair. If, as shown in the image below, illustrated with the seating assembly in a low position, the Scout is in line with an obstacle and the radar can detect it, then LUCI will slow the chair.



SPEED BUMP PARKING BLOCK

However, as the seat height is raised, the Scout is also elevated off the ground and LUCI's ability to see low objects decreases accordingly.



SPEED BUMP PARKING BLOCK

LUCI's collision avoidance coverage is part of a driver assistance system. It is important to keep in mind several things when using LUCI:

- **LUCI's sensors are not only the best ones in the industry, they are best-in-class in any industry**; but just like all the sensors on cars, trains, and airplanes, that doesn't mean that they can see everything.
- Sloped ground and high speeds cause momentum that can prevent LUCI from coming to a complete stop before colliding with a detected object. Once LUCI detects anything, however, the driver will be 'assisted' in a response, by the slowing of the chair by LUCI.
- LUCI does not apply emergency braking, to prevent tipping the chair and/or throwing the occupant in an avoidance maneuver.
- A power chair, like all motorized vehicles should be operated with an awareness of the dangers in the environments of use.
- LUCI is not a replacement for wheelchair skills training.

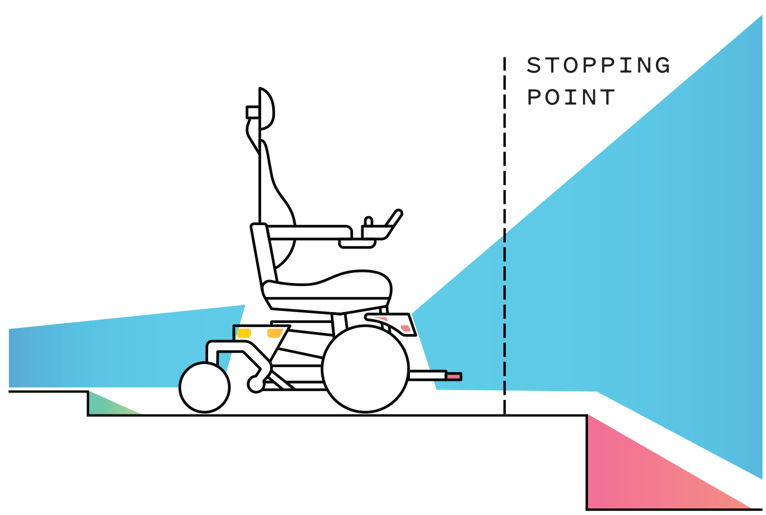
Drop-off Protection

LUCI helps the user manage the stability of the wheelchair by monitoring ground features, including the slope of the ground and ramps as well as drop-offs such as curbs and steps.

MINIMUM DETECTION RANGE	Objects closer than 3 cm (1.2 in) to the wheelchair may not be registered accurately	Measured from the edge of the wheelchair
MAXIMUM DETECTION RANGE	Forward: up to 4.5 m (14.8 ft) Backward: up to 1.2 m (3.9 ft) Sides: up to 1.3 m (4.2 ft)	Measured from the edge of the wheelchair
STEP DETECTION	LUCI will detect steps with a height greater than the wheelchair's published step threshold	See the wheelchair user manual for the published step threshold
SLOPE DETECTION	LUCI will detect slopes with an angle greater than the wheelchair's published slope threshold	See the wheelchair user manual for the published slope threshold
LIMITATIONS	Conditions that may challenge the sensors are sudden changes in light level and extremely rough terrain. Mud, snow, water, sand and other soft surfaces may be incorrectly detected as rigid and/or safe surfaces.	

LUCI's edge detection attempts to prevent users from driving off a curb, stairs, or other drop-off that would cause the wheelchair to tip over based on the published curb capability of the base wheelchair. LUCI will allow users to drive down small steps (~2-4inches for most wheelchairs depending on make and model) which are within the chair's specified capability but will monitor for dangerous curbs and steps.

Drop-off protection is like emergency braking, pedestrian detection, or air bags in an automobile – please don't test it on purpose! If you drive at high-speed settings toward an unsafe drop-off, LUCI may not be able to overcome the momentum of the chair to bring the chair to a complete stop in time. Just like with collision avoidance, once LUCI detects a drop-off, LUCI will slow the chair; assisting the driver to be aware that there is a drop-off ahead.



LUCI's drop-off protection coverage has been proven to work very well for users, but it is important to keep in mind several things when using LUCI:

- **LUCI's sensors are not only the only ones in the industry, they are best-in-class in any industry;** but just like all the sensors on cars, trains, and airplanes, that doesn't mean that they can see everything.
- Sloped ground and high speeds cause momentum that can prevent LUCI from coming to a complete stop before falling off a detected drop-off. Once LUCI detects anything, however, the driver will be 'assisted' in a response, by the slowing of the chair by LUCI.
- LUCI does not apply emergency braking, in order to avoid tipping the chair and/or throwing the occupant out of the chair in an avoidance maneuver.
- A power chair, like all motorized vehicles should be operated with an awareness of the dangers in the environments of use.
- LUCI is not a replacement for wheelchair skills training.

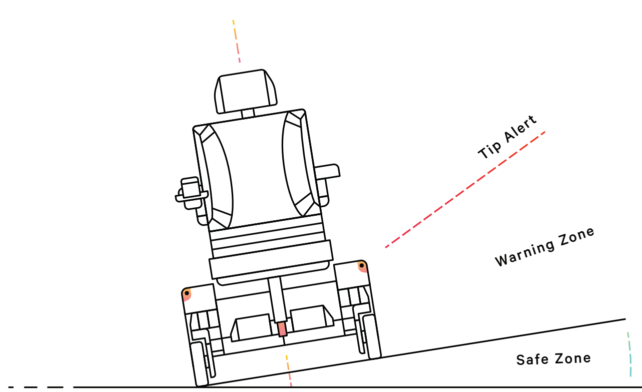
Ground Confidence

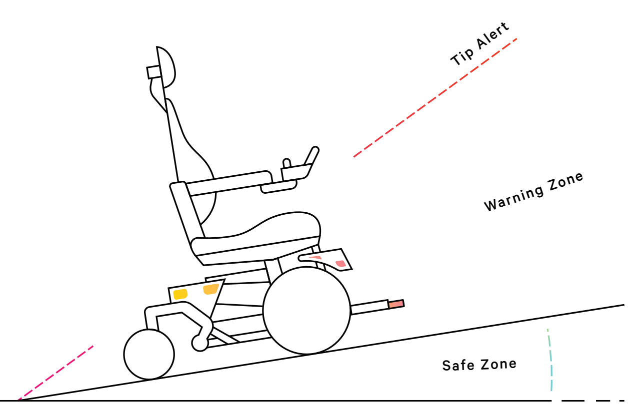
LUCI's ground confidence algorithm adds an extra layer of protection to keep users safe while driving on uneven terrain. **The ground confidence system checks ground data at approximately 2 meters from the chair and if the ground can't be clearly made out it slows down the chair to a walking speed.**

This slowing gives LUCI's drop-off protection system more time to react if it turns out that there is unsafe ground ahead. The speed allowed when ground confidence is triggered was selected so that the chair can still effectively maneuver in situations where shiny floors or other false positives might cause unreliable ground data. As with all LUCI's features, the goal of ground confidence is to provide users feedback and the time they need to navigate their environment safely, successfully.

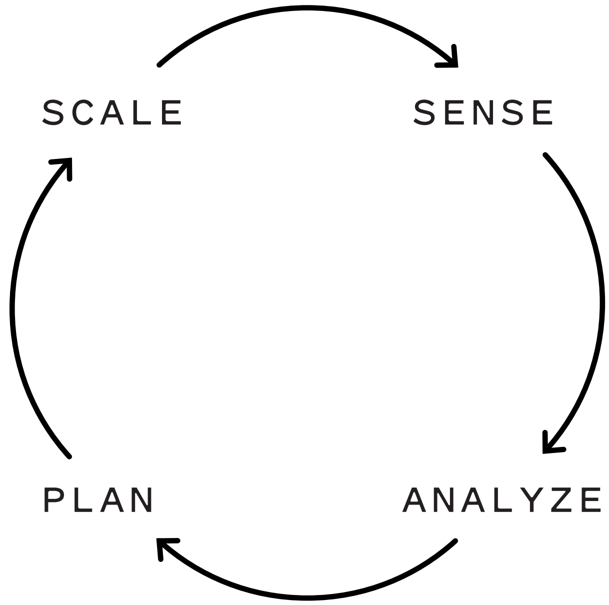
Tip Protection

The wheelchair's actual tip limit may be different from the manufacturer's published limit due to seating assembly position, user positioning, user weight, attachments on the chair like backpacks, etc., or ground conditions. To help mitigate the effect of ground conditions, LUCI includes tip protection warnings to alert the user if they are driving on unsafe slopes. LUCI uses onboard IMU's to notify the user with an audible warning beep and flashing light on the dashboard if the wheelchair is on a slope that is greater than the maximum recommended slope for the wheelchair based on the wheelchair manufacturer's recommendations. As the slope becomes steeper the beeping becomes more insistent.





LuciCore Software: Plan and Scale



LUCI's goal is not autonomy, it is driver assistance that leads to increased independence. LuciCore is our software, the brain, that makes everything LUCI does possible.

LUCI's processing involves receiving massive amounts of asynchronous data from our sensor system. Data from our **Sensors** arrives anywhere from 12 times per second to 100 times per second depending on the sensor type. Our software then **Analyzes** the surroundings and **Plans**, using user input, for what needs to be done. Finally, LUCI **Scales** the user input to slow the chair if an obstacle or drop-off is detected in the direction the user wants to go.

Throughout this whole process **LUCI never adds to the joystick input of the user, it only reduces the input to the system.** This entire decision-making loop is repeated 10 times per second to keep users safe. Which means...

LUCI takes action to avoid collisions, drop-offs, and potential injuries 10 times per second, which is two times faster than a human can.

OVERRIDE IS A FEATURE

To catch as many unsafe conditions as possible, LUCI is tuned to be cautious which will lead inevitably to some situations where the user would like to continue moving in a direction LUCI is stopping movement. LUCI users always have the option to reject the assistance offered by LUCI and move in any direction they desire. This feature is called Override and it's available at the push of a button.

Override is a LUCI feature that should be used!

Sometimes users need to push things open with their footplate. Sometimes they need to pull in and touch the dashboard when they get in their van, sometimes they want to jam the chair up against something for transfer. In all these situations LUCI is going to stop the user short and it's ok to use override. The Dashboard, typically located just above the joystick on the wheelchair control panel includes a LUCI Button, which can be used to temporarily override LUCI. This button should only be pressed in situations when LUCI sees a danger that the user knows to be false, allowing them time stop, consider the situation and then to navigate without LUCI's assistance. When this button is pressed, the blue light will blink for 25 seconds, or until the button is pressed again. During this time, LUCI is temporarily disengaged, and users should take extra precautions to ensure their personal safety.

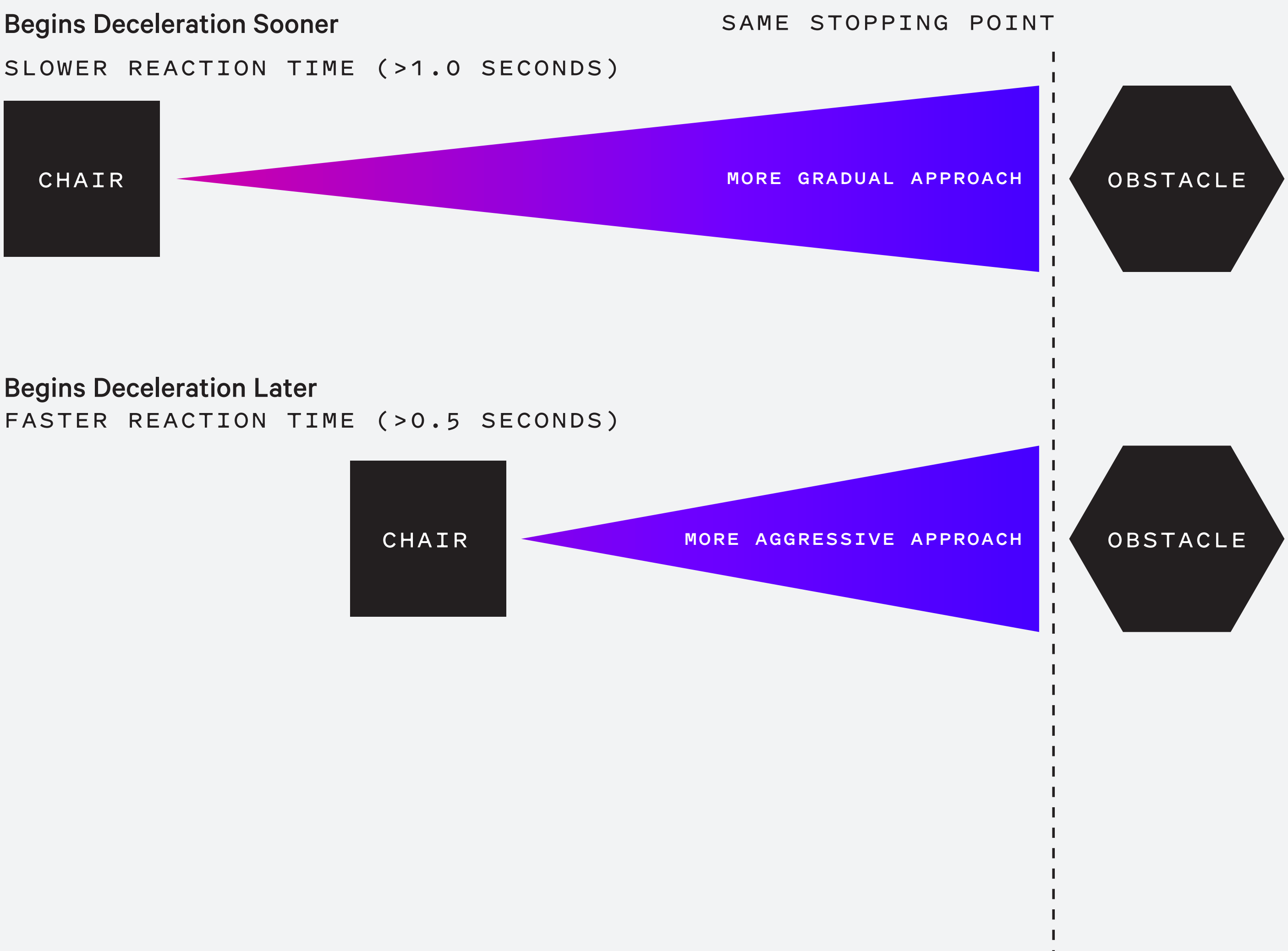
Override can be personalized to meet each user's individual needs in software and by installation. In the LUCI Setup Tool, the allowable wheelchair speed during override can be adjusted to the users' comfort level and capabilities. In addition, override can be completely disabled if desired. In addition, the Dashboard can be mounted in multiple locations to meet the needs of a user and an auxiliary switch plugged into the port on top of the Dashboard can be used to trigger override which provides additional options for safe, effective use of the override feature.

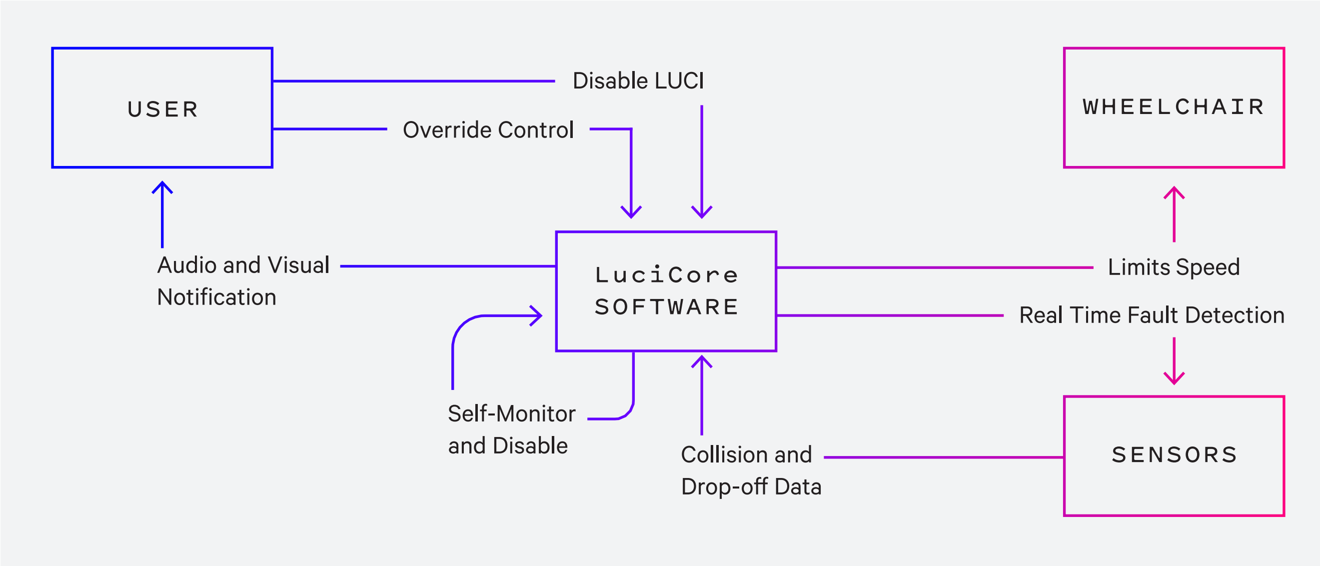
KEEPING THE HUMAN IN THE LOOP

LUCI provides wheelchair drivers the time they need to successfully navigate their environment independently.

To accomplish this, LUCI's calculations incorporate the user's reaction time in the hope that LUCI won't need to completely stop motion of the wheelchair. When LUCI is working best for a user, it is assisting them to drive safely and smoothly in situations they might not otherwise be able to navigate successfully by keeping the world within their ability to react to it. A user with a faster reaction time will find that LUCI speeds up and slows down more rapidly than it does for a user with a longer reaction time. LUCI is particularly suited to users with longer reaction times, but no matter what, LuciCore keeps the human in the loop.

A user's reaction time tends to remain relatively consistent day-to-day, but many LUCI users struggle with spasticity, poor muscle tone, vision deficits, or other intermittent issues with focus or motor control. These can cause driving in one part of the day to be safe and effective and driving in other conditions or times to be a real challenge. LUCI's human in the loop processing listens to the user and helps correct driving errors that could cause collisions and injuries leading to safer, more effective driving for longer periods of time and in more conditions.





LUCI IS "FAIL SAFE"

LuciCore software has been written from the ground up to keep users safe and keep them moving. LUCI uses a multi-tiered architecture to monitor and react to any failures in a safe way.

If the green or yellow LUCI Status light is on, the user can be confident that LUCI is monitoring the environment. LUCI actively monitors the onboard sensors for faults. If LUCI detects that sensor data is corrupt or missing, it safely stops the chair and notifies the user with both audio and visual indicators.

LUCI controls the wheelchair speed at the most fundamental levels of hardware and software using a real-time system. If this system detects issues in the LuciCore collision or drop-off protection systems, it will safely bring the wheelchair to a stop. At this point, if a user wants to continue 'unassisted' then LUCI can be turned off and the chair will continue to operate.

In either of the above scenarios, LUCI mitigates risk and brings the wheelchair to a stop safely in the event of a system failure. LUCI then mitigates leaving the user stranded.

- If a sensor on LUCI stops working, the user can press the LUCI button on the Dashboard to activate override and continue driving. Restarting the wheelchair will typically allow LUCI's self-recovery to fix sensor errors.
- If restarting the wheelchair doesn't fix the issue, then the user can use the Setup Tool or MyLUCI app to disable LUCI for a longer period until LUCI can be serviced.

LuciCore uses onboard hardware and software to monitor operation and status of LUCI. If this low-level firmware detects that a core component has failed or LUCI is not correctly operating it disables LUCI automatically to allow the wheelchair to operate without LUCI, but at a reduced speed. Failsafe mechanisms in LUCI ensure that if LUCI is not active, the LUCI light and system status light on the dashboard will not be illuminated so that the user knows they are operating without LUCI. Furthermore, if LUCI's computer experiences a catastrophic failure, there is an automatic switch that closes, enabling the wheelchair to be driven until LUCI can be serviced.

In all cases, the worst failure of LUCI leaves the user with a wheelchair no more dangerous than a wheelchair without LUCI.

TESTING AND VALIDATION METHODS

LUCI gives power wheelchair riders unparalleled stability, security and connectivity through cloud-connected software and hardware mounted between the seat and base of their current chair.

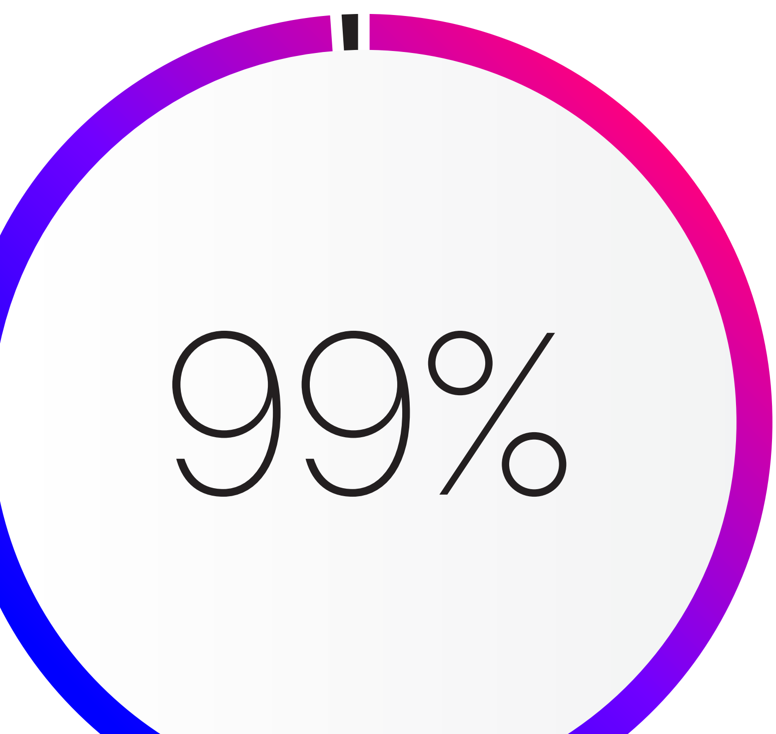
As an accessory to a power wheelchair LUCI is an FDA Class I, exempt medical device and meets the associated requirements of the FDA and FCC. In addition, LUCI meets the applicable requirements of IEC 60601 for home use medical electrical equipment.

The essential performance of the system requires that LUCI not create unintended motion of the wheelchair and that LUCI alert the user to detected unsafe conditions. These basic safety requirements have been tested in a wide variety of environmental conditions, while exposed to extreme electromagnetic interference, and under multiple failure conditions of the base wheelchair and LUCI. We have had no known safety failures of LUCI.

LUCI's internal technology verification process involves completing over sixty analyses, simulations, tests, and reviews covering...well...everything.

LUCI tests at the module, subassembly, and final assembly level to prove that it is worthy of use by the wheelchair riders we know and love. While we could dive into the details of our IP54 water and dust protection testing, medical grade electromagnetic immunity, RESNA approved impact and durability testing, or use of third parties to review our architecture and risk assessment methodologies, it is more important to focus on the wheelchair collision avoidance and drop-off protection safety test standards that we have invented.

No system will ever prevent all collisions or tip events, but we have developed rigorous test protocols to evaluate LUCI. We are constantly working to find the perfect balance between an amazing user experience and the impossible bar of absolute safety. It is our sincere hope that by sharing these methods and results we can spark an honest discussion in the industry around user safety.



Drop-Off Protection Testing

Drop-off protection testing is performed on each wheelchair model. Each model is driven at a curb from various angles, at various speeds, and with different LUCI settings totaling more than 230 individual attempts to drop off the curb, per model of wheelchair.

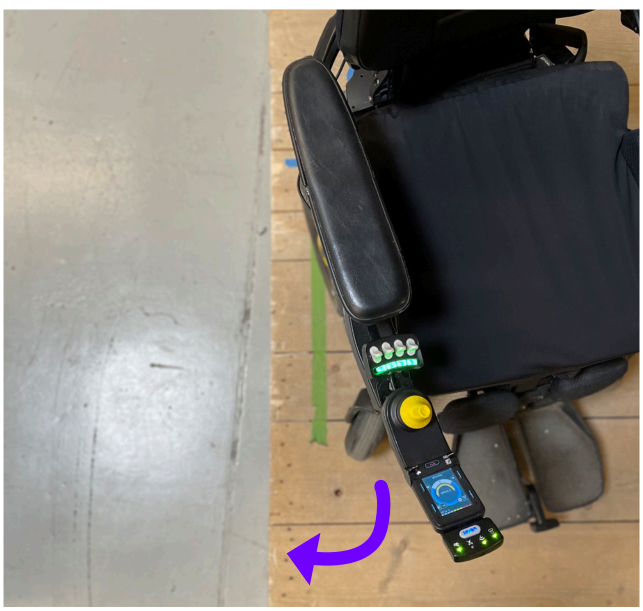
LUCI's drop-off protection is greater than 99% effective based on our curb drop-off protection testing.

THE PROCEDURE

The wheelchair is driven toward a standard height curb (15 cm, 90-degree edge), with varying speeds (ranging from 0.5 to 3.5 mph[13] for each model), three different reaction times, and various configurations of back and foot zone clearance (standard and extended). In all cases, factory default RNET settings for the model being tested are used.

Front and back drop-off is tested by driving directly at the curb from 12 to 18-feet away so that the wheelchair will be up to speed before slowing. The joystick is held at full speed the entire run.

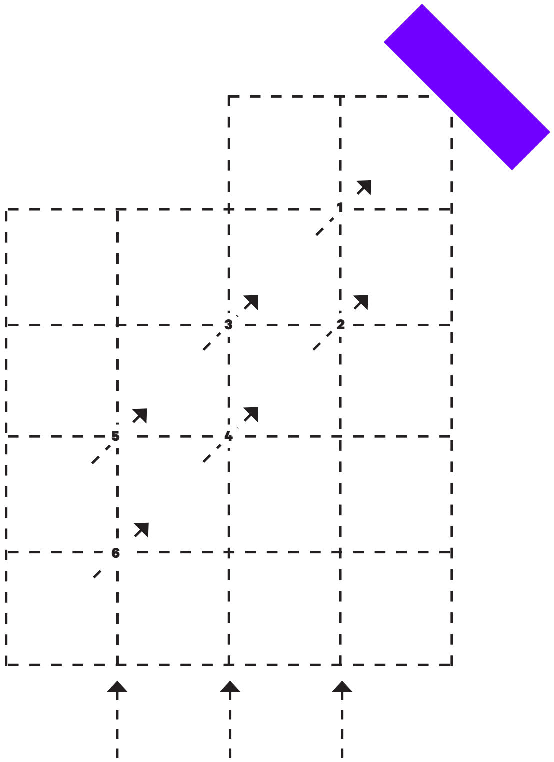
FRONT APPROACH



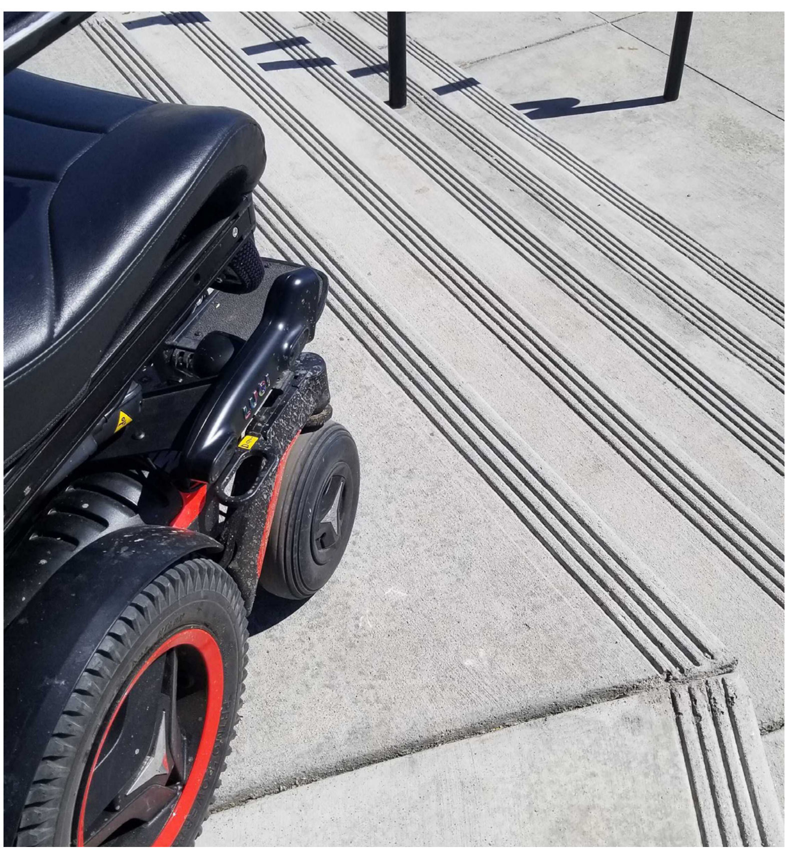
REAR APPROACH

Zero-point drop-off is tested by parking the wheelchair 20-25cm from the edge of the curb/drop-off with the wheelchair's right or left side aligned parallel to the drop-off. Then holding the joystick towards the curb to turn the chair towards it and attempt to turn the wheel/caster off the drop-off.

[13] This speed is approximately equivalent to outdoor or "normal" speed three on most chairs and represents an "average walking speed" for crowd travel on sidewalks.



Diagonal drop-off testing is done by driving forward at varying speeds and turning directly toward the curb at the last moment. The turn is initiated at varying distances, shown with the arrows on a 0.5m grid. The joystick is held full forward so the chair can get to speed, when the footplate of the chair goes over the correct arrow, the joystick is pointed at a 45-degree angle towards the curb and kept in that position until the chair slows to a stop.



The 3-step test is done by driving directly toward three (or more) steps.

The swish test is performed by continuing to hold the joystick towards the obstacle and then slowly "swishing" the joystick into a turn until the chair starts moving after the drop-off protection has already stopped the chair.

Drop-off protection is considered a failure if the wheelchair falls off the curb or if the wheelchair caster goes off the curb when the wheelchair comes to a stop. In most cases when there was a failure reported, a caster went off the curb slightly, resulting in the wheelchair being tilted or unable to get back up onto the step at worst. The wheelchair did not tip over completely in any of the tests.

Results are reported as a ratio of the number of tests passed to the total number of tests performed.

MODEL (LuciCore 1.4)	FRONT DROP-OFF	BACK DROP-OFF	ZPT DROP-OFF	DIAGONAL DROP-OFF	3-STEP TEST	SWISH TEST
100 - Permobil M3 (pre-2019)	24:24	30:30	54:54	36:36	3:3	82:84
100 - Permobil M3 (post-2019)	24:24	30:30	54:54	36:36	3:3	84:84
101 - Permobil F3	24:24	30:30	53:54	36:36	3:3	83:84
104 - Permobil M5	24:24	30:30	54:54	36:36	3:3	84:84
107 – Quickie Q500 M	24:24	30:30	54:54	36:36	3:3	84:84
108 – Quickie Q700 M	24:24	30:30	54:54	36:36	3:3	84:84
109 – Quickie Q300 M	24:24	30:30	54:54	36:36	3:3	84:84
111 – ROVI X3	24:24	30:30	54:54	36:36	3:3	84:84

Collision Avoidance Test

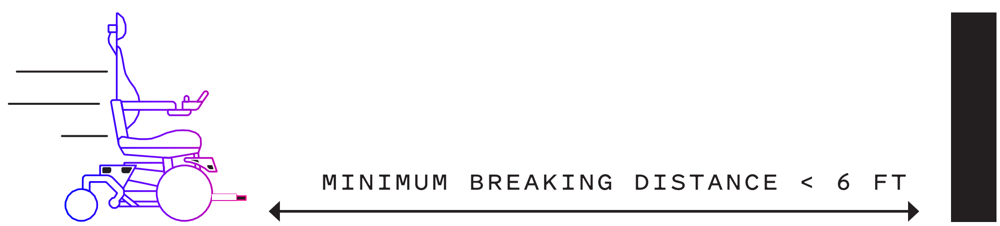
Collision avoidance testing is performed on each wheelchair model. Each model is driven at a target from various angles, at various speeds, and with different LUCI settings totaling more than 282 individual attempts to collide with obstacles per model of wheelchair.

LUCI's collision avoidance is 100% effective at slowing the chair before a collision with a detected stationary object and is approximately 97% effective at stopping the wheelchair completely before contact based on our test methods.

If LUCI stops the chair from colliding and then the user is allowed to aggressively attempt to hit the obstacle by moving the joystick around, we call this the swish test. Our data from the swish test shows, LUCI still manages to keep the chair from touching the obstacle in approximately 95% of cases. When there is a "collision" in this swish test case it is a minor caster scrape or toe drag on the obstacle that is unlikely to harm the user.

SENARIO A: WITHOUT LUCI

SENARIO B: WITH LUCI

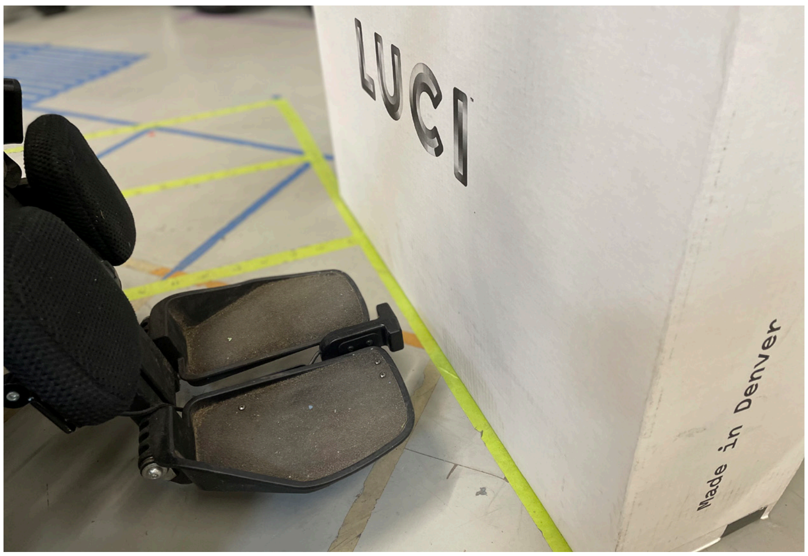


Let's compare the collision avoidance scenario for a power wheelchair user driving at top speed toward a detected target. In Scenario A, without LUCI, the user would need to identify the obstacle and let go of the joystick up to 9.2-feet from the obstacle, depending on wheelchair model, in order to avoid a collision based on published minimum braking distances of the wheelchair. Now looking at Scenario B, with LUCI, the same user driving at the same obstacle with the same initial speed could continue to hold full forward on the joystick while approaching the obstacle and would have a 100% chance of a lesser collision and a 97% chance that in spite of their reckless driving they would not even contact the obstacle! LUCI still takes time to slow the chair down smoothly to avoid launching the driver out of the chair (slowing a 300+ lb. object from 6 – 6.5 mph down to zero in less than 6 feet is a major deceleration). If you replace the reckless driver with a typical driver, then LUCI will slow the chair to a safe speed and give the user time to maneuver around the obstacle safely.

THE PROCEDURE

An obstacle is placed in an open space and the wheelchair is driven at the obstacle with combinations of three different speeds (slowest, medium and fastest for each model, which varies from 0.1 to 7.6 mph depending on model), three different reaction times, and various configurations of back and foot zone clearance (standard and extended). In all cases, factory default RNET settings are used. For the purposes of this report we'll use a LUCI box since it is easy for anyone with a LUCI unit to get.

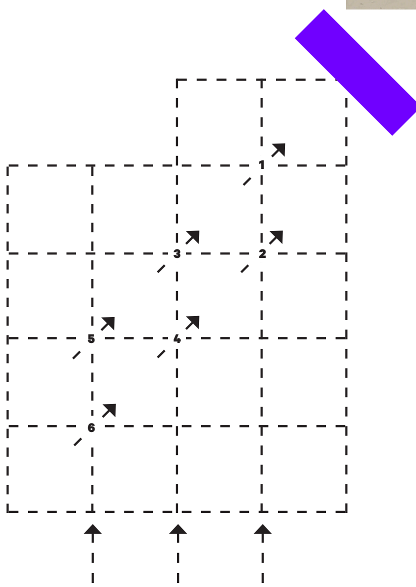
Front collision is tested by driving directly toward the obstacle after allowing the chair to reach maximum speed at the current speed setting. Back collision is tested by driving directly backwards toward the obstacle after allowing maximum speed to be reached.

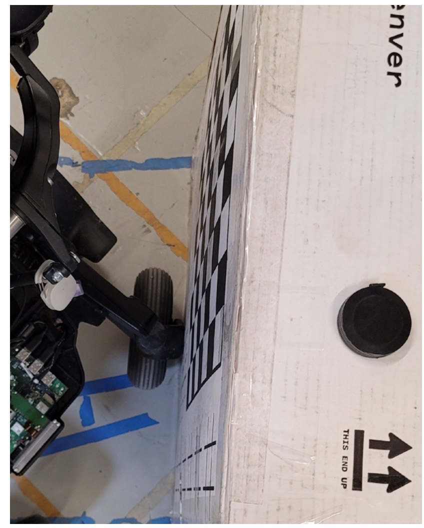


Zero-point collisions are tested by parking the wheelchair 20-25cm from the obstacle with the wheelchair's right or left side aligned parallel to the obstacle. Then holding the joystick towards the obstacle to turn the chair towards it and attempt to turn into it. In the reported results, the chair is first swung away from the obstacle and then turned back towards it to make the test more difficult.

Diagonal collisions are tested by driving forward at varying speeds and turning directly toward the obstacle at the last moment. The turn is initiated at varying distances, shown with the arrows on a 0.5m grid as shown below. The joystick is held full forward so the chair can get to speed, when the footplate of the chair goes over the correct arrow, the joystick is pointed at a 45-degree angle towards the obstacle and kept in that position until the chair slows to a stop.

The swish test is performed during select runs of the front, back, and zero-point collision tests by continuing to hold the joystick towards the obstacle and then slowly "swishing" the joystick into a turn until the chair starts moving after the collision protection has already stopped the chair.





In all collision test cases, the test is considered a "pass" if the wheelchair does not touch the obstacle. If the wheelchair does touch the obstacle, the test is considered a "fail." In most cases with a reported fail, the wheelchair slows and gently bumps the obstacle, which is considered a "fail" by our rigorous standards, although a gentle bump would, in most cases, not cause injury to the rider. The swish test is an attempt to intentionally scrape against the obstacle from a standstill; failures in this test are typically a caster or armrest scraping the obstacle, which in most cases would not cause injury to the user.

Results are reported as a ratio of the number of tests passed to the total number of tests performed.

MODEL (LuciCore 1.4)	FRONT COLLISION	BACK COLLISION	ZPT COLLISION	DIAGONAL COLLISION	SWISH TEST
100 - Permobil M3 (pre-2019)	39:39	47:48	85:87	49:54	41:54
100 - Permobil M3 (post-2019)	39:39	47:48	87:87	52:54	43:54
101 - Permobil F3	39:39	47:48	85:87	52:54	47:54
104 - Permobil M5	39:39	48:48	87:87	54:54	43:54
107 – Quickie Q500 M	39:39	48:48	86:87	54:54	54:54
108 – Quickie Q700 M	39:39	48:48	87:87	54:54	54:54
109 – Quickie Q300 M	39:39	48:48	87:87	51:54	54:54
111 – ROVI X3	39:39	48:48	87:87	53:54	51:54

LUCI In The Real World

LUCI achieves an incredible level of safety for the user in both collision avoidance and drop-off protection. However, most wheelchair riders aren't actively trying to drive off curbs and run into things on purpose like we do in the lab. Therefore, a large part of our testing is done in real-life situations just trying to drive around.

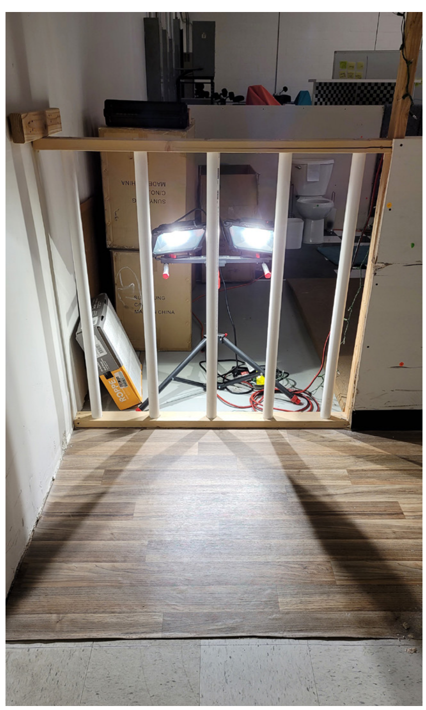
Real world testing is done in three main test courses: inside our mock home, outside the home in the community around our offices, and while entering/exiting accessible vehicles to go places for testing. In these tests, the wheelchair is driven at medium speeds typical of our users (~3.5 mph), standard reaction times, with standard back and foot zone configurations and factory default RNET settings. Because safety (collision and drop-off) testing is broken out into separate tests, this group of tests is looking for areas that LUCI causes you to use override when you wouldn't expect it to (a false positive). Because...

If LUCI isn't sure if a situation is safe, it will slow or stop the wheelchair out of an abundance of caution.

Don't worry though, that is what override is for. If you disagree with LUCI you win and it's ok to use override when you know it's safe. At the same time, it's our goal to make LUCI drive so well that you forget the override button exists! **LUCI currently has an approximately 5% false-positive rate that would cause an experienced user to have to use override when there is not a valid obstacle.**

THE PROCEDURE

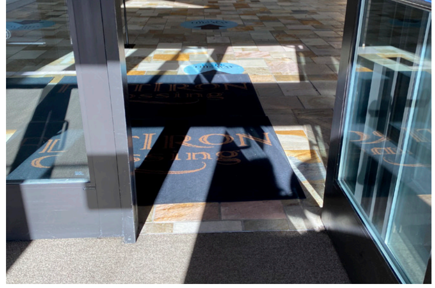
Inside the home testing includes driving down narrow hallways, through doorways at various angles, entering and exiting an elevator, pulling up to a kitchen cabinet, work bench and toilet, varying lighting conditions and flooring patterns, and slowing to avoid collisions with objects that pass across the wheelchair's path.



Outside the home testing is performed inside and outside a mall, including shiny floors, multiple elevators, navigating around clothing on racks, varying lighting conditions and floor patterns, driving up and down sloped sidewalks, curb cuts, and packed-dirt paths.

Accessible vehicle tests include driving both forward and backward, into and out of an accessible van. Note that false positives are only counted when driving into and out of the accessible van. The interior of an accessible van is too tight to allow the wheelchair to spin into position without pressing override on many of the models tested.

Results are reported as a ratio of the number of driving scenarios that were navigated without unexpected overrides, to the total number of scenarios tested. Decreasing false positives without impacting system safety is a major focus of the LUCI development team.



MODEL	INSIDE THE HOME	OUTSIDE THE HOME	ACCESSIBLE VEHICLE	ACCURACY
100 - Permobil M3 (pre-2019)	16:16	38:38	2:4	96.5%
100 - Permobil M3 (post-2019)	16:16	38:38	2:4	96.5%
101 - Permobil F3	16:16	36:38	2:4	93.1%
104 - Permobil M5	16:16	38:38	2:4	96.5%
107 – Quickie Q500 M	16:16	36:38	2:4	93.1%
108 – Quickie Q700 M	16:16	38:38	2:4	96.5%
109 – Quickie Q300 M	16:16	36:38	2:4	93.1%
111 – ROVI X3	16:16	38:38	2:4	96.5%

Listening To Users

We believe "The Bridge Must Stand" regarding technical testing of the product. However, it is critical that the users' voices are included too! That is why, when we developed LUCI, we included wheelchair users, caregivers, and clinicians in a two-stage, multi-year product validation phase before we even announced LUCI. This product validation led to a number of changes to our hardware, software and user interface. The basic flow of our pre-launch validation is shown below.

ALPHA PHASE →	GATE 1 →	BETA PHASE →	GATE 2
Alpha Mid Drive User Alpha Front Drive User Clinician Demos	No safety failures Evaluate basic function: Installation (VAL.1) Setup App (VAL.2) Home Operation (VAL.3) Observe additional functionality: Non-Home Operation (VAL.4) Cloud Communication (VAL.5) Maintenance (VAL.6)	Beta Mid Drive 1...n Beta Front Drive 1...n Clinic On-Site Demos/Trials	No safety failures User Trials Evaluate: Home Operation (VAL.3) Non-Home Operation (VAL.4) Cloud Communication (VAL.5) Maintenance (VAL.6) Clinic Demos/Trials Evaluate: Installation (VAL.1) Setup App (VAL.2) Non-Home Operation (VAL.4) ↓ VALIDATION RESULTS REVIEW

This process of working with users and clinicians continues today. LUCI maintains an active program to give select users early access to future features we are exploring so they can provide us with feedback. In addition, our customer experience team is listening and feeding user feedback from the field to our developers constantly. We are always listening and improving. While we have the mandatory processes in place for receiving reports and addressing corrective and preventative action based on field reports, at LUCI we are using technology to go beyond basic compliance in two important ways.

LUCI's telemetry system collects and analyzes anonymous log data from all connected, deployed safety systems so LUCI can monitor fleet health, capture fleet-wide trends, and act on possible issues. The anonymized fleet-wide data aggregation allows us to evaluate the performance of the LUCI fleet in pseudo real time to inform future product changes. Our telemetry also allows LUCI to diagnose errors on individual safety systems. This allows us to intervene quickly, even before a user notifies us of a problem in some cases.

Every LUCI user can help us with this process of continuous improvement by pressing the LUCI button on their Dashboard five times fast when they encounter a situation with LUCI that they don't like. When you press the button on your unit five times fast, an anonymous packet of sensor data is sent to the engineering team at LUCI to analyze and used to improve the product.

All of this feedback and data, gets turned into new software releases that are pushed over-the-air to LUCI and make it consistently better for every user.

CONCLUSION

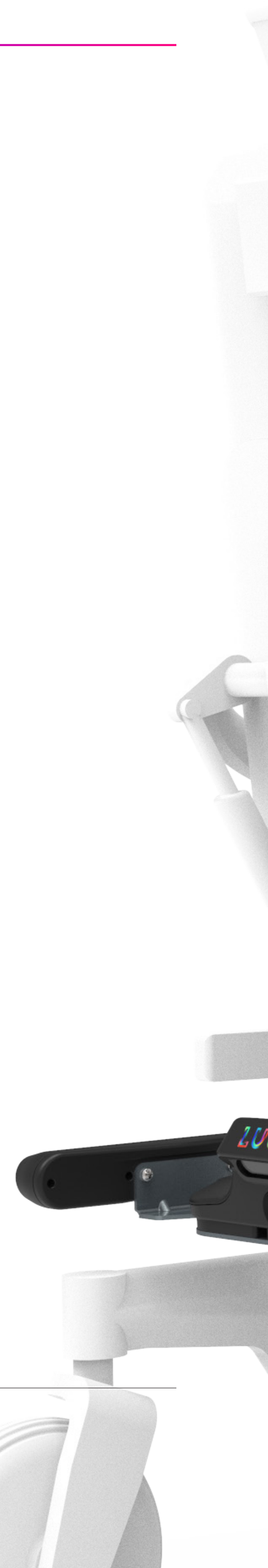
Since 2018, LUCI has been working on bringing modern technology and safety to power wheelchair riders. We are committed to safety, by process, by design, by testing, and by engagement with wheelchair users and clinicians. At LUCI we have a culture that puts safety first and we are committed to openly communicating about where we are with our technology.

In the time it took you to read this report LUCI prevented approximately 115 potential injuries and repairs.[14]

We are leading the industry in safety:

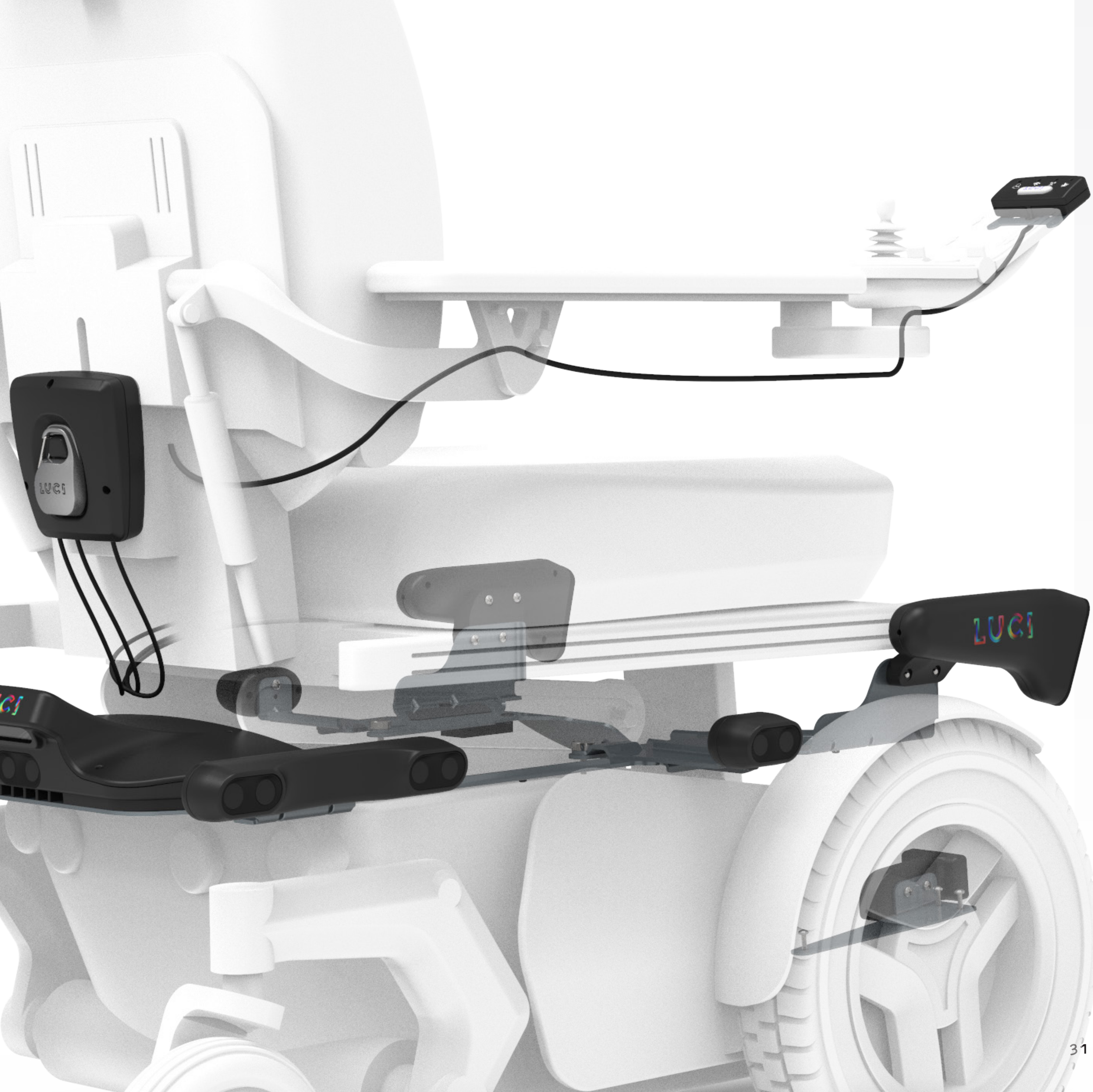
- LUCI's drop-off protection is greater than 99% effective based on our published curb drop-off protection testing methods.
- LUCI's collision avoidance is 100% effective at slowing the chair before a collision with a detected stationary object and is approximately 97% effective at stopping the wheelchair completely before contact based on our published test methods.
- LUCI currently has an approximately 5% false-positive rate that would cause an experienced user to have to use override when there is not a valid obstacle.

We are committed to reimagining mobility for the wheelchair users we know and love. This report summarizes our continuing efforts to ensure the safety of our product and is meant to spark conversations in the industry about how safety should be defined and discussed. We hope that RESNA and the International Wheelchair Standards community will begin to work with us on new and critical standards for safety as wheelchairs enter the modern world.



[14] We're making lots of assumptions here about how fast you read and what time of day you are reading this at, but you get the idea.

LUCI is proven, effective technology providing security, stability, and connectivity for power wheelchair users nationwide.



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