Round-a-Doubt — *Innovating at the intersection of safety and mobility*

SYDE 462 Design Analysis Report, Winter 2025

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Abstract—Roundabouts in the Region of Waterloo have been widely implemented due to lower costs, improved traffic flow, and reduced vehicular collisions, but pedestrian safety remains a significant concern, with many reporting anxiety and difficulty crossing. We addressed this gap by designing a novel pedestrian alert system informed by stakeholder interviews, literature, and survey data. Several pedestrian signalling systems were tested in a high-fidelity driving simulator with 15 participants, using eye tracking and driver behaviour data to assess effectiveness. Two designs, a ground-level floor light, and a multi-directional sign, were found to significantly reduce vehicle speeds and improve driver attention on crossing pedestrians. A physical prototype was built with integrated lighting and a camera-based detection system as a proof of concept for real-time pedestrian alerting functionality. This project demonstrates the value of using simulated environments for prototyping and testing transportation design proposals.

Keywords—Roundabouts, Pedestrian Safety, Signage, Driving Simulator, Pedestrian Detection

I. INTRODUCTION

Despite their documented benefits for driver safety and traffic flow [1, 2], multi-lane roundabouts in the Waterloo Region continue to generate public concern regarding pedestrian safety [3, 4], particularly at high-traffic locations like Ira Needles Boulevard [5], with drivers failing to yield to pedestrians up to 43% of the time [6]. While existing infrastructure such as zebra crossings and static pedestrian warning signage meets basic standards for visibility and compliance at pedestrian crossings, several stakeholder interviews revealed that municipalities remain hesitant to adopt new pedestrian alerting systems and safety measures without evidence of their effectiveness. Current state-of-the-art pedestrian alert systems used in non-roundabout settings, such as dynamic flashing signs, have demonstrated safety benefits [2, 7, 8, 9], yet are rarely adapted to roundabout environments.

To address this gap, this project focused on prototyping and evaluating new pedestrian alert concepts specifically designed for 2-lane roundabouts. The goal was to explore how enhanced, real-time alert systems might improve driver awareness and behaviour at roundabout crosswalks. In particular, this project expanded on existing flashing beacon technologies by exploring how signage can go beyond general warnings to communicate more specific, location-based information about pedestrians. This report details the development, implementation, and validation of these prototypes supported by controlled testing in a high-fidelity driving simulator at the University of Waterloo's Autonomous Vehicle Research and Intelligence Lab (AVRIL).

II. PROJECT MOTIVATION, SCOPE AND OBJECTIVES

Improving pedestrian safety at 2-lane roundabouts is a meaningful and actionable engineering challenge, particularly in regions where roundabout adoption has outpaced data-driven adaptations for vulnerable road users. Existing signage often fails to give drivers sufficient awareness of pedestrians. Round-a-Doubt aims to support safer, more walkable communities through evaluating new pedestrian alert concepts, taking the angle of innovating in the signage domain—an area that remains highly unexplored in the context of roundabout design. The three main objectives of this project were to:

1) **Design a novel pedestrian alerting system** informed by stakeholder interviews, literature review, and survey data, that offers more detailed, context-specific information to drivers in 2-lane roundabouts.

2) **Evaluate multiple design variants of this system in a high-fidelity driving simulator**, allowing for controlled testing of drivers' real-time reactions to unfamiliar alerts, and their effectiveness in promoting increased awareness and safe driving behaviour.
3) **Develop a physical proof-of-concept prototype** of an alert system, with a focus on enabling efficient and automatic pedestrian detection using a camera system, eliminating the need for lag-inducing pedestrian-activated signals like push buttons.

Table 1. Summary of Project Scope

In scope	Out of scope
i) Researching existing roundabout solutions and their effect on pedestrians through literature review and stakeholder interviews **ii) Designing and prototyping** a new alert system, both in simulation and as a physical proof-of-concept **iii) Simulator-based testing** to evaluate driver responses and safety outcomes **iv) Data analysis and visualization** to interpret eye-tracking, driving behavior, and user feedback	i) Deployment or testing of the physical prototype in **real-world crosswalk/traffic conditions,** due to safety, legal and time constraints **ii) Near-miss collision detection system**, although a lack of near-miss and collision data at roundabouts was identified as a key gap during stakeholder interviews **iii) Highly customizable computer vision models**: the physical prototype involves pedestrian detection, using established datasets of pedestrian crossing and training protocols

III. SUMMARY OF ENGINEERING ANALYSIS AND DESIGN METHODS

i) STAKEHOLDER INTERVIEWS, RESEARCH AND DATA ANALYSIS

To define the problem space, 15 stakeholder interviews were conducted across academia, government, and industry. Experts included Dr. Lisa Aultman-Hall, Prof. Bruce Hellinga, and Prof. Liping Fu (University of Waterloo); Tyson Moore, Vincentzo Pacioaga, and Dragana Guida (Metrolinx and Transport Canada); Addie Denison and Sina Radmard (Miovision); and Sayan Sivapathasundaram, Kate Hagerman, and Andrew Farr (City of Toronto, UW Sustainability, Halton Region). A recurring theme was the perceived danger of large roundabouts for pedestrians, especially due to driver speed and inconsistent yielding at exit points, as well as a lack of reliable data on roundabout safety in the Region of Waterloo. A literature review and collision analysis of Region of Waterloo data (2015–2022) revealed roundabouts are safer overall than signalized intersections in terms of high-impact crashes [10], but lack adequate near-miss reporting systems [11]. Interviews and research emphasized that "perceived safety" is also a key factor in pedestrian behavior, with users often avoiding crossings altogether. Informal observational data collected by the team supported high failure-to-yield rates when drivers exited two-lane roundabouts, while drivers waiting to enter yielded consistently.

iii) ENGINEERING SPECIFICATIONS

Based on the above observations, a Quality Function Deployment (QFD) analysis was conducted (Appendix A, Figure A1), from which three key engineering specifications were generated to be referenced when designing the final prototype. These specifications are as follows, in order of priority, with corresponding target metrics reported in Table 2:

1) ***Minimize vehicle-pedestrian collisions and near-collisions:*** Any number of collisions in a roundabout with pedestrians can be life-threatening or fatal. Near-misses are indicative of a possible collision risk. [10]
2) ***Maximize driver yielding rates for pedestrians:*** Yielding behaviour at two-lane roundabouts is highly inconsistent, especially at exit lanes. [6]
3) ***Minimize driver distraction:*** Roundabouts already demand high cognitive load from drivers due to continuous scanning and decision-making. [12] The alert system should enhance pedestrian awareness without introducing unnecessary visual or cognitive distractions.

Table 2. Engineering Specification Metrics

Metric	Related Specification(s)	Measurement	Justification
Driver's deceleration when braking for pedestrians.	*1) Minimize collisions* *2) Maximize driver yielding rates*	Aim for a solution that minimizes the magnitude of deceleration when drivers brake for pedestrians. Decelerations less than 3.048 m/s^2 (10 ft/s^2) are ideal. [13]	"Hard braking events" show significant correlation with crash locations, and indicate a shortfall in reaction time for the driver. [13]
Driver's average speed through the roundabout.	*1) Minimize collisions* *2) Maximize driver yielding rates*	Favour solutions that are found to reduce driver speeds through the roundabout (km/h) compared to having no alert in place.	From stakeholder interviews, municipalities identified high-speed roundabouts as the most problematic.
Percent of total fixations, and average fixation duration on the alert.	*3) Minimize driver distraction*	Using eye-tracking data from simulator trials, each fixation (≥150 ms) [14] is recorded and mapped to objects of interest (e.g., alert signs, pedestrians). ***% of total fixations:*** Proportion of all fixations directed at an element. [14] ***Average fixation duration:*** Mean time (ms) spent per fixation on an element. [14]	Alerts should be noticeable but not overly demanding. Effective designs capture attention briefly and clearly without drawing focus away from the pedestrian. Long fixation durations may indicate confusing information [12, 14].
Qualitative comments and user perceptions of alerts.	*1) Minimize collisions* *2) Maximize driver yielding rates* *3) Minimize driver distraction*	Post-simulator survey where users rank the usefulness of each alert. Participants share feedback on clarity and preferred real-world implementation of each alert type.	Subjective feedback provides insight into how well the alert communicates intent, how easily it's understood, and whether it would be trusted or followed in real-world driving.

iv) AVRIL DRIVING SIMULATOR TESTING

To evaluate alert designs safely and effectively, testing was conducted in the Autonomous Vehicle Research and Intelligence Lab (AVRIL) driving simulator in partnership with Professor Siby Samuel. The simulator features a full-sized vehicle, haptic feedback, and a 270° field-of-view screen, with customizable scenarios including weather, time of day, and traffic conditions. Given limited real-world data and ethical concerns around live testing, the simulator offered a controlled, risk-free environment to capture driver eye movements, velocity and acceleration behavior, and realistic reactions to each prototype.

v) LOW-FIDELITY PROTOTYPE DESIGNS

Three alert concepts, shown in Figure 1 (Left), were initially developed to address the common visibility and yielding issues at roundabouts outlined in Table 2. The primary design, the **Multi-crosswalk sign**, uses real-time pedestrian detection to light up directional indicators, showing drivers where pedestrians are crossing at any leg of the roundabout. Two simpler alternatives were also created: the **Top-light sign**, featuring a single blinking light to signal pedestrian presence, and the **Light-up crosswalk**, which illuminates the crosswalk itself for added pedestrian visibility.

All designs were informed by the Ontario Traffic Manual (OTM) [15] to ensure the use of familiar iconography and compliance with road signage standards, including fonts, border placement, shape, and colour. These decisions are further elaborated on in Appendix A, Figure A2. These alerts offer varying levels of information and complexity, allowing the simulator testing to explore the balance between helpful cues and cognitive overload. Both the multi-crosswalk and top-light signs were designed to be positioned *before* roundabout entry, giving drivers advanced notice without drawing attention away from pedestrians—an issue observed in existing studies of Pedestrian Hybrid Beacons and Rectangular Rapid Flashing Beacon, where drivers often fixate on the beacon rather than the person crossing [16].

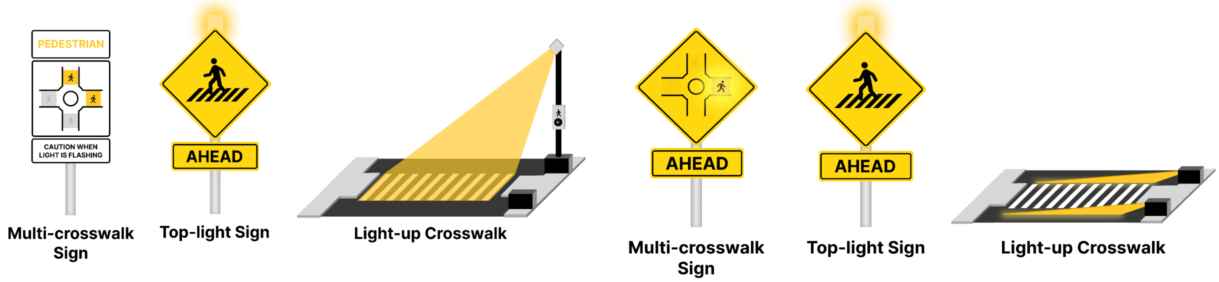

Figure 1. Design changes between survey (left 3) and simulation testing (right 3)

v) FURTHER PROTOTYPE DESIGN ITERATIONS

After the first design phase, a survey with 55 respondents was conducted to compare the early alert concepts. The **Top-light sign** was preferred by 76.4% of respondents over the **Multi-crosswalk sign** (29.1%), with many finding the latter confusing or slow to interpret. Respondents also preferred a **yellow diagonal sign shape** (avg. understanding score: 3.26/5) over a white rectangular design (2.44/5), and favored shorter text like "AHEAD." These findings informed updates to the signs used in simulator testing, shown in Figure 1 (Right). The **Light-up crosswalk** was also revised, moving the light source closer to the ground to avoid glare and improve safety by casting a clear beam along the crossing path. With these improvements in place, the next major goal became evaluating whether seeing the signs in context, connected to real-time pedestrian activity in the simulator, would improve comprehension compared to only viewing them visually.

vi) DRIVING SIMULATOR ASSET CREATION

In order to test in the driving simulator, a digital model of Ira Needles Blvd. / Erb St., a large two-lane roundabout in the Waterloo Region, was created using MATLAB's RoadRunner, then imported into the WorldSim driving simulator software via Unreal Engine. Custom alert assets were built in Blender to ensure accurate 3D rendering of the sign designs. Due to lighting limitations in RoadRunner, ground-level light strips were used to simulate the light-up crosswalk. All alert variations were integrated into the map for use in simulator trials.

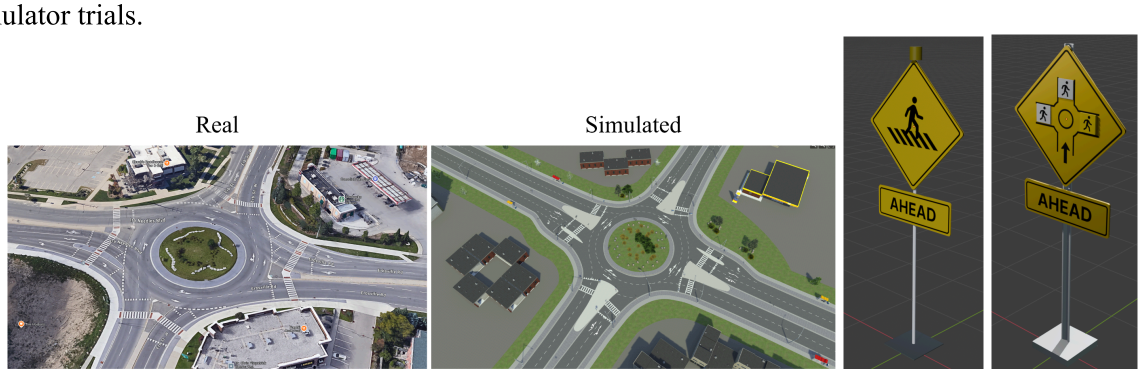

Figure 2. RoadRunner Roundabout Environment (Left), Blender Alert Assets (Right)

vi) SIGN CONTROL IN THE ROUNDABOUT

To control the alert systems, a computer vision-based detection method was implemented to minimize false triggers, a common issue with standard pedestrian push buttons [17]. A YOLOv8-based model (Roboflow

Object Detection 3.0) [18] was trained to detect when pedestrians enter or exit the crosswalk, enabling real-time activation and shutoff of lights for improved accuracy and driver trust.

IV. SOCIAL, ECONOMIC, AND ENVIRONMENTAL IMPACTS

A sustainability analysis comprehensively addressed the social, economic, and environmental impacts of the proposed alert system through SDG and GPM frameworks. Socially, the design targets Sustainable Development Goals 3, 9, 10, and 11 by improving pedestrian safety—particularly reducing risk for vulnerable populations including the visually impaired, children, and those with mobility limitations, who may have more difficulty crossing roundabouts with no existing alert systems [19]. The approach to testing in the AVRIL driving simulator supports "Project Health and Safety" from the GPM by preventing adverse safety effects while gathering critical data for municipalities [7]. Simulator testing also enhances "Business Agility"(+2.0) by enabling iteration without material costs or disruptive road closures, and the project has potential to have a positive "Local Economic Impact" (+1.0). The workbook also showed significant improvements in "People" metrics, with scores increasing in human rights (+1.3), society and customers (+1.8), and labour practices (+1.4), due to the system's prioritization of equity for vulnerable populations by protecting pedestrian safety, and the project's focus on community engagement through proper construction techniques and public education campaigns.

Economically, the design balances immediate safety needs with long-term sustainability, supporting SDGs 9 and 10. The system creates favourable Business Case Analysis and Social Return on Investment despite installation costs (~$20,000+ per intersection), as pedestrian-friendly areas boost property values (5-10 mph traffic reductions can increase values by ~20% [20]) and business activity. Environmentally, the analysis revealed mixed impacts, with some trade-offs necessary to achieve safety goals. The system encourages emission-free transportation alternatives that improve air quality and reduce traffic congestion, supporting SDG 13. However, introducing electrical infrastructure into roundabouts consumes energy and resources [10], resulting in slightly reduced "Planet" scores in the GPM assessment, particularly in energy usage (-1.7) and consumption (-1.0). Appendix B, Figure B1, shows a full report of GPM Workbook scores.

V. DESIGNED SOLUTION

Since the main goal of the project was to determine whether increased alerting information was beneficial to pedestrian safety and how to best present that information, the results from the simulator tests (Section VI) were the primary outcomes. However, to present the findings in an informative and interactive manner, it was decided that a physical prototype should be built to communicate the findings and ideas behind the design to experts and the general public. Thus, three physical proof-of-concept prototypes were created.

i) MULTI-CROSSWALK SIGN

The multi-crosswalk sign prototype, which showed promising results in simulator tests (Section VI), was professionally manufactured by Cedar Signs [21] using the custom design outlined in Section III. Standard sign mounting hardware was purchased from Grainger Canada [22], with LED strips borrowed from the DEN and electronics components purchased from Amazon. An Arduino Uno was initially used to test the relay system, but ultimately a Raspberry Pi 4 with a camera accessory was implemented to run computer vision models while controlling the LEDs. Logic level converters were required to bridge the Pi's 3.3V outputs with the 5V relay inputs.

The pedestrian-detector computer vision model was implemented on the Raspberry Pi, processing camera feed to extract bounding box coordinates for detected pedestrians. Due to budget constraints, a single camera controlled all relays rather than the four required for a full solution implemented at a roundabout. The feed was divided into three sections, with pedestrian detection in each zone activating the corresponding sign direction through relay activation, allowing for simultaneous detections.

For the implementation of LEDs, strips were cut to size and attached using built-in adhesive, with four strips per intersection leg (42 LEDs per leg, 126 total). The 12V LEDs consumed 0.64A when tested, requiring a

12V/2A power supply. These were soldered in parallel configurations with ground and power lines routed through drilled holes in the aluminum sign. Wiring connected to relays and power source via a 2.1mm jack terminal block adapter and output terminal blocks, enabling computer vision control of each LED section.

Figure 3. (left to right) Electronics implementation/testing, support, and casing for sign

Finally, a custom electronics housing was designed in OnShape and 3D-printed using PLA plastic for its cost-effectiveness and ease of printing. The housing featured strategic ventilation holes to prevent Raspberry Pi overheating and included a specialized camera mount at the top. Custom lightboxes for LED sections were iteratively designed to optimize light diffusion while minimizing protrusion from the sign face. After testing various configurations, black pedestrian icons mounted behind the lightbox pane proved optimal for visibility when illuminated while remaining unobtrusive when off. Yellow kapton tape was applied to match the sign color, and the entire assembly was mounted on a black-painted wooden base with a 2x4 vertical support.

ii) LIGHT-UP CROSSWALK

The light-up crosswalk was built to demonstrate above-ground illumination as an alternative to in-ground lighting solutions [23]. A high-intensity 990000 lumen LED flashlight was purchased, approximately 7.8× brighter than average sunlight per square meter [24]. After testing various 3D-printed shades, a single 2mm slit design proved optimal for balancing light output and minimizing divergence. Testing determined that positioning the light at a 60° angle approximately 80 cm from the ground provided ideal beam coverage.

Figure 4. Light-up crosswalk design and prototype

A custom housing was designed in CAD and 3D printed to maintain the optimal angle. Due to material constraints, the stand was omitted for demonstration purposes. The flashlight was disassembled and directly connected to a relay and 5V power supply using a 2.1mm jack terminal block adapter, with the LED drawing approximately 1.2A at 5V. The control system synchronized the crosswalk illumination with the sign's middle LED array. The prototype was built at half-scale, lighting 3m (one lane) instead of the 6m (two lanes) required in real environments.

iii) ROUNDABOUT DIORAMA

As a communication tool, a roundabout diorama was created to demonstrate how multi-crosswalk signs would cooperate within a real roundabout environment. The Ira Needles Blvd. and Erb St. double-lane roundabout was modeled in CAD, 3D printed, and decorated. Miniature versions of the multi-crosswalk signs were printed with LED cutouts, while buttons installed at each crosswalk were wired to an Arduino

Uno microcontroller. The system was programmed to illuminate three corresponding signs when any crossing button was pressed to demonstrate functionality for simultaneous crossings.

iv) SIMULATOR EXPERIMENT ENVIRONMENT

As previously iterated, beyond physical prototyping, a major outcome of the project was the creation of a custom roundabout simulation environment, purpose-built for testing new pedestrian safety technologies. Since a core objective was to evaluate the effectiveness of novel alerts, significant design effort was dedicated to experiment creation, conduction, and data analysis—key components of the overall engineering process, further detailed in Section VI.

Figure 5. Driving simulator environment eye tracker point-of-view

Using AVRIL's DriveSim and WorldSim software, the simulated roundabout was carefully designed with realistic visuals, environmental assets, traffic patterns, functional light-up sign prototypes, and strategically placed targets and distractors to induce real-world decision-making scenarios. Crossing pedestrians were timed precisely using WorldSim triggers to be encountered by the driver. A Simulink model was created and connected to the driving simulator to capture the desired key engineering metrics (i.e. vehicle speed and braking acceleration) outlined in Table 2. Figure 5 shows a driver's point of view driving through the designed environment, wearing an eye tracker.

VI. SUMMARY OF DESIGN EVALUATION AND VALIDATION

i) SIMULATOR EXPERIMENT DESIGN

In the designed experiment, 15 participants (primarily 4th-year undergraduate students) were asked to drive through the simulated roundabout multiple times, taking a different exit each time. Without being told in advance what to expect, they encountered various pedestrian crossing scenarios paired with different alert combinations (**Multi-crosswalk sign**, **Top-light sign**, and **Light-up crosswalk**). Data collection focused on three key areas: (1) eye tracking to understand gaze and attention patterns, (2) velocity and acceleration as indicators of driving safety, and (3) qualitative feedback to capture perceptions of each alert's usefulness.

Independent Variables: The experiment manipulated three independent variables: (1) the vehicle's turning movement through the roundabout, (2) the specific combination of pedestrian alerts in use, and (3) the location (exit lane crosswalk) of the pedestrian crossing. The pedestrian's location was varied across exits to ensure drivers could not anticipate whether they would appear in each scenario.

Dependent Variables: Primary dependent variables included the driver's average velocity through the roundabout (km/h), the minimum acceleration (m/s^2) when braking for a pedestrian (as a proxy for hard braking events), and participants' rankings of each alert based on clarity, usefulness for navigation, and real-world implementation preference after completing each of the scenarios. These relate directly to the metrics in Table 2, tying to the desired engineering specifications for the final design

Control Variables: Key control variables, such as roundabout geometry, traffic conditions, pedestrian speed, and time of day, were kept consistent across trials. In an effort to standardize participants' familiarity with the simulator environment, subjects with limited experience completed a three-minute test drive prior to the experimental trials. An elaborated list of control variables, as well as known confounding variables, are reported in Appendix C, Table C1.

Given the three independent variables in the study—*vehicle turning movement*, *alert system*, and *pedestrian crossing location*—and the number of levels each can take on, a full factorial experiment design would require 72 trials to capture all possible combinations (see Appendix C, Table C2), which was deemed impractical due to time constraints and participant fatigue. Since *alert system* was the primary variable of interest, a subset of 15 trials was selected using a D-optimal design approach [25]. D-optimal design is a method that selects the most informative subset of trials by maximizing the determinant of the Fisher Information Matrix between independent variables, effectively minimizing confounding effects. [25] The resulting set of 15 trials, reported in Appendix C, Table C3, minimized correlation between alert system configurations while maintaining an even distribution of alert types across the trial set (see Appendix C, Figure C1 for the correlation matrix).

ii) ANALYSIS OF VELOCITY AND BRAKING ACCELERATION

Real-time outputs from the driving simulator combined with the Simulink model captured each participant's longitudinal velocity (km/h) and acceleration (m/s^2) for each trial. The driver's average velocity through the roundabout was calculated within the segment between passing the entrance crosswalk, and exiting the roundabout. To determine whether the alert type influenced driving speed, a repeated measures ANOVA was conducted. This method was appropriate given that each participant experienced all alert conditions, allowing for within-subject comparisons while accounting for individual variability. [26] Before conducting the ANOVA, the distribution of average velocity values was tested for normality using the Shapiro-Wilk Test, followed by a check for sphericity, with the appropriate correction [26] applied.

Table 3. Summary Statistics for Average Velocity and Braking Hardness Values per Alert Type

	Driver's avg. velocity through roundabout (km/h)		**Driver's minimum braking acceleration for pedestrian (m/s^2)**	
Alert Type	***Mean***	***Std. Dev***	***Mean***	***Std. Dev***
No alert	27.62	±7.83	-4.69	±2.77
Multi-crosswalk sign	22.02	±4.46	-4.18	±2.54
Top-light sign	21.26	±4.06	-4.15	±2.31
Light-up crosswalk	27.91	±9.54	-3.80	±2.73

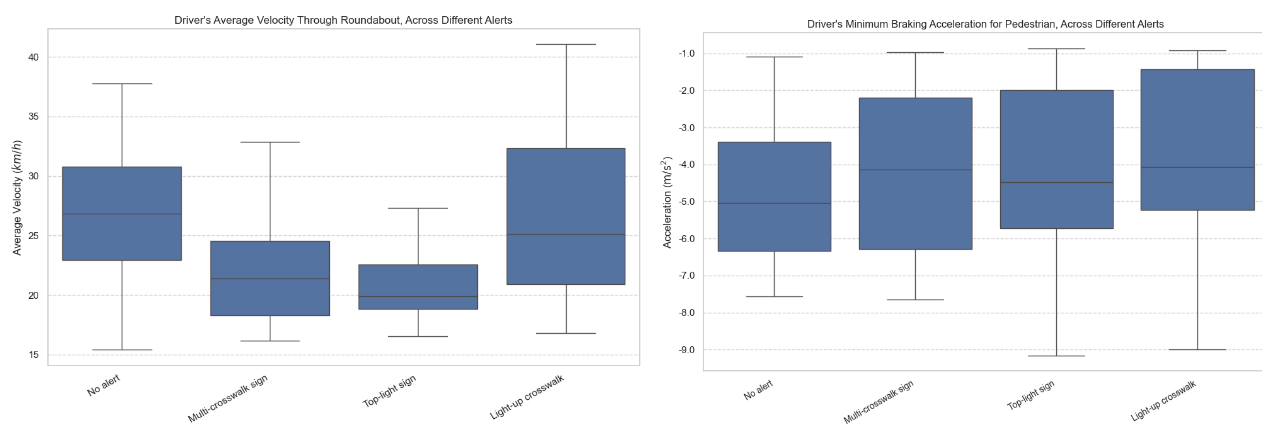

Figure 6. Box plots of Average Velocity Through Roundabout (Left), and Minimum Braking Acceleration (Right), by alert type

The analysis revealed a statistically significant effect of alert type on average velocity *($p = 0.002$)*. Follow-up paired t-tests showed that both the multi-crosswalk sign and the top-light sign led to significantly lower driving speeds when compared to both the light-up crosswalk and the no-alert condition *($p < 0.05$)*. Full statistical test results are reported in Appendix C, in figures C2 and C3.

In addition to velocity, each driver's minimum acceleration (m/s^2) during the window of braking for the pedestrian (for trials where braking was necessary), representing their hardest braking event, was analyzed. A repeated measures ANOVA was conducted to evaluate whether alert type influenced braking aggressiveness, but the results did not reveal any statistically significant effect *($p = 0.384$)*. Means and standard deviations for each analysis, as well as corresponding box plots, are reported in Table 3 and Figure 6. Preliminary results suggest that that light-up crosswalk was associated with the least aggressive braking, while having no alert in place led to the hardest braking responses.

iii) ANALYSIS OF EYE TRACKER DATA

Driver attention was analyzed using the Dikablis Ergoneers eye tracker, along with its associated software for timestamping and classifying gaze and fixation events. In literature, a fixation is defined as concentrating on an area of interest for 150 milliseconds or longer [14], indicating meaningful awareness and cognitive processing of that element. For this analysis, fixations were compared across individual objects of interest across all trials—the pedestrian, each of the alert signs, and the light-up crosswalk—to understand how visual attention was distributed. Two primary metrics were used: i) the *percentage of total fixations* on each object of interest quantified the proportion of visual attention consistently allocated to each element [14]; and ii) the *average fixation duration* measured the time spent per fixation on each object, with longer durations suggesting deeper processing [14]. Together, these metrics helped evaluate not just whether drivers noticed the alerts, but how they interpreted and prioritized them in relation to pedestrian visibility. The results are reported in Table 4.

Table 4. Summary Statistics for % of Total Fixations and Average Fixation Duration for Objects of Interest

	% Total fixations on object		**Average fixation duration (ms)**	
Object	***Mean***	***Std. Dev***	***Mean***	***Std. Dev***
Pedestrian	9.48	±6.49	598	±479
Multi-crosswalk sign	8.01	±5.33	593	±464
Top-light sign	5.76	±6.12	733	±436
Light-up crosswalk	5.71	±3.64	393	±177

Across the trials, the pedestrian consistently drew the highest proportion of visual attention (9.48%), followed closely by the multi-crosswalk sign (8.01%). The top-light sign and light-up crosswalk received fewer fixations overall (5.76% and 5.71%, respectively), but the top-light sign had the longest average fixation duration (733 ms), suggesting it may have been initially confusing or required more effort to interpret. The light-up crosswalk had the shortest average fixation duration (393 ms), possibly indicating it was more immediately understood, followed by the multi-crosswalk sign (593 ms), which was comparable to the pedestrian (598 ms).

iv) EXIT SURVEY RESULTS

Table 5 reports the exit survey ranking results, along with summaries of qualitative participant comments. After completing all trials, when the participants were asked to recall which alerts they saw in the simulator, the light-up crosswalk was remembered most often (14/15 participants), followed by the top-light sign (12/15) and the multi-crosswalk sign (11/15). This may suggest that participants either overlooked or confused the more detailed signs, especially the multi-crosswalk display, which required more visual processing. Some participants noted that, due to its unfamiliar format, they simply ignored the multi-crosswalk sign if they didn't immediately understand it, potentially explaining why it drew less attention overall compared to the more familiar top-light sign. The light-up crosswalk ranked highest overall across all categories, particularly in speed of interpretation, due to its simplicity and visibility. Meanwhile, the multi-crosswalk sign, while rated as the most informative, was often described as overwhelming or confusing. The top-light sign was seen as intuitive but vague, offering less specific guidance to drivers.

Table 5. Exit Survey Results

	Avg. rank from 1-3 (1 is best, 3 is worst)			**Summary of Comments**	
Alert	***Speed of interpreting alert***	***Usefulness of alert***	***Desire to see alert implemented***	***Positive***	***Negative***
Multi-crosswalk sign	2.28	2.00	2.07	Clearly showed where pedestrians were located, advance warning reduced uncertainty.	Initially confusing or overwhelming; often hard to interpret quickly due to its complexity.
Top-light sign	2.14	2.42	2.28	Simple and familiar, gave a general heads-up of pedestrians ahead without too much complexity.	Too vague and easy to overlook; didn't specify pedestrian location. Was sometimes dismissed or ignored.
Light-up crosswalk	1.5	1.64	1.71	Highly eye-catching and intuitive; crosswalks were more noticeable, making it easier to slow down on time.	Some found that it offered too late of a warning. Effectiveness questioned in certain conditions (daylight, snow).

Overall, the multi-crosswalk sign and top-light sign were most effective at reducing driver speed, directly supporting the engineering specification to minimize collisions and improve yielding (Table 2). While braking acceleration differences were not statistically significant, both signs showed gentler braking trends than the no-alert condition. Eye-tracking data revealed the multi-crosswalk sign captured high attention with moderate fixation duration, aligning with the specification to minimize distraction. The light-up crosswalk, though less effective at reducing speed, had the shortest fixation duration and highest recall, suggesting strong intuitive appeal. Overall, the **multi-crosswalk sign** and **light-up crosswalk** best met different subsets of the specifications, with the former excelling in behavior change and the latter in visibility and ease of interpretation. Interestingly, perceptions of the multi-crosswalk sign significantly improved once it was seen in action (compared to the initial survey), highlighting the importance of realistic, contextual interactions.

v) PHYSICAL PROTOTYPE VALIDATION

For the electrical elements, each voltage and current rating was recorded from datasheets and manual testing using a multimeter. From this, proper power supplies that fit the required voltage and current specifications were sourced. Finalized values for the various components are presented in Appendix D, Table D1. For the computer vision system, a validation dataset with images of pedestrians in crosswalks was used. This included images that were dark, bright, and cloudy to represent night time, day time and foggy conditions, which were generated from pre-existing images using image editing software. An 86% average precision for the human class was achieved through training, and after hyperparameter tuning, an 86.4% precision and 77.9% recall were achieved. The f1 score (the harmonic mean of precision and recall) is frequently used by literature to balance precision and recall to better evaluate computer vision classification algorithms [27]. The f1 score in this case was 81.9%, comparable to similar experimental models in literature [28]. Training curves are reported in Appendix D, Table D2.

VII. DESIGN SAFETY AND REGULATIONS

Since the main objective of this project is increasing pedestrian safety, safety was considered an utmost priority throughout the design and testing process. To eliminate risks to pedestrians and drivers, all tests were conducted in the AVRIL driving simulator, which created a realistic environment for gathering eye-tracking and driving data. The study itself posed minimal risks, using the existing VI-Grade system in the AVRIL lab without additional modifications. Motion sickness, a known risk of using high-fidelity driving simulators, was monitored, and participants were asked to exit the study if they felt sick. Testing in the simulator did not involve vulnerable populations.

The design of the sign itself followed Ontario Traffic Manual standards [15], critical for driver comprehension in dynamic environments. Sign manufacturing was completed in partnership with Cedar Signs to ensure adherence to Ministry of Transportation specifications [29], using 3M Reflective Sheeting for nighttime visibility, weather-resistant inks and vinyls, and standard MTO-approved dimensions (60x60cm diamond, 60x30cm rectangular). The prototype, although in its early stages, includes safety features such as robust casings with cooling vents, a weighted base to prevent tripping, fused/insulated circuitry with voltage/power analysis, UL/CUL certified power components, and rounded edges to prevent injury.

The camera system operates in a controlled environment, using open-source datasets and explainable AI models to maintain ethical standards. No footage of unidentified individuals was collected. Image augmentation simulated various conditions (night, bright sun, fog, snow). This approach fulfills the Professional Engineers Ontario Code of Ethics requirements for "fidelity to public needs" and "competence in performance." [30]

VIII. LIMITATIONS OF DESIGNED SOLUTION

The use of a QFD and surveys helped to prioritize engineering requirements and designs, but were limited by convenience sampling that was not fully representative of diverse roundabout users [31]. Future work should use more rigorous methods such as stratified sampling (categorizing by driver status and location) or cluster sampling (random sampling within different neighborhoods) to more realistically represent the full spectrum of roundabout drivers.

Several limitations affected the simulator study. Eye-tracking data was successfully collected for only 5 out of 15 participants due to an unnoticed connection issue with the recording device, significantly reducing the sample size for fixation analysis. Participant demographics were also limited, with most individuals being 4th-year Engineering students, which is not representative as a sample of typical roundabout drivers. Additionally, some trials suffered from data logging errors in the Simulink model and WorldSim reference points, resulting in incomplete velocity and acceleration data for 2 out of 15 participants. Lastly, with more time and participants, the study could have tested a broader range of designs, including existing pedestrian beacons like PHBs or RRFBs for more comprehensive comparisons.

In terms of physical prototyping, only one functioning sign and floor light were built, though a full system would require four of each to cover a full intersection. As a result, the floor light was hard-coded to one crossing direction, and its brightness was insufficient for real roadway use. To illustrate the system's full functionality, a simplified diorama was created for demonstration purposes rather than technical validation. The computer vision model attached to the sign, while functional, was limited in precision due to the use of a lightweight, explainable model (Roboflow on Raspberry Pi, as opposed to a custom-trained model running on more powerful GPU-based hardware). Outdoor testing proved challenging due to the lack of a safe, controlled environment for pedestrian-vehicle trials, and the team did not have sufficient time to determine the right conditions for meaningful, controlled testing.

In future iterations, achieving and rigorously validating high-accuracy pedestrian detection, with minimal missed detections across varying weather and lighting conditions, will be critical to developing a safe, efficient and deployable system. Enhanced model accuracy and real-world testing should be treated as top priorities moving forward.

IX. CONCLUSIONS AND RECOMMENDATIONS

The project set out with three primary objectives: (1) designing novel pedestrian alert systems for roundabouts informed by stakeholder input, (2) evaluating these designs in a high-fidelity driving simulator, and (3) developing a proof-of-concept physical prototype. Through this work, pedestrian safety concerns at two-lane roundabouts were successfully addressed. By exploring alert concepts and signage strategies not found in existing literature, the project yielded actionable insights and concrete findings to inform future designs, simulation-based evaluation methods, and real-world implementation of new pedestrian safety systems.

The simulator study showed that placing an advance warning sign at the roundabout entry effectively reduced driver speeds, aligning with the goal of minimizing collision risk. In contrast, a light-up sidewalk, while less effective at slowing vehicles, was immediately helpful and intuitive to drivers for noticing pedestrians more easily. Notably, participants' understanding of the novel multi-crosswalk sign improved once they saw it in action, suggesting that while unfamiliar or complex alerts might initially create hesitation, they still hold strong potential. This highlights that innovation in traffic signalling does not have to be avoided due to uncertainty—investing time into testing and refining new solutions, especially in a low-risk simulator environment, can meaningfully improve safety outcomes for all road users.

Future work should prioritize enhancing objective (3) by improving the computer vision detection system to achieve higher accuracy across varying weather and lighting conditions at real crosswalk locations. A comprehensive field trial with multiple alert systems installed at a test roundabout would provide critical real-world validation. Additionally, expanding the participant demographics in simulation studies and incorporating vulnerable road user perspectives would strengthen the inclusivity of the design.

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APPENDIX A. Design Specification Methods

Relationship Matrix	
Correlation Level	Weight
Strong	9
Medium	3
Weak	1
None	0

Ideal Value Matrix		
Meaning	Symbol	
High	↑	
Low	↓	
Between a	range	

What	Customer Requirements \ Design Requirements	Who: Pedestrians / Bikers	Who: Drivers	Who: City Planners / Buyers	Successful pedestrian crossings	Driver ignoring pedestrian waiting to cross	Near collisions	Collisions	Time until looking at sign	Time until looking at pedestrian / crosswalk	Duration looking at sign	Duration looking at pedestrian / crosswalk	Time to brake	Duration of braking	Sign visibility	Pedestrian / light up crosswalk visibility	Community surveying / research costs	Materials and manufacturing costs	Installation and maintenance service costs	Electricity and operational costs	Heathcare / policing / legal cost burden	
					↑	↓	↓	↓	↓	↓	range	range	range	range	↑	↑	↓	↓	↓	↓	↓	Ideal Value
Real safety	Minimizing collisions	4.875	5	4.875	9	9	9	9	3	9	3	9	9	9	3	9	0	0	0	0	1	
	Minimizing near-collisions	4.375	4.5	3	9	9	9	9	3	9	3	9	9	9	3	9	0	0	0	0	1	
Percieved	Minimizing pedestrian anxiety	3.375	2.5	3.5	9	9	9	9	3	9	3	9	9	9	3	3	0	0	0	0	9	
	Minimizing driver anxiety	2.625	4.25	3.625	9	3	9	9	9	9	3	9	9	9	3	3	0	0	0	0	9	
Advance notice of pedestrian (design of signage)	Large size	3.75	4.125	4.125	9	9	9	9	9	0	9	0	9	9	9	0	3	9	9	9	3	
	Convenient location	4.375	4.75	4.5	9	9	9	9	9	0	9	0	9	3	9	0	0	0	3	1	0	
	Notable colour	3.875	3.875	3.875	3	3	9	9	9	0	9	0	9	3	9	0	1	9	3	0	1	
	Flashing	3.75	3.625	3.375	1	3	3	9	9	0	3	0	3	3	9	0	3	9	9	9	3	
	Familiar icons	3.125	3.625	4.25	1	1	1	3	3	0	3	0	3	3	3	0	0	3	1	1	0	
	Descriptive text	2.5	2.75	3.5	1	1	1	3	1	0	3	0	3	3	3	0	0	1	1	0	0	
Real time pedestrian visibility (at crosswalk)	Crosswalk (ground) lighting	3.75	3.5	3.25	3	9	9	9	0	9	0	9	9	9	0	9	9	9	3	9	1	
	Overhead lighting (visible from far	3.875	4.5	4.5	3	9	9	9	0	9	0	3	3	3	0	9	3	9	3	9	1	
	Four-season visibility (e.g. snow)	4.25	4.125	4.625	1	3	3	3	0	9	0	9	9	3	0	9	3	3	9	9	0	
	Night time visibility	4.375	4.75	4.625	3	9	3	3	0	9	0	9	9	3	0	9	1	3	3	9	0	
Technical Importance: Absolute	Pedestrians / Bikers				267.38	331.13	343.88	377.63	215.13	245.25	181.88	222.00	358.13	282.38	204.38	209.25	76.13	196.00	133.88	183.00	97.25	
	Drivers				286.00	344.25	364.50	399.00	235.25	261.00	193.50	234.00	378.75	298.50	215.25	220.50	76.88	204.50	140.25	192.88	105.38	
	City Planners / Buyers				272.50	331.75	349.00	384.75	225.88	246.38	190.88	219.38	365.25	287.25	211.13	203.63	73.75	202.25	137.50	187.63	106.13	
Technical Importance: Relative	Pedestrians / Bikers				0.07	0.08	0.09	0.10	0.05	0.06	0.05	0.06	0.09	0.07	0.05	0.05	0.02	0.05	0.03	0.05	0.02	
	Drivers				0.07	0.08	0.09	0.10	0.06	0.06	0.05	0.06	0.09	0.07	0.05	0.05	0.02	0.05	0.03	0.05	0.03	
	City Planners / Buyers				0.07	0.08	0.09	0.10	0.06	0.06	0.05	0.05	0.09	0.07	0.05	0.05	0.02	0.05	0.03	0.05	0.03	
Importance Rank	Pedestrians / Bikers				3	2	2	1	4	4	5	4	2	3	5	5	7	5	6	5	6	
	Drivers				4	3	2	1	5	5	6	5	2	4	6	6	8	6	7	6	7	
	City Planners / Buyers				4	3	2	1	5	5	6	5	2	4	6	6	9	6	7	6	8	
Average Level of Importance					4	3	2	1	5	5	6	5	2	4	6	6	8	6	7	6	7	

Importance Level Scale

Not Important → Important

Figure A1. QFD Analysis for Pedestrian, Driver, and City Planner Needs

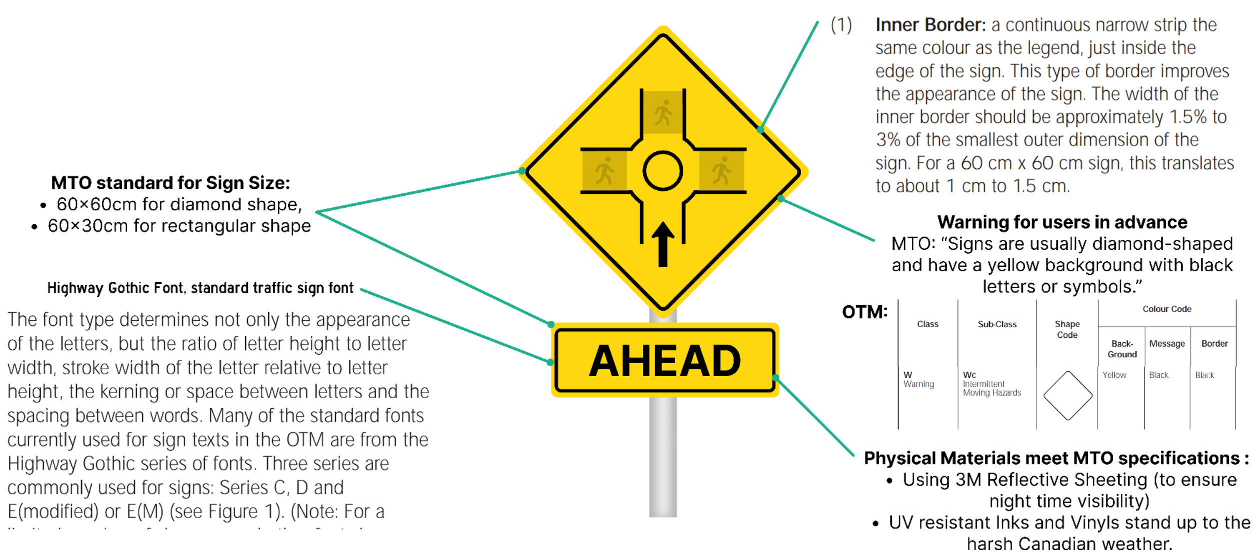

Figure A2. Sign Design Rationales

APPENDIX B. Sustainability Report

People Impacts	Initial Score	New Score	Change
Labor Practices and Decent Work	2.9	4.3	1.4
Society and Customers	2.7	4.5	1.8
Human Rights	3.8	5.0	1.3
Ethical Behavior	3.0	3.8	0.8
Overall People New Score		4.4	
Planet Impacts	**Initial Score**	**New Score**	**Change**
Transport	2.8	3.3	0.5
Energy	4.0	2.3	-1.7
Land Air, and Water	3.0	2.8	-0.2
Consumption	4.8	3.8	-1.0
Overall Planet New Score		3.0	
Prosperity Impacts	**Initial Score**	**New Score**	**Change**
Project Feasibility	3.3	4.5	1.3
Business Agility	2.5	4.5	2.0
Local Economic Impact	2.7	3.7	1.0
Overall Prosperity New Score		4.2	
Overall Lifespan Lens Project Scores	**Initial Score**	**New Score**	**Change**
	15.1	19.0	3.9

Figure B1. Green Project Management Workbook Scores

APPENDIX C. AVRIL Driving Simulator Study

Table C1. Independent and Control Variables for Simulator Study

Type	Variable	Possible values	Notes
Control	Roundabout type	Two-lane roundabouts	Studying 2-lane roundabouts specifically is justified by literature
Control	Placement of advance warning sign	Center island, in front of entry leg (visible to the driver when they're stopped and ready to enter)	Justified by literature, professional stakeholder interviews, field observations of existing signs (i.e. we're uniquely trying to study this new sign location)
Control	Setting	Cloudy, Dusk, Dry	
Can't control	Demographics of driver	Young adults, registered in University	Ideally would ensure a wide range of demographics, especially wide age range
Control	Traffic volume	Mimicking actual traffic volume from Ira Needles is not feasible, as it causes significant disruption to the participant's ability to drive through the simulated roundabout. Actual value: ~10 cars in the simulation	Ideal value: from actual traffic flow at Ira Needles roundabout with available data. [11] AADT within roundabout: 43,305 One simulation pass is ~1 minute. Therefore, 30 vehicles on each leg of road + roundabout in the simulation.
Control	Pedestrian count	1 pedestrian	We will always have a pedestrian crossing, as it doesn't make sense to test when our alert system "fails"
Control	Pedestrian crossing	Will always appear within the crosswalk. Crosses from	Can control this by triggering the pedestrian to cross depending on where

	position	the center block between crosswalks → outside.	the driver is.
Control	Pedestrian speed	1.2 m/s [32]	
Can't control	Driver experience	Varies in how often they drive.	Would ideally control for X amount of driving hours, or look at a variety of experiences.
Control	Experience in simulator	Minimal to no prior experience	Level the playing field by doing practice drives

Table C2. Independent Variable Levels and Factorial Design Considerations

Independent variable	Levels	Factorial design considerations
Vehicle turning movement through roundabout	4 levels	4 * 6 * 3 = 72 possible combinations for a full factorial design. Objective: choose a subset of these 72 possible trials, ideally ~15, that will: ● Minimize confounding between the effects of different independent variables ● Prioritize being able to distinguish the effect of the **alert system combination** variable, above others
Alert system combination	6 levels	
Exit where pedestrian is crossing	3 levels	

Table C3. Final List of Experiment Scenarios Per Participant

Trial	Driver's Direction	Alert Combination	Ped. Crossing
1	Left	Sign 2 + crosswalk	Straight ahead
2	Straight (left lane)	Crosswalk	To driver's left
3	Straight (right lane)	None	To driver's left
4	Straight (right lane)	Sign 2 + crosswalk	To driver's right
5	Left	Sign 3	To driver's left
6	Straight (left lane)	None	To driver's right
7	Left	Sign 3 + crosswalk	To driver's left
8	Left	Sign 3 + crosswalk	Straight ahead
9	Straight (right lane)	Sign 3	Straight ahead
10	Right	Crosswalk	Straight ahead
11	Left	Sign 2	To driver's right
12	Right	Sign 3	To driver's right

13	Left	Crosswalk	To driver’s left
14	Right	Sign 2	To driver’s left
15	Straight (left lane)	Sign 2	Straight ahead
16*	Left	None	To driver’s left

* Trial 16 was added retrospectively and completed by 4/15 participants, upon realizing that additional information was needed to study drivers’ braking behaviour with no alerts present.

```
              direction  alert  ped_crossing
direction          1.00  -0.06          0.09
alert             -0.06   1.00         -0.02
ped_crossing       0.09  -0.02          1.00
```

Figure C1. Independent Variable Correlation Values for D-Optimal Selected Trials

```
Repeated-Measures ANOVA for Alert Combination:
             Source           SS  DF          MS         F     p-unc  \
0  Alert_Combination   552.292752   5  110.458550  4.313364  0.002033
1             Error  1536.506739  60   25.608446       NaN       NaN

   p-GG-corr       ng2       eps sphericity   W-spher   p-spher
0   0.026577  0.189566  0.386777      False  0.018865  0.000331
1        NaN       NaN       NaN        NaN       NaN       NaN
```

Figure C2. Repeated Measures ANOVA Results for Alert Combination Affecting Average Velocity

```
Post-hoc tests:
             Contrast                  A                  B  Paired  \
0   Alert_Combination          Crosswalk           No alert    True
1   Alert_Combination          Crosswalk             Sign 2    True
2   Alert_Combination          Crosswalk  Sign 2 + crosswalk   True
3   Alert_Combination          Crosswalk             Sign 3    True
4   Alert_Combination          Crosswalk  Sign 3 + crosswalk   True
5   Alert_Combination           No alert             Sign 2    True
6   Alert_Combination           No alert  Sign 2 + crosswalk   True
7   Alert_Combination           No alert             Sign 3    True
8   Alert_Combination           No alert  Sign 3 + crosswalk   True
9   Alert_Combination             Sign 2  Sign 2 + crosswalk   True
10  Alert_Combination             Sign 2             Sign 3    True
11  Alert_Combination             Sign 2  Sign 3 + crosswalk   True
12  Alert_Combination  Sign 2 + crosswalk            Sign 3    True
13  Alert_Combination  Sign 2 + crosswalk  Sign 3 + crosswalk   True
14  Alert_Combination             Sign 3  Sign 3 + crosswalk   True
```

```
    Parametric         T   dof alternative     p-unc    BF10    hedges
0         True  0.484984  12.0   two-sided  0.636421   0.308  0.200830
1         True  2.740529  12.0   two-sided  0.017914   3.615  0.982824
2         True  1.796722  12.0   two-sided  0.097576   0.977  0.586116
3         True  2.733486  12.0   two-sided  0.018149   3.578  1.131168
4         True  2.028914  12.0   two-sided  0.065253   1.318  0.778601
5         True  2.259454  12.0   two-sided  0.043253   1.805  0.755001
6         True  1.080386  12.0   two-sided  0.301206   0.454  0.349906
7         True  3.861830  12.0   two-sided  0.002261  19.869  0.908185
8         True  2.053217  12.0   two-sided  0.062516   1.362  0.541989
9         True -2.518675  12.0   two-sided  0.026975    2.61 -0.613409
10        True  0.853779  12.0   two-sided  0.409947    0.38  0.251809
11        True -1.316251  12.0   two-sided  0.212678   0.567 -0.367126
12        True  2.729282  12.0   two-sided  0.018291   3.555  0.851865
13        True  1.321203  12.0   two-sided  0.211072    0.57  0.282361
14        True -2.994503  12.0   two-sided  0.011180    5.29 -0.626566
```

Figure C3. Paired t-test Results for Alert Combination Affecting Average Velocity

```
Repeated-Measures ANOVA for Alert Combination:
             Source        SS  DF        MS         F     p-unc       ng2  \
0  Alert_Combination  1.685362   3  0.561787  1.140026  0.384207  0.020977
1             Error  4.435064   9  0.492785       NaN       NaN       NaN

        eps
0  0.482178
1       NaN
```

Figure C4. Repeated Measures ANOVA Results for Alert Combination Affecting Minimum Braking Acceleration

APPENDIX D. Validation of Physical Prototype

Table D1. Electrical draws of prototype parts

Part	Voltage	Current	Resistance	Power
For main sign+ floor light prototype				
Floor Light	5V	1.2A	4.17 Ω	6W
LEDs for sign	12V	152.7mA at 12V for 30 LEDS 42 LEDs per section Total 126 LED bulbs (152.7mA/30)*126 = 0.64134A total	18.71 Ω	7.70W
Relay	5V (per relay) input logic level			
Logic level converters	3.3V input 5V output			
Raspberry PI	3.3 V logic output			
For diorama				
Arduino	5V output			

Table D2. Computer Vision Validation Report

Metrics for Test Set

Trained On: yolov9human-2u7yv *1102 Images* View Version →
Model Type: Roboflow 3.0 Object Detection (Fast)
Checkpoint: COCOn

mAP 85.7% | Precision 86.4% | Recall 77.9%

View Model Graphs →

F1 score = 2*(precision*recall)/(precision+recall)2*(0.864*0.779)/(0.864+0.779)= 0.819

Training curves