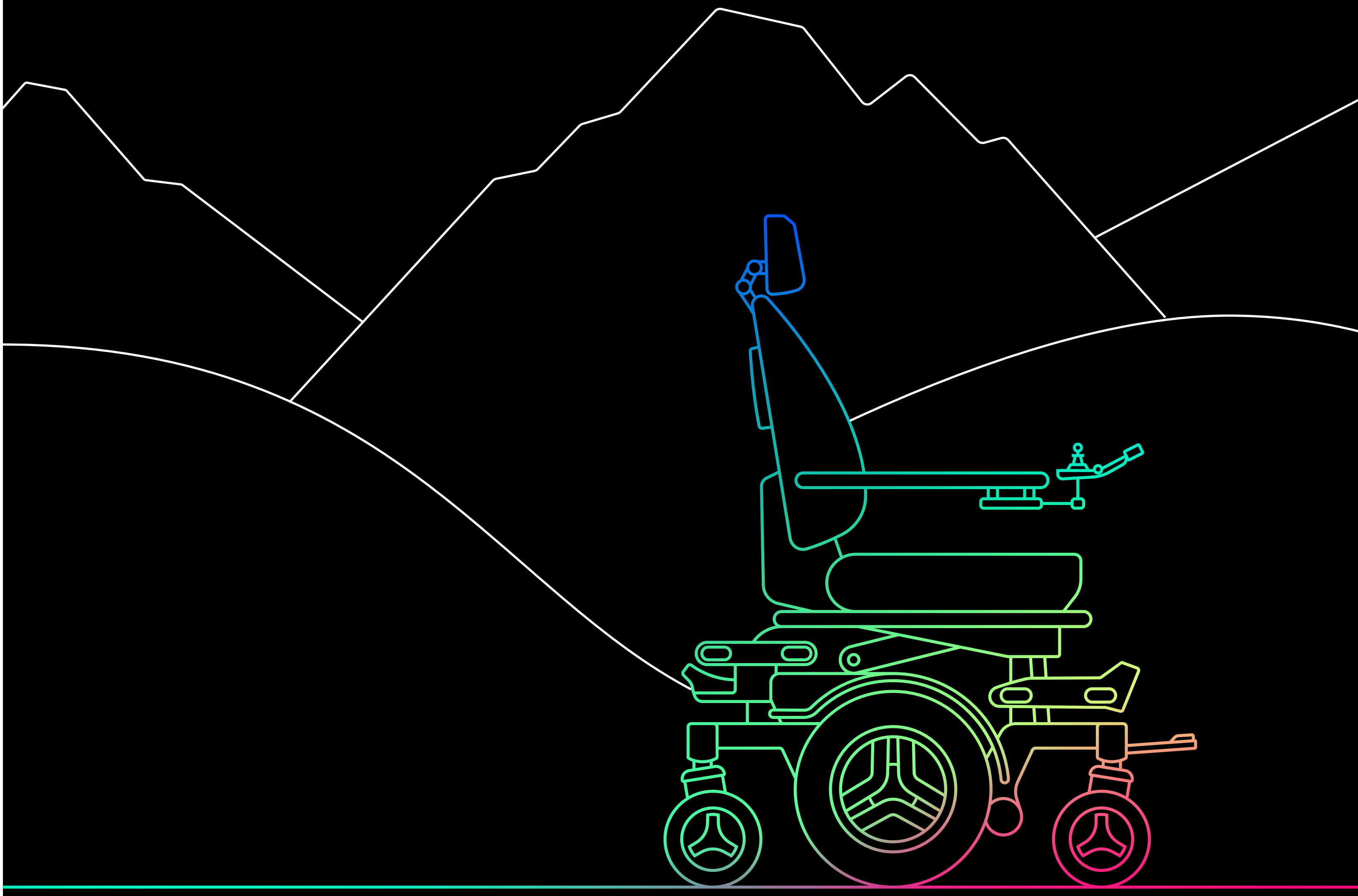
LUCI®

Safety Report

2021



INTRODUCTION

At LUCI, user safety and independence are at the heart of everything we do.

We have invented the first driver assistance system for power wheelchairs and in doing so have had to invent the safety practices for the industry, as well. LUCI's technology has over 40,000 hours of in-chair 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 technology is safe:

- LUCI's drop-off protection is greater than 99% effective based on our curb drop-off protection testing.
- LUCI's collision avoidance is 100% effective at slowing the chair before a collision with a stationary object and is approximately 95% effective at stopping the wheelchair completely before contact based on our test methods.
- LUCI currently has an approximately 4% false-positive rate that would cause an experienced user to have to use override when there is not a valid obstacle.

This report provides an overview of our processes for the safe testing and deployment of this technology, and the work we are doing to make LUCI safe and easy to use.

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 new and small, but we believe in leading. To this end we've already released Judging Smart[1], a framework for thinking about what "smart" should mean in power mobility products. Now, leading requires that we release this report outlining 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 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.[2] 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 believes that we can do better as an industry by using modern technology to reduce the risk of injury to wheelchair users.

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

Collision Avoidance

Starting next 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 a huge number of options for collision avoidance, automation, and safety in the automotive market ranging from Tesla's AutoPilot to the pedestrian crash prevention technologies on a Nissan Altima. These technologies are amazing, and helpful. Any life saved or collision avoided is considered a positive, but they are far from perfect. In fact, pedestrian crash prevention systems may only be effective about 40% of the time[3] and automated emergency braking systems are almost completely ineffective outside of extremely controlled scenarios.[4] 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]

The automotive industry has shown that balancing more effective collision avoidance against the annoyance of false positives that stop the vehicle is a challenge.

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

- There is no exterior surface 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 sensor may see 'the obstacle', which leads to more false positive slowing events.
- The boundaries of the vehicle are constantly changing as the seating system moves, legs elevate, the seat back reclines.
- 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."
- 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.

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[3] https://newsroom.aaa.com/2019/10/aaa-warns-pedestrian-detection-systems-dont-work-when-needed-most/
[4] https://www.caranddriver.com/features/a24511826/safety-features-automatic-braking-system-tested-explained/

- Uncontrolled caster stem rotation (the “caster flip problem”) can cause several centimeters of unexpected/uncontrolled movement at any moment when turning.

All these challenges, plus the fact that wheelchairs can pivot around their center (zero-point-turn) makes the physics modeling of the wheelchair challenging. In addition, the question “what are standard collision obstacles?”, as not been defined in any wheelchair test methods.

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 interaction with the world.

Drop-off Protection

Every power wheelchair manufacturer publishes a safe step threshold for their chair. This safe step limit is typically in the range of 3-3.5 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 position, accessories and attachments, user weight, 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. 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 have to work with.

Predictive drop-off protection is something that is unique to the world of power wheelchairs and LUCI is leading the way in developing a solution. 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 uses 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 damaging. Every tip avoided is one less, potentially catastrophic injury.

Challenge Accepted

It's a tough problem, 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 should 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.[2] LUCI's collision avoidance protects riders while allowing them greater independence with fewer accidents and fewer costly chair repairs.

LUCI changes the industry's current discussions around innovation and safety and offers a platform for progress. Ultimately, we hope the experience and information LUCI provides will lead to real improvements in riders' experience, health, 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 continued to evolve into the first comprehensive and robust system for evaluating wheelchair driver assistance devices.

It is, unfortunately, 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 recommendations, training recommendations, or disclosures. We use a variety of hazard identification methods such as Risk Assessment and Design Failure Modes and Effects Analyses (DFMEA). This continuous process goes hand-in-hand 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, specifically, the Permobil M3/M5 and F3/F5 series of wheelchairs. 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 publish 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!

Model	Minimum Braking Distance, as published by the manufacturer[5]
Permobil M3	11.5 feet
Permobil M5	9.2 feet
Permobil F3	3.3 feet[6]
Permobile F5	9.2 feet

This is what LUCI starts with.

[5] Taken from the user manual for each model as listed on www.permobilus.com
[6] Testing at LUCI has found this value to be much higher, greater than 6 feet, but for the purposes of this report we are using the published value.

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 bolts 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 an authorized 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 allow 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 above:

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

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.

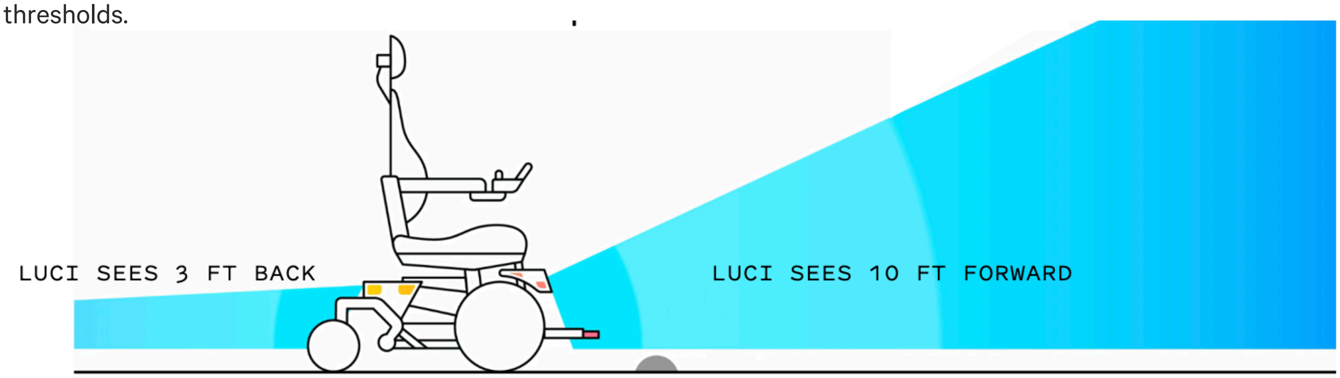
Sensor	Why it is cool
Stereo vision camera with infrared projector	These sensors perceive depth like the human eye does. They give LUCI a depth value to every pixel in an image. Thanks to the infrared projectors (which LUCI controls intelligently) LUCI can still see in the dark! LUCI uses these sensors to map the ground and look for potential collisions.
mmWave Radar	This is 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 noisy environments too.
IMU	LUCI's IMU modules use accelerometers and gyroscopes to figure out how the wheelchair is moving. It's unfortunate but true, since current power wheelchairs don't really have modern control systems, we use our own IMU's to try to do amazing things anyway.

Collision Avoidance

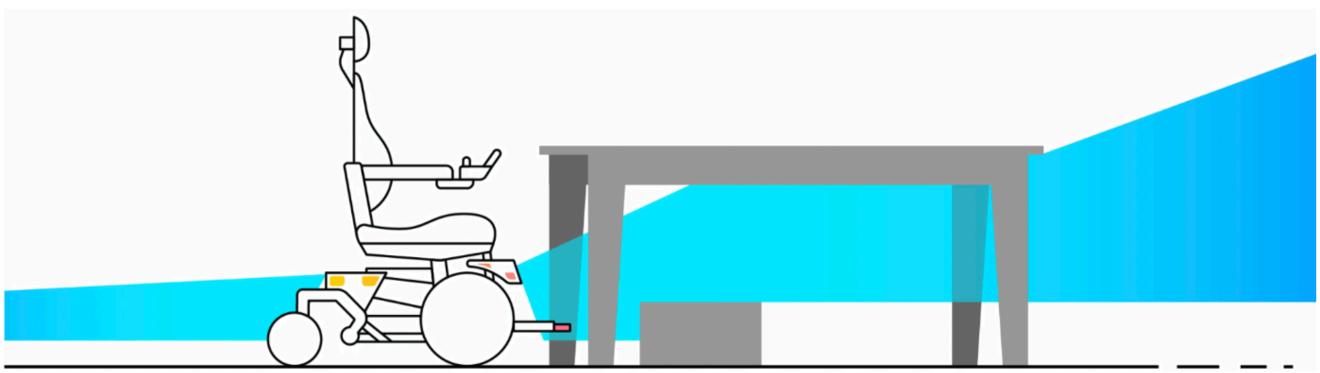
LUCI uses multiple types of sensors to identify and cross-check potential obstacles. The data from these sources is fused and analyzed to ensure the safety of the surroundings. LUCI obstacle detection has the following capabilities.

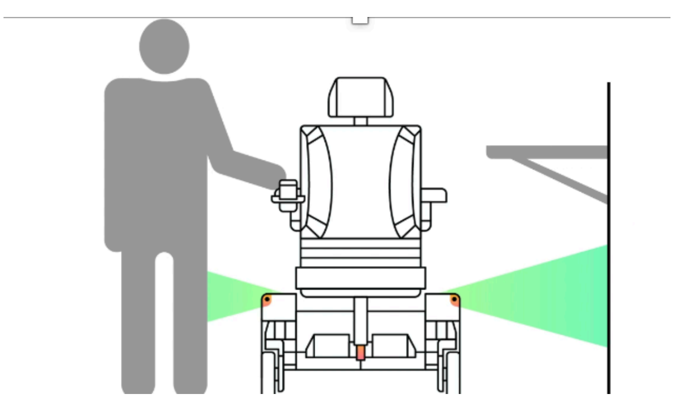
MINIMUM DETECTION RANGE	Objects closer than 3 cm (1.2 in) to the wheelchair may not be registered accurately	Measured from the edge of the wheelchair
MAXIMUM DETECTION RANGE	Forward: up to 3.5 m (11.5 ft) Backward: up to 1 m (3.3 ft) Sides: up to 2 m (6.6 ft)	Measured from the edge of the wheelchair
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. To avoid limiting the capability of the wheelchair, LUCI allows the chair to climb over small steps and door thresholds.



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).

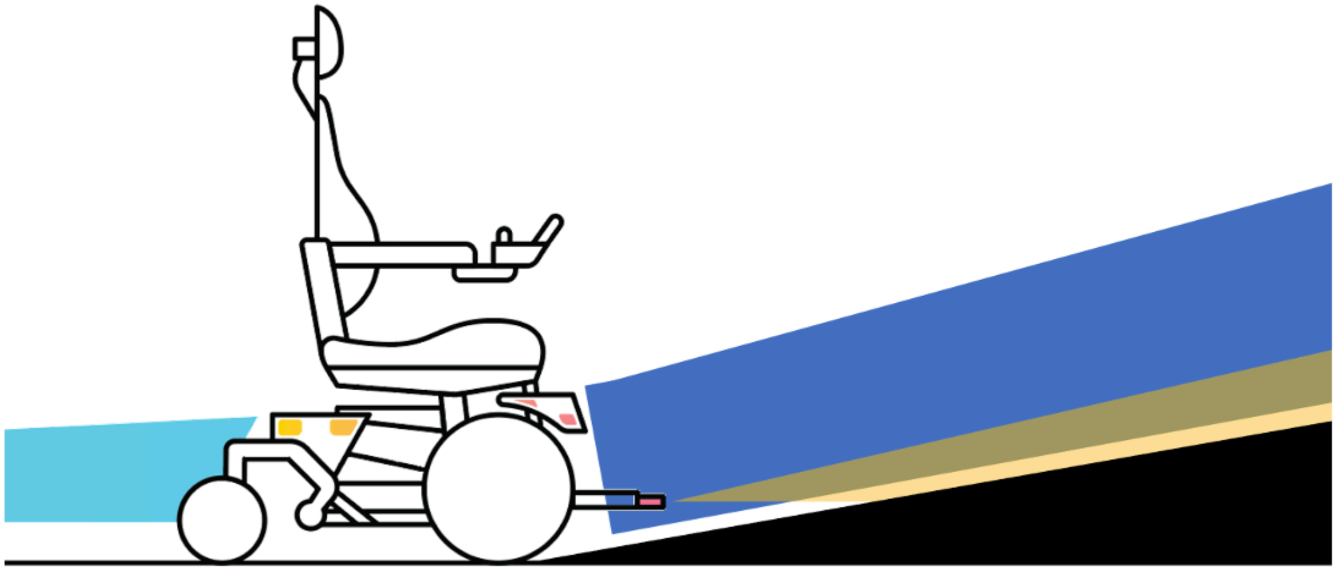




Side sensor coverage is like the front-back coverage. LUCI will see a person's leg but not their toes. LUCI will see a wall but not an overhanging object like a wall shelf, doorknob, or handrail. It is important to know that based on user feedback, LUCI is tuned to get close to things on the side, even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

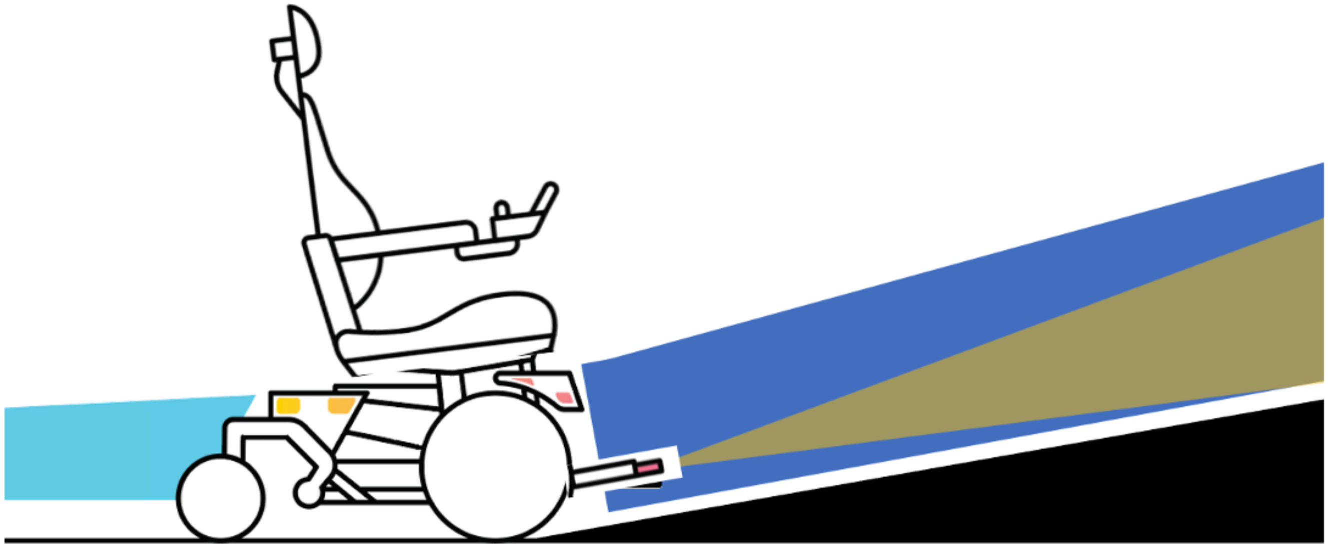
LUCI's sensor coverage changes with the seating assembly position, specifically with the height and angle of the Scout. The Scout is LUCI's forward facing radar.

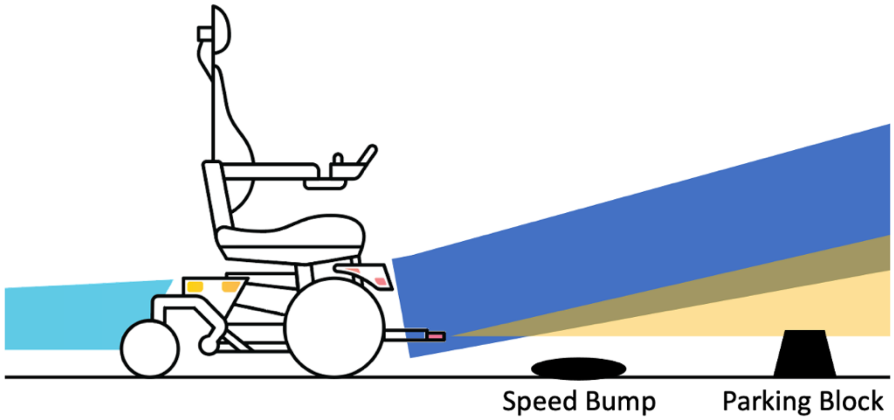
The fact that the Scout moves with the seating assembly is a good thing because users need to be able to go up ramps!



The picture above shows a wheelchair with the Scout pointed straight at a ramp. The dark blue indicates camera collision coverage; notice that it is limited so that LUCI won't stop you on ramps. The yellow indicates the Scout collision coverage which will identify the ramp as an obstacle.

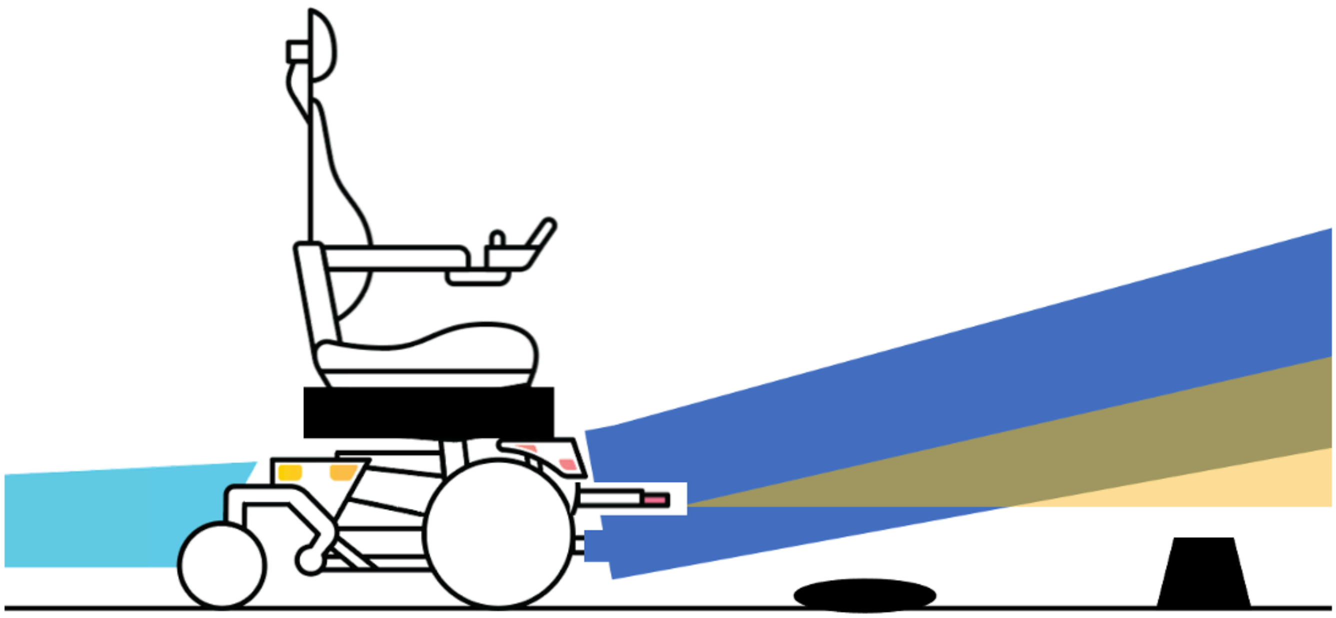
If you tilt the seating assembly or elevate the footrest, the ramp will no longer register as an obstacle for the Scout as shown below.





This same behavior impacts LUCI's ability to see speed bumps, parking blocks, and other ground objects up front. 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.

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



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 is not a replacement for wheelchair skills training.
- A power chair, like all motorized vehicles should be operated with an awareness of the dangers in the environments od use.
- 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 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, in order to avoid tipping the chair and/or throwing the occupant in an avoidance maneuver.

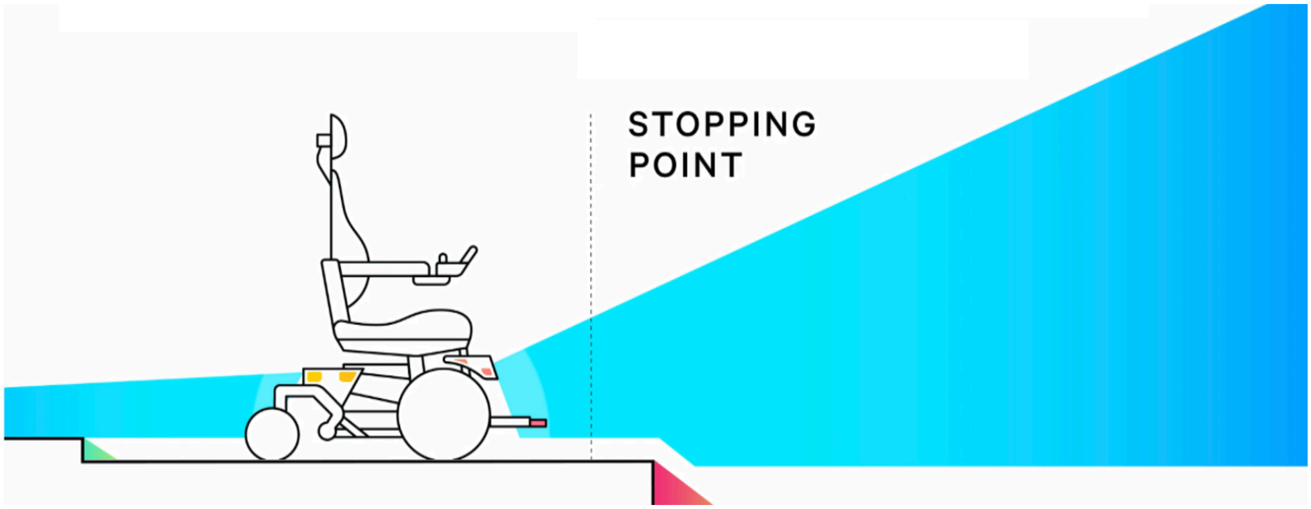
Drop-off Protection

LUCI manages 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 3.5 m (11.5 ft) Backward: up to 1 m (3.3 ft) Sides: up to 2 m (6.6 ft)	Measured from the edge of the wheelchair
STEP DETECTION	LUCI will detect steps with a height greater than your wheelchair's published step threshold	See your wheelchair user manual for the published step threshold
SLOPE DETECTION	LUCI will detect slopes with an angle greater than your wheelchair's published slope threshold	See your 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 going 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 (~3-4inches for most wheelchairs depending on make and model) which are within your 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 your momentum to bring your chair to a complete stop in time. Just like with collision avoidance, once LUCI *detects* a drip-off, LUCI will slow the chair; assisting the driver to be aware that there is a drop-off ahead.



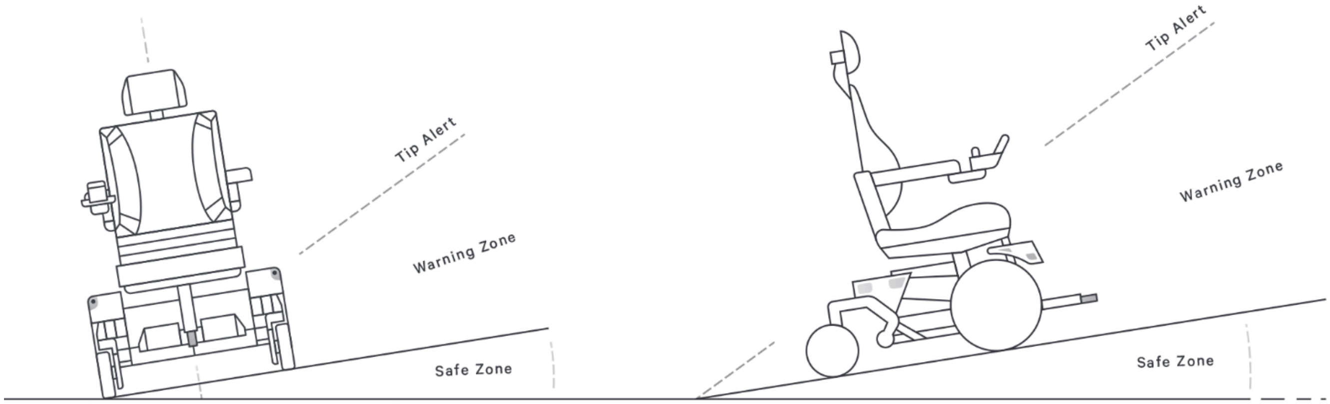
LUCI's drop-off protection coverage tends to work very well for users, but it is important to keep in mind several things when using LUCI:

- LUCI is not a replacement for wheelchair skills training.
- A power chair, like all motorized vehicles should be operated with an awareness of the dangers in the environments od use.
- 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 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, in order to avoid tipping the chair and/or throwing the occupant in an avoidance maneuver.The wheelchair's actual tip limit may be different from the manufacturer's published limit due to seating assembly position, user weight, attachments, 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.

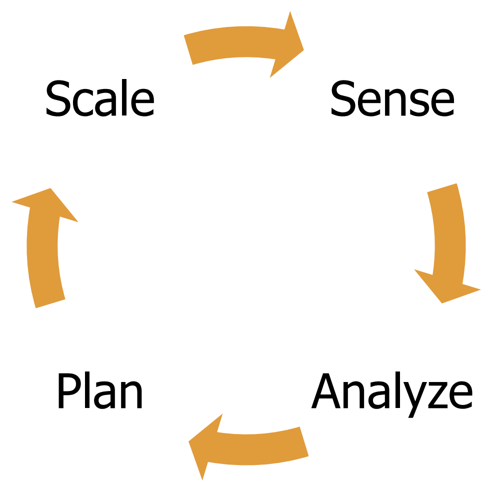
Tip Protection

The wheelchair's actual tip limit may be different from the manufacturer's published limit due to seating assembly position, 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.



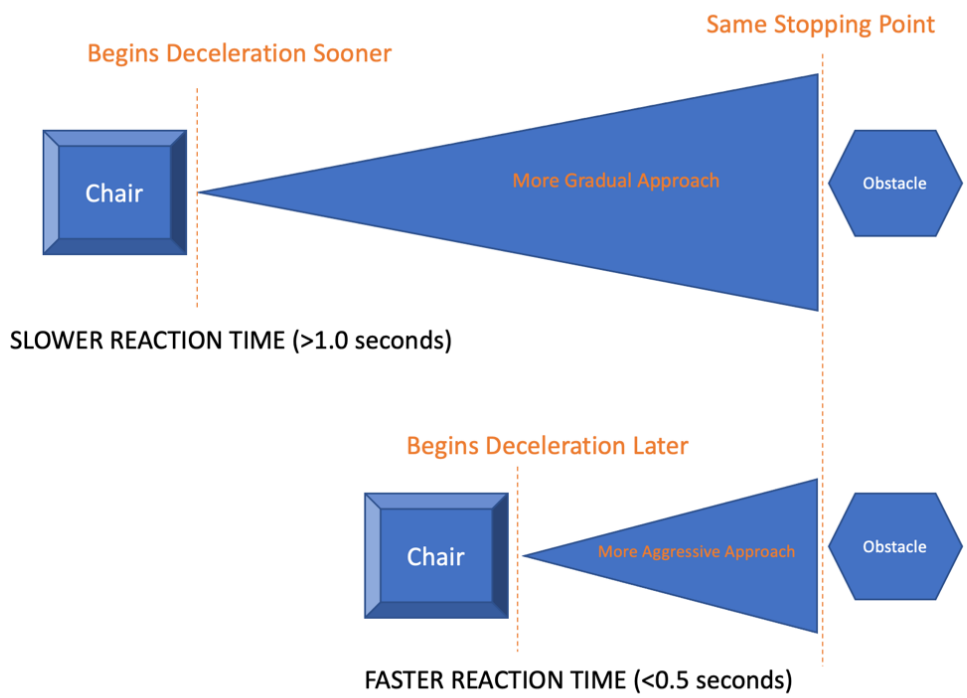
LUCI's processing involves receiving massive amounts of asynchronous data from our sensor system. Data from our **Sensors** arrives anywhere from 100 times per second to 12 times per second depending on the sensor type. Our software then **Analyzes** the surroundings and **Plans**, using user input,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

KEEPING THE HUMAN IN THE LOOP

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. LuciCore keeps the human in the loop.



OVERRIDE IS A FEATURE

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. We have tried to catch as many unsafe conditions as possible which will lead to some false positives. Override makes sure the user always wins in a disagreement with LUCI.

Override is a LUCI feature that should be used!

Sometimes users need to push things open with their footplate. Sometimes they'll need to pull in very close and touch the dashboard when they get in their van, sometimes they'll want to jam the chair up against another surface to complete a safe transfer. In all these situations LUCI is going to stop them short and it's ok to use override.

The LUCI Dashboard, 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 be pressed in situations when LUCI sees a danger that the user knows to be false, and the driver needs to take over 'unassisted'. When the button is pressed, the blue light will blink for 20 seconds, or until the button is pressed again. During this time, LUCI is temporarily disengaged.

GROUND CONFIDENCE

While stopping or slowing the chair for every drop-off is impossible, LUCI's ground confidence algorithm aims to keep users safe while driving on uneven terrain.

The ground confidence system checks ground data at approximately 2.5 meters from the chair and if the ground can't be clearly made out it slows down the chair to a walking speed.

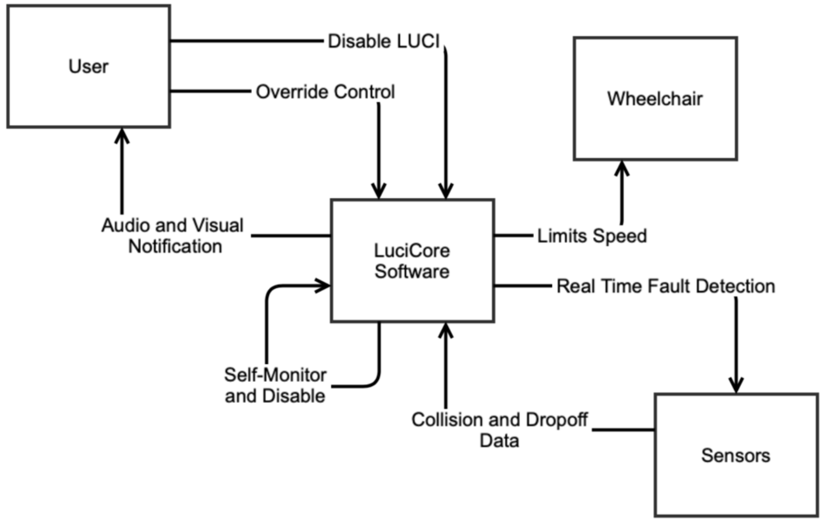
This slowing gives LUCI's drop-off protection system more time to react if it turns out that there is unsafe ground ahead.

When ground confidence triggers, LUCI gets the chair speed down to a walking speed. This speed was selected so that the chair was still usable in situations such where shiny floors or other false positives cause unreliable ground data.

LUCI FAIL SAFE

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

LUCI actively monitors all 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. If the green or yellow LUCI Status light is on, the user can be confident that LUCI is monitoring the environment.



LUCI controls the wheelchair speed at the most fundemental levels of hardware and software using a real-time system. If this system detects issues in the advanced LuciCore collision or drop-off protection system, 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 operate as if it was never equipped with LUCI.

With these protections, LUCI mitigates risk and brings the wheelchair to a stop safely in the event of a system failure. Here are more details on how LUCI 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.
>
> The user can also use the Setup Tool to disable LUCI completely for a longer period until LUCI can be serviced. This allows the user freedom and use of their wheelchair without the protection of LUCI.

If a core component fails, LuciCore uses onboard hardware and software to monitor operation and status of LUCI. When this low-level firmware detects that LUCI is not correctly operating it disables LUCI automatically to allow the wheelchair to operate as if LUCI was not installed. 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 up so that the user knows they are operating without LUCI. Furthermore, if LUCI experiences a severe 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 wheels 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 in our testing.

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 hazard analysis 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 totally more than 250 individual attempts to get 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 (slowest, mid and fast for each model, which varied from 0.5 to 3.5 mph[7] 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.

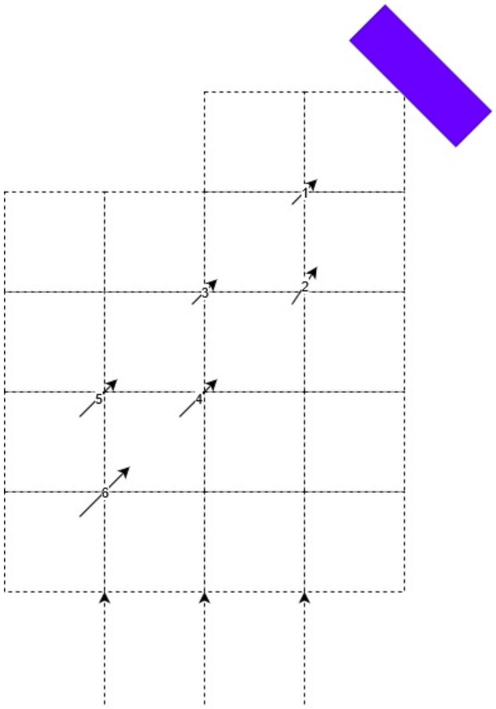
Front drop-off is tested by driving directly at the curb. Back drop-off is tested by driving backwards toward a curb.

FRONT APPROACH

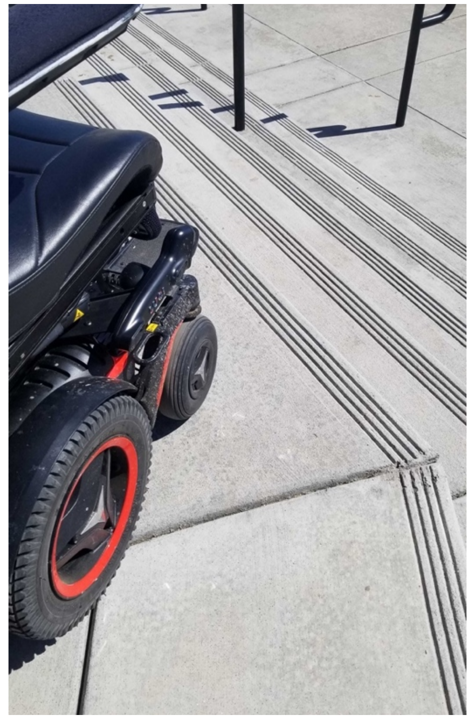
REAR APPROACH

Zero-point drop-off is tested by parking the wheelchair near a drop-off and attempting to turn off the curb with the front or back wheel.

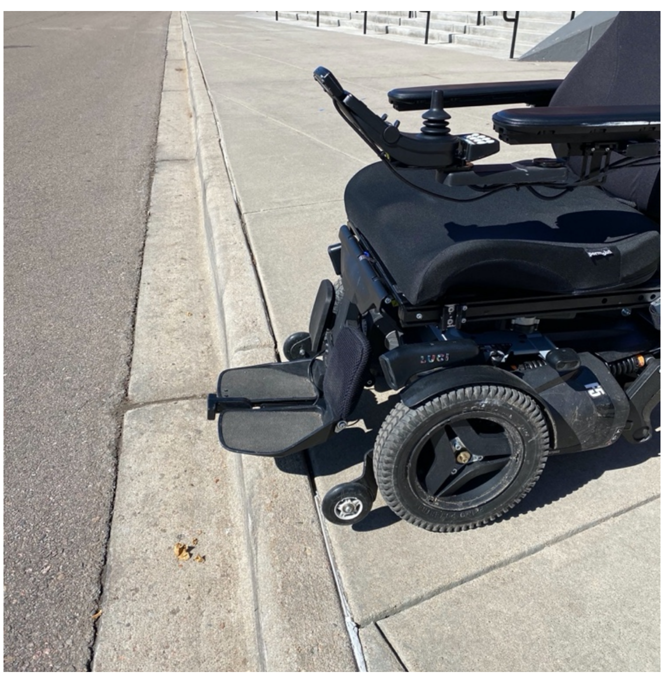
[7] This speed is approximately equivalent to outdoor speed three on most chairs and represents an "average walking speed" for crowd travel on sidewalks.



Diagonal drop-off testing is done by driving diagonally toward a curb and turning toward it at varying distances.



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



The swish test is performed by attempting to intentionally turn and drive the wheelchair off a curb from a standstill after the drop-off protection had already stopped the chair.

Drop-off detection is considered a failure if the wheelchair falls off the curb or if any part of the wheelchair (typically a 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, resulting in the wheelchair being tilted and unable to get back up onto the step. 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	FRONT DROP-OFF	BACK DROP-OFF	ZPT DROP-OFF	DIAGONAL DROP-OFF	3-STEP TEST	SWISH TEST
100 - Permobil M3	24:24	30:30	54:54	36:36	3:3	144:144
101 - Permobil F3	24:24	30:30	53:54	36:36	3:3	143:144
104 - Permobil M5	24:24	30:30	54:54	36:36	3:3	108:108
105 - Permobil F5	24:24	30:30	54:54	36:36	3:3	106:108

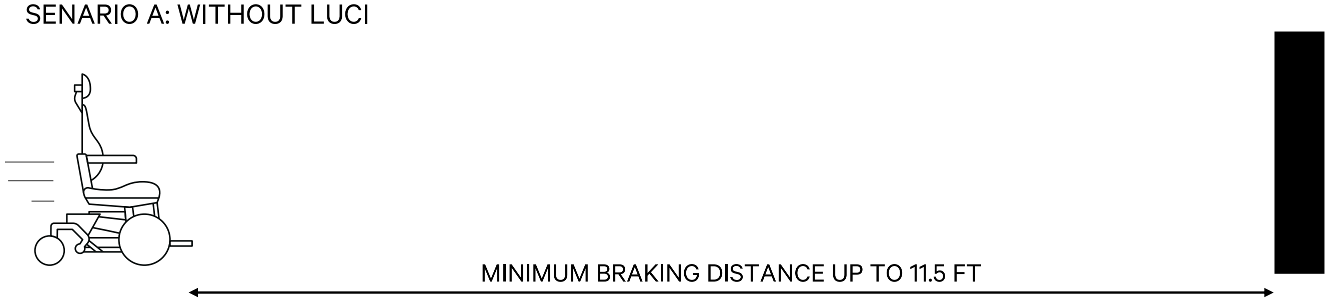
COLLISION AVOIDANCE TEST

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 totally more than 275 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 95% 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 90% 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 would not harm the user.

SENARIO A: WITHOUT LUCI



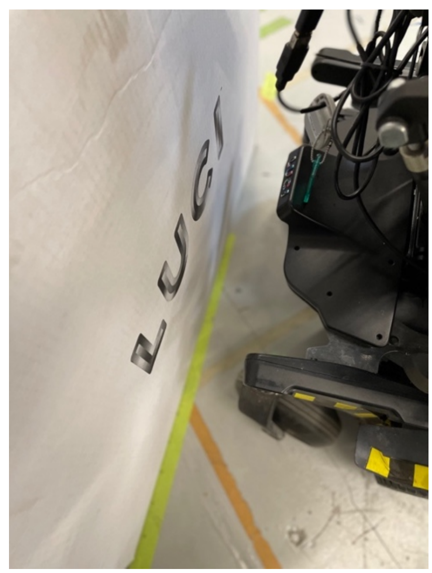
SENARIO B: WITH LUCI

Let's compare the collision avoidance scenario for a power wheelchair user driving at top speed towards a detected target. In Scenario A, without LUCI, the user would need to identify the obstacle and let go of the joystick up to 11.5 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 95% chance that in spite of their reckless driving they wouldn't even contact the obstacle! LUCI still takes time to slow the chair down smoothly in order to avoid launching the driver out of the chair (slowing a 300+ lb. object from 6 – 6.5 mph 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 them time to maneuver around the obstacle.

The Procedure

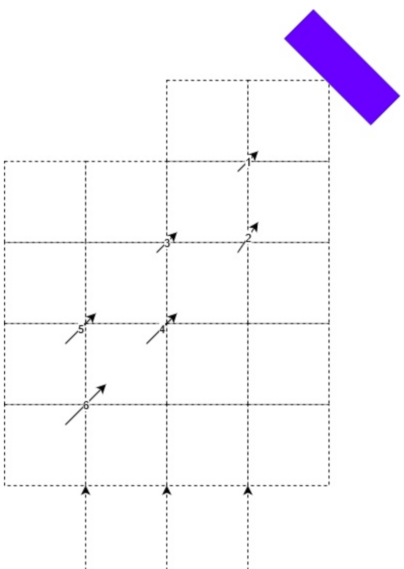
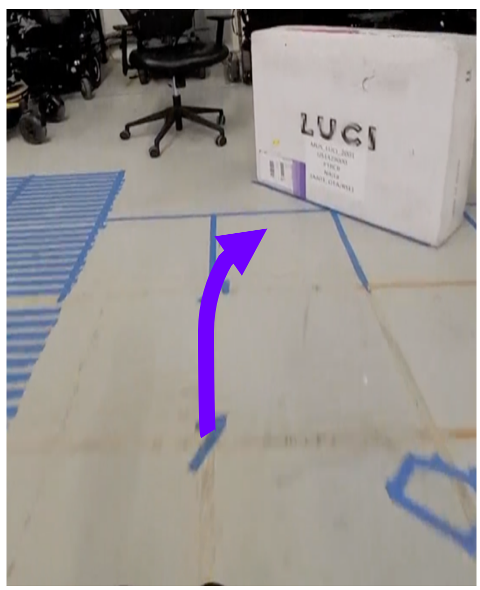
An obstacle is placed in an open space and the wheelchair is driven at an obstacle with combinations of three different speeds (slowest, medium and fastest for each model, which varies from 0.1 to 6.5 mph depending on model), three different reaction times, and various configurations of back and foot zone clearance (standard and extended). In all cases, factory default RNET settings are used.

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 next to the object and attempting to turn into a collision on both front and back.

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.

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, 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, with an overall success rate calculated for each model.

MODEL	FRONT COLLISION	BACK COLLISION	ZPT COLLISION	DIAGONAL COLLISION	SWISH TEST
100 - Permobil M3	69:69	95:96	161:165	82:90	84:110
101 - Permobil F3	69:69	70:87	147:156	79:90	76:99
104 - Permobil M5	39:39	48:48	87:87	54:54	60:76
105 - Permobil F5	30:30	46:48	76:87	54:54	38:51

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...

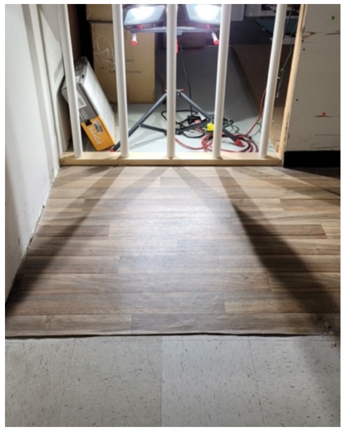
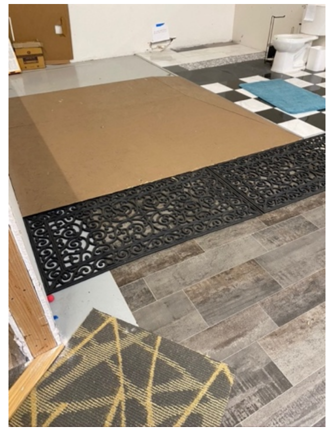
If LUCI isn't sure if a situation is safe, it will slow or stop the wheelchair out of an abundance of caution.

Don't worry though, that is what override is for. If you disagree with LUCI you win and it's ok to use override. At the same time, it's our goal to make LUCI drive so well that you forget the override button exists!

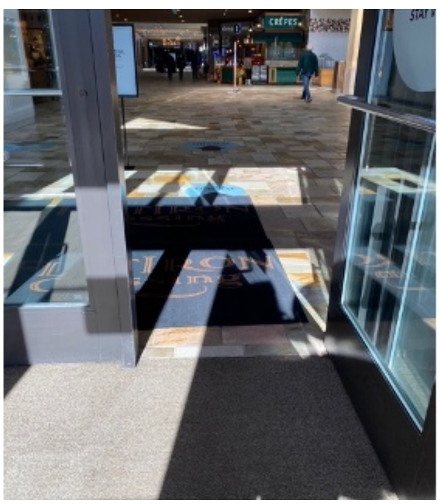
LUCI currently has an approximately 4% false-positive rate that would cause an experienced user to have to use override when there is not a valid obstacle.

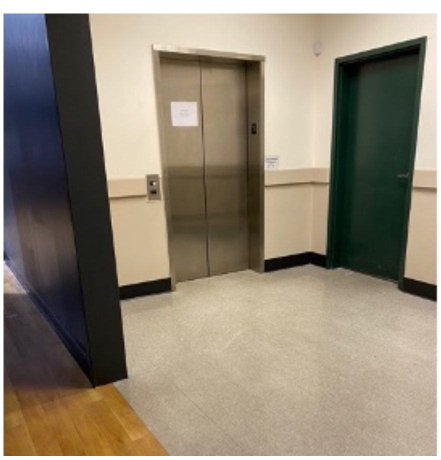
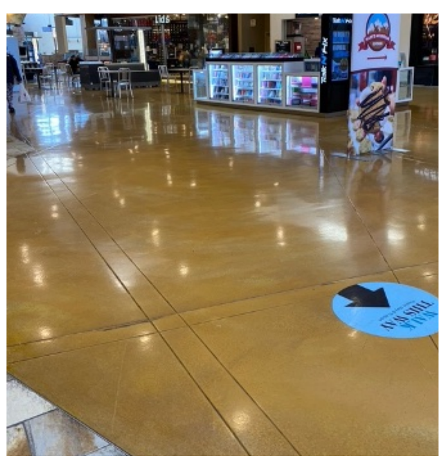
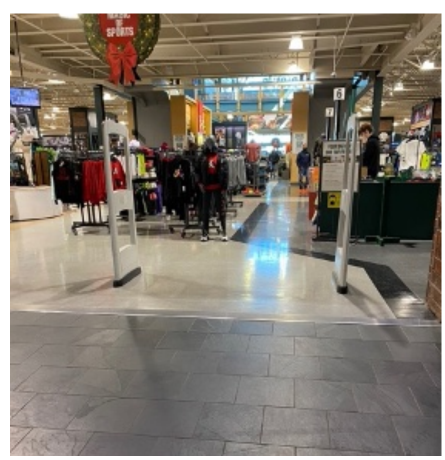
The Procedure

Inside the home testing includes driving down narrow hallways, through doorways at various angles, entering and exiting an elevator, pulling up to a bed, table 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.



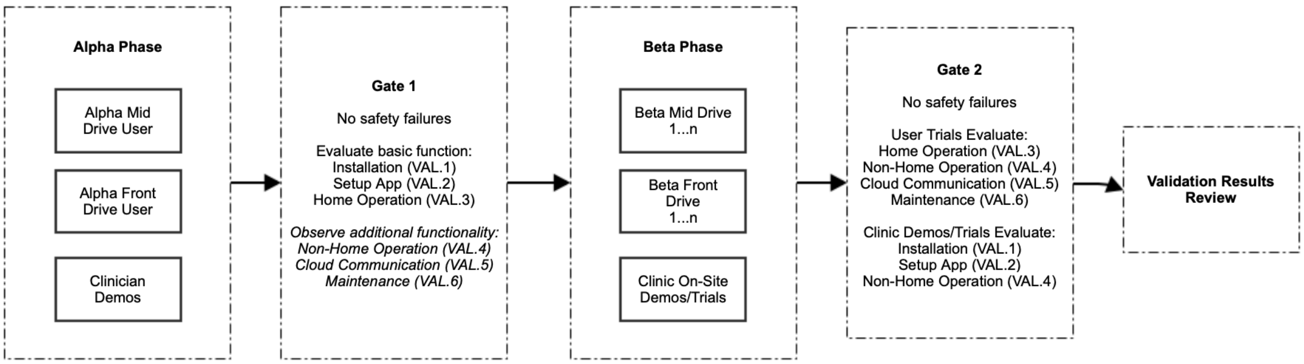
Accessible vehicle tests include driving both forward and backward, into and out of an accessible van. Note that false positives are only counted when driving into and out of the accessible van. The interior of an accessible van is too tight to allow the wheelchair to spin into position without pressing 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	16:16	37:38	4:4	98.3%
101 - Permobil F3	16:16	36:38	2:4	93.1%
104 - Permobil M5	16:16	38:38	2:4	96.6%
105 - Permobil F5	16:16	37:38	3:4	96.6%

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 product validation phase. This product validation led to massive changes to our hardware, software and user interface. The basic flow of our pre-launch validation is shown below.



This process of working with users and clinicians continues today. LUCI maintains an active "Beta User" program to get consistent user feedback from the field. 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 have used technology to go beyond the basic compliance that is so typical in the industry 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 use to improve the product.

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.

And where we are, is leading the industry in safety:

- LUCI's drop-off protection is greater than 99% effective based on our curb drop-off protection testing.
- LUCI's collision avoidance is 100% effective at slowing the chair before a collision with a stationary object and is approximately 95% effective at stopping the wheelchair completely before contact based on our test methods.
- LUCI currently has an approximately 4% 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 efforts to ensure the safety of our product and is meant to spark conversations in the industry about how safety should be defined for the industry. 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.

We are excited about the potential for this technology and look forward to continuing to provide security, stability, and connectivity for power wheelchair users.