Cruise AV SF Incident—Pedestrian Collision (Exponent Project 2310645.000)

Technical Root Cause Analysis

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December 12, 2023

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Acronyms and Abbreviations

ABS	Anti-lock Braking System
ADS	Automated Driving Systems
AV	Autonomous Vehicle
[redacted]	[redacted]
DDT	Dynamic Driving Task
DDT-F	Dynamic Driving Task, Fallback
EV	Electric Vehicle
GPS	Global Positioning System
[redacted]	[redacted]
Lidar	Light Detection and Ranging
ODD	Operational Design Domain
[redacted]	[redacted]
MRC	Minimum Risk Condition
[redacted]	[redacted]
NHTSA	National Highway Traffic Safety Administration
ODD	Operational Design Domain
Radar	Radio Detection and Ranging
RCA	Root Cause Analysis
SGO	Standing General Order
[redacted]	[redacted]
TCS	Traction Control System
VIN	Vehicle Identification Number
VRU	Vulnerable Road User

Limitations

This report summarizes Exponent's work performed to-date as part of its independent, third-party technical root cause analysis of the incident that occurred on October 2, 2023, at approximately 9:29 PM PDT, and presents the findings resulting from that work. The findings presented herein are made to a reasonable degree of engineering and scientific certainty. Exponent relied upon information and data provided by Cruise to conduct its investigation and develop root cause and contributing factors assessments. Exponent cannot guarantee the accuracy or completeness of this source material; however, Exponent exercised usual and customary care in the conduct of these analyses represented in this document, including the assessment of source material provided by Cruise. Exponent reserves the right to supplement this report and to expand or modify findings and conclusions based on review of additional material as it becomes available through ongoing discovery, if any, and/or through any additional work or review of additional work performed by others. A review of Cruise's overall safety systems, culture, and technology is beyond the scope of this investigation.

Executive Summary

Exponent was retained by Cruise to perform an independent, third-party technical root cause analysis of the incident that occurred on October 2, 2023, at approximately 9:29 PM PDT. The incident occurred in the area of the intersection between Cyril Magnin Street, where it transitions to 5th Street, and Market Street in San Francisco, California. A Cruise autonomous vehicle (AV) named [redacted] operating in autonomous mode, was stopped at a red light at the intersection in the rightmost of two southbound driving lanes, and a Nissan Sentra (Nissan), operated by a human driver, was stopped in the adjacent lane to the left of the AV, traveling in the same direction. When the light turned green, both vehicles proceeded through the intersection, crossing Market Street. As the vehicles proceeded southbound through the intersection, a pedestrian traversed the opposite crosswalk from the southwest corner of the intersection traveling east, against a "*Do Not Walk*" pedestrian signal. The pedestrian proceeded through the AV's lane of travel (right lane), paused in the Nissan's lane of travel (left lane), and was subsequently struck by the Nissan. The Nissan's brake lights illuminated post-collision indicating that the Nissan hit the pedestrian without braking. The collision with the Nissan threw the pedestrian into the AV's lane of travel. The AV struck the pedestrian before coming to an initial stop, which lasted less than 0.1 s, and the AV then proceeded forward approximately 20 feet, dragging the pedestrian, before the AV stopped again at its final point of rest.

Exponent's investigation focused on identifying the technical root cause and the contributing factors relevant to the AV's overall behavior, responses, and actions during this incident, which first included an evaluation of the root cause of the AV-pedestrian collision and, second, the AV's post-collision response. Prior to Exponent's investigation, Cruise performed its own root cause analysis. As part of Exponent's investigation, Exponent reviewed Cruise's root cause analysis along with video and other data collected by the subject AV before, during, and after the incident; engineering and system documentation; vehicle maintenance records; the traffic collision report; the Standing General Order report provided by Cruise to the National Highway Traffic Safety Administration, as well as documentation and videos provided to government officials; and other relevant records and technical and scientific literature. Additionally, Exponent inspected the [redacted] vehicle, assessed the AV's recorded data of the event using Cruise's Webviz open-source data visualization tool, and met with Cruise engineers both in-person and remotely on numerous occasions. Exponent did not identify any evidence of reported vehicle, sensor, actuator, or computer hardware failures or software faults that could have contributed to the incident. The subject AV maintenance records did not show any persistent issues pertinent to the incident.

Leading up to the collision between the Nissan and pedestrian, the AV accurately detected, classified, and tracked both the pedestrian and the Nissan. As the Nissan approached the in-path pedestrian, who was first crossing and then paused in lane, the AV's predicted paths for the pedestrian and Nissan became consistent with a potential collision. The Nissan was traveling at a speed of approximately 21.7 mph when it struck the pedestrian without braking. At the same time as the collision between the Nissan and pedestrian, the AV was traveling at a speed of approximately 17.6 mph and was not predicting that either the Nissan or the pedestrian would enter the AV's travel path. The collision between the Nissan and pedestrian occurred approximately 2.9 s before the collision between the AV and the pedestrian.

Following the collision between the Nissan and the pedestrian, the pedestrian remained engaged with the Nissan for approximately 1.7 s, first at the vehicle hood and then tumbling to the roof. During this time, the Nissan moved left, crossing the centerline into the lane of oncoming traffic. Approximately 1.0 s after contact between the Nissan and the pedestrian, the Nissan moved right toward the AV travel lane. The pedestrian then separated from the Nissan approximately 1.17 s prior to the collision between the AV and the pedestrian. At this separation time, the AV was traveling at a speed of approximately 17.9 mph and was approximately one car length behind the Nissan in the adjacent right lane. The brake lights on the Nissan illuminated approximately 0.1 s after the Nissan struck the pedestrian. The AV was traveling at approximately 18.4 mph when the tumbling pedestrian was thrown at an unknown velocity and landed face down in the left region of the traffic lane occupied by the approaching AV, approximately 0.78 s prior to being struck by the AV. The Nissan came to rest at a small, clockwise angle relative to its lane of travel with the right front tire positioned near the white lane stripe.

As evidenced by the video and sensor data, the classification and tracking of the pedestrian became intermittent within 1.0 s after the initial contact between the pedestrian and the Nissan until the last correct object classification occurred at approximately 0.3 s prior to the collision between the AV and the pedestrian. This intermittent classification and tracking of the pedestrian led to an unknown object being detected but not accurately tracked by the automated driving system (ADS) of the AV and the AV detected occupied space in front of the AV. The ADS started sending steering and braking commands to the vehicle at approximately 0.25 s prior to the collision between the AV and the pedestrian due to the detection of occupied space in front of the AV. Consequently, just prior to the collision with the pedestrian, the AV's heading momentarily changed rightward, and the vehicle began decelerating. This deceleration resulted in a vehicle speed reduction from approximately 19.1 mph, prior to the onset of braking, to approximately 18.6 mph at the time of impact with the pedestrian. After the AV's front bumper first contacted the pedestrian, the ADS collision detection system detected a collision. In order to determine the location of

impact, the collision detection system refers to available object tracking information immediately prior to the detected impact. In the time immediately prior to impact, the pedestrian was substantially occluded from view of the lidar sensors, which facilitate object detection and tracking for the collision detection system. Only the pedestrian's raised leg, which was bent up and out toward the adjacent lane, was in view of these lidar sensors immediately prior to collision. Due to a lack of consistent detections in this time frame, the tracking information considered by the collision detection system did not reflect the actual position of the pedestrian. Consequently, the collision detection system incorrectly identified the pedestrian as being located on the side of the AV at the time of impact instead of in front of the AV and thus determined the collision to be a side impact. After contacting the pedestrian, the AV continued decelerating for approximately 1.78 s before coming to its initial stop with its bumper position located forward of the Nissan. The AV's left front wheel ran over the pedestrian and triggered an anti-lock braking system event approximately 0.23 s after the initial contact between the pedestrian and the AV's front bumper.

The determination by the ADS that a side collision occurred, and not a frontal collision, led to a less severe collision response being executed and resulted in the AV performing the subsequent outermost lane stop maneuver instead of an emergency stop. After coming to its initial stop, the AV began moving again, approximately 1.83 s after the initial contact between the pedestrian and the AV, to accomplish its outermost lane stopping maneuver. During this maneuver, the AV reached a speed of 7.7 mph and traveled approximately 20 feet while dragging the pedestrian before reaching its final rest position. The pedestrian's feet and lower legs were visible in the wide-angle left side camera view from the time of the collision between the pedestrian and the AV through to the final rest position of the AV. The ADS briefly detected the legs of the pedestrian while the pedestrian was under the vehicle, but neither the pedestrian nor the pedestrian's legs were classified or tracked by the ADS after the AV contacted the pedestrian. A traction control system event was recorded at approximately 3.8 s after the initial contact between the pedestrian and the AV due to the pedestrian physically resisting the motion of the vehicle. An accumulated offset between the wheel rotation of the left-rear wheel relative to the others from the wheel speed sensors led to the AV entering a degraded state approximately 5.8 s after the initial contact between the pedestrian and the AV. This degraded state caused the vehicle to initiate an immediate stop, and the vehicle reached its final point of rest approximately 8.8 s after the initial contact between the pedestrian and the AV.

The AV's collision with the pedestrian was caused by the pedestrian being projected in the AV's path of travel due to the collision with the Nissan. Calculations of potential AV stopping distance indicate that a collision of the AV with the pedestrian may not have been avoidable, even if the ADS had reacted to the

collision between the Nissan and the pedestrian. The AV's lack of anticipation of a potential future incursion of the pedestrian into its travel lane was a contributing factor to this incident. Reasonable human drivers would face challenges reacting to the pedestrian being projected into their lane of travel and would likely not have been able to avoid the collision under similar circumstances. This difficulty could be due to violations of expectancy, glare, or A-pillar obstruction, or a combination of these, as well as to a failure to predict the collision of the Nissan with the pedestrian in the adjacent lane and/or the resulting redirection of the pedestrian into their lane of travel. Moreover, reasonable human drivers would not likely have had adequate time to avoid the collision once the pedestrian was struck by the Nissan.

The root cause of the AV's post-collision movement, after the initial brief stop, was the inaccurate determination by the ADS that a side collision had occurred, which led to the triggering of an outermost lane stop maneuver instead of an emergency stop. Because all non-vehicles are treated in the same manner as a pedestrian with respect to a post-collision response, the intermittent classification of the pedestrian was not a contributing factor to the post-collision response. However, due to the inaccuracy of the object track considered by the collision detection system and the resulting disparity between this track and the pedestrian's actual position, the ADS failed to accurately determine the location of the pedestrian at the time of impact and while the pedestrian was underneath the vehicle. This contributed to the inaccurate side collision determination and the post-collision movement of the AV. When the AV came to an initial stop after the AV-pedestrian collision, the AV was already occupying the outermost lane and therefore, satisfied the location requirement for an outermost lane stop. However, the ADS did not consider this location as an acceptable stopping location because the outermost lane edge was mislabeled in the semantic map. This inaccurate determination by the ADS that it was not already in an acceptable stopping location was a contributing factor to the post-collision movement of the AV. After the AV contacted the pedestrian, an alert and attentive human driver would be aware that an impact of some sort had occurred and would not have continued driving without further investigating the situation.

1 Background

1.1 Incident Summary

Based on the information currently available, the subject incident occurred on October 2, 2023 at approximately 9:29 PM PDT[1] in the area of the Cyril Magnin Street and Market Street intersection in San Francisco, California (Figure 1 and Figure 2). Approaching the incident location from the north, Cyril Magnin Street intersected Market Street at a perpendicular orientation. South of the intersection, Cyril Magnin Street transitioned to 5th Street. Cyril Magnin Street/5th Street was a northwest to southeast oriented roadway that included two north and two southbound traffic lanes separated by a yellow painted centerline. In the area of the incident on southbound 5th Street, a dedicated bike lane separated from vehicle traffic by flexible vertical markers was available between the right through lane and adjacent curb. Vehicle travel was controlled by traffic signals located on each corner of the intersection. For pedestrians, signal-controlled crosswalks were also available. The speed limit for southbound traffic was 25 mph[2].

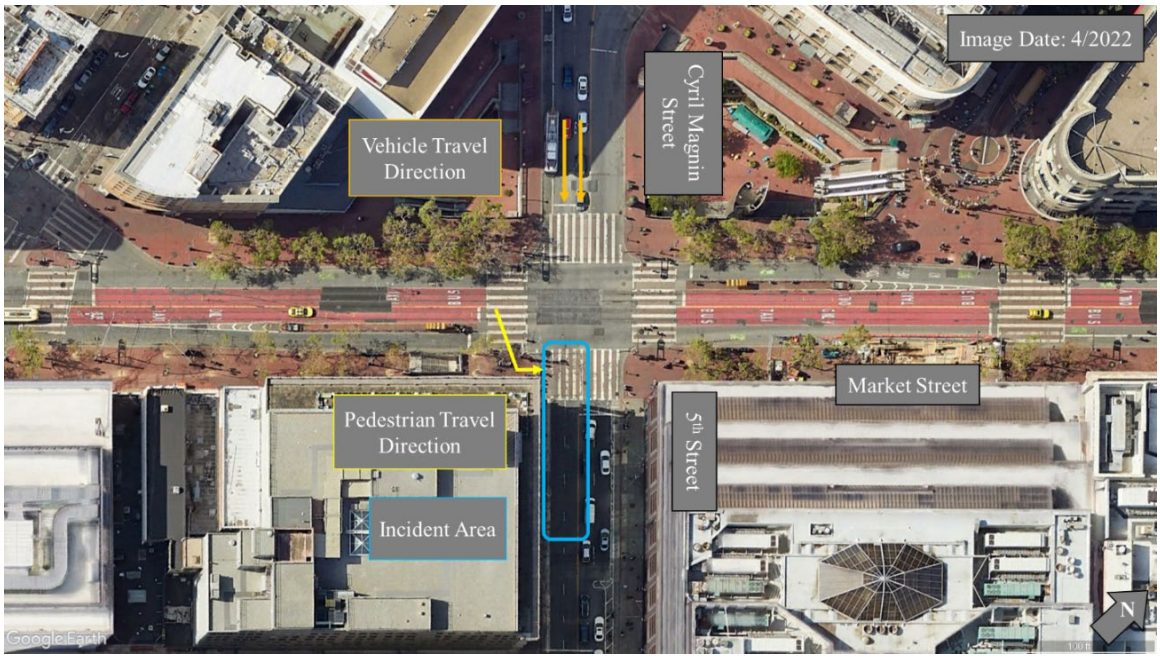


Figure 1. Annotated aerial image depicting incident area and generalized travel paths of the two vehicles and pedestrian. The image was rotated clockwise for clarity when referring to directionality.

[1] Incident Report (NHTSA Standing General Order), Report No. 30412-6395-2

[2] Incident Report (NHTSA Standing General Order), Report No. 30412-6395-2

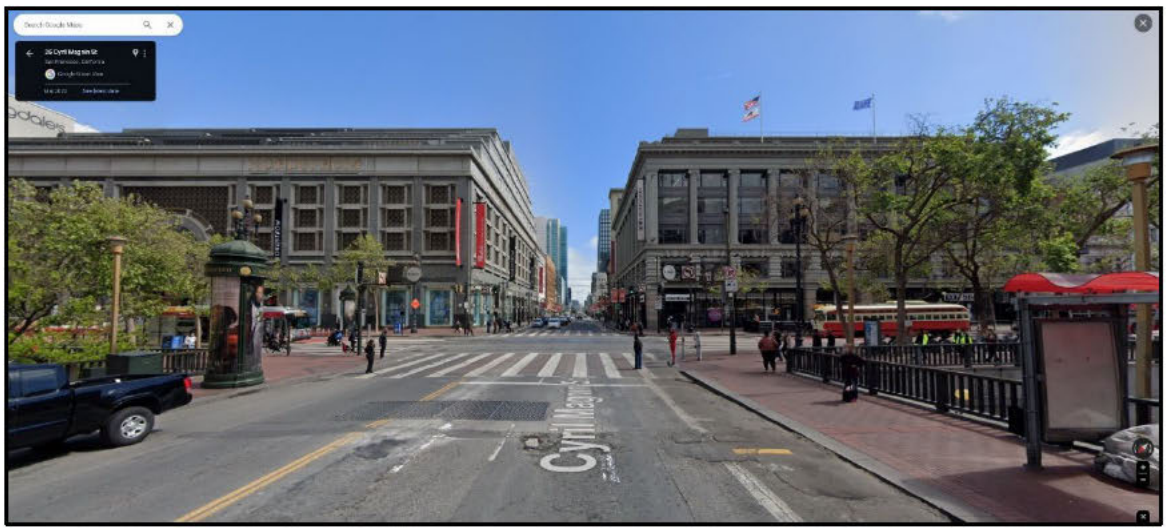


Figure 2. Street view image depicting approach to Market Street from the north and surrounding infrastructure.

The Cruise Autonomous Vehicle (AV) was equipped with an onboard sensor system capable of recording video in numerous directions surrounding the exterior of the vehicle. This footage was provided to Exponent for independent review and analysis, and it provided information regarding the accident sequence and vehicle environment. In addition to other currently available information, the video was considered in generating the following incident summary.

Immediately preceding the subject incident, the AV, operating in autonomous mode, was occupying the outside (right) through lane of southbound Cyril Magnin Street and was stopped for a red traffic signal near the stop bar at Market Street. At the same time and location, a human-driven Nissan Sentra (Nissan) was positioned adjacent to the AV, stopped in the inside (left) through lane. As the AV was stopped, a pedestrian traveled through the adjacent crosswalk (across Market St.) and paused at the 5th Street crosswalk. After the traffic signal turned green, both vehicles proceeded southbound while the pedestrian entered the 5th Street crosswalk and advanced to the east, against a "*Do Not Walk*" pedestrian signal. While in the crosswalk, the pedestrian paused and was struck by the front of the Nissan. During this interaction, the pedestrian was carried to the south with the Nissan before separating and being redirected, falling to the ground within the AV's travel lane. The AV struck the pedestrian before coming to a stop. From its initial point of rest, the AV then moved forward, dragging the pedestrian, before reaching its final point of rest. The AV's onboard video indicated that at the time of the incident, the roadway was dry and it was dark with lighting present in the area of the intersection. Other vehicle and pedestrian traffic was present in the area, as can be observed in the incident video.

1.2 Subject Vehicle Description

The Subject Vehicle is a model year 2023 Cruise AV (AV), which is small 4-door hatchback with an electric powertrain and is built on the Chevrolet Bolt electric vehicle (EV) platform. The AV bears the name [redacted], and the Vehicle Identification Number (VIN) is 5G21A6P0XP4[redacted]. According to the VIN plate, the AV was manufactured in February 2023 (Figure 3). The Cruise Automated Driving System (ADS), with a [redacted] hardware version and d[redacted] software version, was added to the base Bolt EV platform.[3] A review of the National Highway Traffic Safety Administration's (NHTSA's) recall database showed that the [redacted] vehicle did not have any unrepaired recalls. At the time of the subject collision, the Bolt had approximately 5,091 miles on the odometer.[4]



Figure 3. Photographs showing the rear of AV (left), vehicle moniker label on left side C-pillar (top-right), and vehicle VIN sticker (bottom-right).[5]

Exponent performed a limited inspection of the AV. Photographs of the exterior of the vehicle can be found in Figure 4 below. During the inspection, the state of the vehicle was documented, and no visible structural damage was observed.

[3] Incident Report (NHTSA Standing General Order), Report No. 30412-6395-2

[4] Incident Report (NHTSA Standing General Order), Report No. 30412-6395-2

[5] Exponent Inspection of subject Cruise AV



Figure 4. Photographs of the outside of the AV.

Upon request, Cruise provided Exponent with the work order history of the AV. This included a total of 19 work orders starting on June 20, 2023 and ending on October 2, 2023. A review of the work orders and related documents indicated that there were no detected hardware or software faults that contributed to the incident.

The majority of the work orders related to work carried out in order to bring the vehicle into service and were not tied to any faults or issues with the base vehicle or ADS. On the morning of October 2, 2023, the morning of the incident, a work order was issued due to a request from the vehicle for recalibration of the right front camera.[6] The work order creation date and time was noted as 10/02/2023 at 04:33:15 PDT, and the completion date and time was noted as 10/02/2023 at 11:41:56 PDT. As part of this work order, sensor cleaning was performed, and calibration tests were completed to confirm that the issue was resolved. [redacted] As shown in Figure 5, the AV was not in a degraded state immediately prior to the incident on October 2, 2023.

[6] Documentation pertaining to Work Order No. [redacted]



Figure 5. Degraded state status of the AV over a 70 s time window with t=0 corresponding to a time of approximately 21:28:27 PDT.

1.3 Cruise ADS System Description

The Cruise ADS consists of multiple hardware and software subsystems. While the interaction of these subsystems and their contribution to overall ADS performance is a complex topic, we provide a high-level description of primary inputs and software subsystems relevant to our root cause analysis. [redacted] These subsystems are not described in detail below, but they will be discussed as needed for our analysis. A high-level system diagram depicting the main subsystems of the Cruise ADS that are relevant for this analysis is shown in Figure 6.



Figure 6. High-level system diagram of Cruise ADS.[7]

[7] The system diagram is a non-exhaustive representation of the subsystems and interactions of the ADS. [redacted]

1.3.1 Sensing

The AV is equipped with a suite of sensors to enable perception, prediction, and motion planning. These include [redacted] cameras, [redacted] lidars, [redacted] roof mounted radars, [redacted] ultra-short-range radars, and microphones.[8] [redacted] Figure 7 shows some of the externally visible sensors mounted on the roof of the AV.



Figure 7. Roof mounted sensor array which includes lidars, cameras, and radars.

[redacted]

[8] Exponent inspection of Cruise AV enabling hardware.

[9] Cruise LLC's Responses to NHTSA's October 20,2023, Interim Information Request in Preliminary Evaluation 23-018.

[redacted][10]

In addition to lidars, cameras, radars, and microphones, a multitude of other sensors are equipped on the AV, which enable vehicle state estimation and prediction. [redacted]

1.3.2 Perception

[redacted]

As mentioned previously, the AV has an array of different sensors which enable object detection and classification. [redacted]

[redacted]

[10] Cruise LLC's Responses to NHTSA's October 20,2023, Interim Information Request in Preliminary Evaluation 23-018.

[11] [redacted]

[12] [redacted]

[13] [redacted]

[redacted]



Webviz was developed by Cruise as an open-source data visualization tool.[14] Within Webviz, it is possible to visualize the perception data related to these subsystems as well as individual sensors. [redacted] Two examples of visualized camera and lidar data are depicted in Figure 8.

[14] https://getcruise.com/technology/



Figure 8. Example of how object classifications are visualized in Webviz [redacted]

In addition to object classification, Webviz facilitates observations of object tracking. Figure 9 shows an image captured in Webviz with two tracked objects and the perception subsystems associated with each object at that instance.[15]

15 [redacted]



Figure 9. Example of two tracked objects depicted in Webviz with overlaid information.



Figure 10.

[redacted]

1.3.3 Prediction

The Cruise ADS employs an end-to-end deep learning-based prediction model in order to interpret the motion of tracked objects and contextual scene information in order to generate predicted object trajectories. [redacted] This may be used to plan the AV's trajectory, causing it to yield or adjust its course, among other things.

1.3.4 Planning

The planning system is responsible for orchestrating the AV's actions [redacted]

[redacted] A diagram depicting the architecture of the motion level of the planning system is shown in Figure 11.



Figure 11. High-level system diagram of Cruise ADS Planning system.[16]

[redacted]

[16] The diagram shows an abstract view [redacted] and does not represent a comprehensive view of the planning system functionality.

[redacted]



Figure 12.



1.3.5 Cruise ADS Collision Protocol

Collision Detection

The collision detection system facilitates detections of contact with the exterior of the AV. The collision detection system relies on output from [redacted], as well as from other collision detection enabling hardware. The system's enabling hardware includes [redacted] When a dynamic threshold (which considers the various data streams) is exceeded, a potential collision is determined to have occurred, at which point the collision severity is estimated. Collision severity levels are ranked by the Cruise ADS according to injury likelihood, with lower levels corresponding to a greater risk of injury (inversely proportional to the Maximum Abbreviated Injury Scale (MAIS), which ranks injury severity with lower levels corresponding to a lesser degree of injury).

Several variables are considered when assigning a collision severity and prescribing a stopping maneuver response. The collision detection system considers the object type, [redacted]. For the purpose of collision detection, [redacted] only determines whether an object is a motor vehicle/large object or a vulnerable road user (VRU)/small object. With respect to collision severity classification and response, all non-motor vehicle/large objects, including unclassified objects and objects classified as Pedestrians, are all treated as VRUs, which are human road users that are not occupying vehicles.

The impact location is also relevant for estimating the collision severity. [redacted] The collision detection system estimates whether the collision occurred to the front, rear, left side, or right side of the vehicle. This concept is depicted in Figure 13.



Figure 13. [redacted][17][redacted][18]

Finally, the collision speed is considered for collision classification. [redacted] The thresholds for collision classification are shown in Table 3.

[17] Exponent inspection of AV's code pertaining to collision detection.

[18] Cruise AV Point of Impact Concept | Cruise, May 9, 2021

[redacted]

Collision Response

Upon detecting a potential collision, the ADS performs a stopping maneuver based on the collision classification (Table 3), which varies according to the estimated severity of the collision. A taxonomy of stopping maneuvers for the AV is outlined in Table 4. [redacted]

[redacted]

[19] Collision Classification Mapping | Cruise, July 19, 2023

[20] [redacted]

[21] Cruise AV Stopping Maneuver Taxonomy | Cruise, October 13, 2023

Cruise implemented the [redacted] maneuver to enable the AV to reposition itself, if possible, to a Minimal Risk Condition (MRC) away from active traffic after a triggering event. Because the execution of an [redacted] "Outermost Lane Stop" is a key event in the incident sequence, Exponent reviewed Cruise documentation defining the design intent and justification of the criteria for allowable pullover areas. [redacted]

1.3.6 Degraded State

Critical hardware and software systems, which enable ADS functionality, are continuously monitored for system malfunctions to ensure nominal performance. If a system malfunction is detected, the AV may switch to a backup system or perform a maneuver to achieve an MRC. Cruise defines a degraded state (DS) as "the presence of one or more latched failures," which corresponds to "the residual driving capability that the AV has to achieve an MRC."[22] Cruise's DS taxonomy assigns a number or rank according to estimated residual driving performance, with higher degraded state numbers corresponding to less residual driving capability.[23]

[22] Cruise Safety Report. Nov, 2022.

[23] Cruise Safety Report. Nov, 2022.

Table 5. Degraded state taxonomy[24]

Degraded State	Description
DS1	The Cruise AV has a benign latent malfunction indicating the need for service and maintenance attention. The Cruise AV maintains full capability to perform the dynamic driving task ("DDT") and dynamic driving task fallback ("DDT-F"). The malfunction does not lead to a hazard so normal vehicle use until the end of the day (or until the next vehicle power cycle) is expected. The Cruise AV can continue all on-road operations for the remainder of the shift.
DS2	The Cruise AV has a tolerated malfunction in a safety system and maintains the capability to perform the DDT and DDT-F and return to the fleet service facility for repair. The Cruise AV is capable of completing the current mission by falling back to stricter driving constraints or limitations as needed, to help maintain an acceptable level of performance until the Cruise AV returns to the fleet service facility and the issue is resolved. The Cruise AV is recovered by the Field Support team at the fleet service facility for repair. No new fleet operations will be assigned to the Cruise AV in this state.
DS3	The Cruise AV has a system malfunction that results in degraded vehicle performance risking the ability to perform the DDT or DDT-F. The Cruise AV is capable of pulling over to a safe location at the side of the road, followed by engaging Park state and activating hazard flashers. The Cruise AV is retrieved by a Field Support team and returned to a fleet service facility for repair. No new fleet operations will be assigned to the Cruise AV in this state.
DS4	The Cruise AV has partial loss of primary autonomous driving functionality, requiring fallback to the secondary autonomous driving functionality to perform the DDT-F. The Cruise AV is capable of gradually slowing to a stop while steering to a safe location out of high-risk areas such as intersections, followed by engaging its transmission in "Park" and activating its hazard flashers. The Cruise AV is retrieved by a Field Support team and returned to a fleet service facility for repair. No new fleet operations will be assigned to the Cruise AV in this state.
DS5	The Cruise AV has a total loss of primary Autonomous Driving functionality. The Cruise AV can quickly slow down to a stop in its lane of travel, followed by engaging its transmission in "Park" and activating its hazard flashers. The Cruise AV is retrieved by a Field Support team and returned to a fleet service facility for repair. No new fleet operations will be assigned to the Cruise AV in this state.

[24] Cruise Safety Report. Nov, 2022.

2 Investigation Process

Exponent's scope of work was to perform an independent, third-party technical root cause analysis, of the October 2 incident involving a Nissan Sentra (Nissan), pedestrian, and AV. This includes the identification of salient events that occurred throughout the relevant time period leading up to, and following, the AV's collision with the pedestrian, along with an investigation into the causes and contributing factors that substantively impacted the outcome of each event. Because of the complexity of the interactions between the AV, the subject pedestrian, the adjacent Nissan that first collided with the pedestrian, and the environment, it is not possible to assign a single root cause to this incident. Instead, the technique used in this analysis was to identify and understand the root cause and contributing factors, each of which contributed in a potentially substantive way to the outcome of this incident. Due to the timeframe-imposed limitations, Exponent could not evaluate all design and performance aspects of the ADS software as they related to the salient events.

2.1 Data Collection

Exponent relied on documentation provided by Cruise to understand software subsystems, data flow, and AV decision making, as well as interviews with Cruise employees and a multi-day in-person inspection to review detailed, frame-by-frame information of the incident. The documentation Exponent reviewed included system-level software architecture diagrams, Cruise's root cause analysis, documents describing parameters for the AV's response to collisions, the Standing General Order (SGO) report provided by Cruise to NHTSA, video footage of the incident, data recorded by the AV's various sensors and systems, vehicle maintenance records, the traffic collision report, documentation and videos provided to government officials. Exponent also reviewed other relevant records and technical and scientific literature. Prior to, during, and after our on-site inspection, Exponent interviewed and was in frequent communication with Cruise employees to better understand their system architecture and AV decision making process.

Exponent conducted an independent multi-day inspection at Cruise. During the inspection, Exponent used the Webviz data visualization tool to review frame-by-frame perception, prediction, and motion planning data captured on the day of the incident. Webviz supports multiple views for displaying information with configurable layouts to display salient information at different points in time and to support different types of analyses. Exponent utilized multiple layouts and panels to analyze, for example, [redacted]

Additionally, Exponent reviewed data collected by the AV's systems on the predicted position and velocity of both the Nissan and the pedestrian throughout the incident.

2.2 Accident Reconstruction & Video Analysis Methodology

The AV is capable of capturing [redacted] exterior views using onboard cameras, which record continuous video footage of the environment surrounding the AV. These cameras can capture frontal, side, and rearward views [redacted]. Of the [redacted] available views, [redacted] were reviewed by Exponent in a single-window compilation with timing between each view aligned to all others [redacted]. Figure 14 provides an example of each view in the compilation, annotated [redacted] in the upper left corner of the frame. A description of the field-of-view from the nine annotated cameras is provided below:





Figure 14. Graphic exhibiting [redacted] onboard camera views from the AV (annotated with numbers [redacted] in the upper left corner of each view by Exponent).

Embedded time information was displayed in the lower right corner of each frame contained within the video compilation. Exponent independently reviewed the footage and used it in evaluating the following:

- overall event timing
- pre-incident vehicle movement
- interaction between the Nissan and the pedestrian
- post-incident response of the AV
- [redacted]

[redacted] In all analyses performed herein, the speed of the AV was referenced from the vehicle kinematics data (shown in Figure 15).

As part of Exponent's analysis of the subject incident, select camera views depicting key frames were identified throughout the incident sequence for evaluation of position and motion of the AV, Nissan, and pedestrian over time. In addition, the video included information regarding overall traffic conditions. This data, in addition to other data, provided sufficient information for a high-level time-and-position analysis

to be conducted. The video was not utilized to evaluate the overall lighting conditions or visibility at the time of the incident, as cameras can interpret lighting conditions differently than the human eye.[25]

2.3 Human Factors Analysis – Methodology

To better understand how various factors might influence driver behavior it is helpful to break down the steps involved in perceiving a hazard and preparing and executing a response, known as perception-response time (PRT), and to understand that there can be variable reasonable driver responses. PRT is typically broken down into four stages: detection, identification, decision, and response.[26] During the detection stage, the driver must first perceive the hazard (i.e. see or hear "something") and orient their attention to the object.[27] Once the object is detected, the driver must identify whether it represents a hazard and then decide how to respond, if at all.[28] After the decision has been made to respond, the driver must finally initiate and carry out that action.[29] While it is difficult to precisely calculate the temporal duration of each stage, based on decades of research it is possible to estimate PRTs for various accident scenarios.[30] In car-driving under "a fairly straightforward situation and minimal time available for a response," most drivers will respond within 1.5 seconds to a "readily identifiable hazard" that appears directly in front of the driver.[31] However, PRTs can be shorter or longer than this estimate depending on the circumstances.[32] For instance, scientific literature suggests that attentive drivers, on average, respond to expected hazards between 1.1 and 1.6 seconds,[33] while drivers respond to unexpected hazards under nighttime conditions in approximately 2.0 to 3.0 seconds.[34]

Relevant factors that impact PRT include visual attention, conspicuity, and expectancy.[35] In order for a visual signal (e.g., a pedestrian entering the roadway or a vehicle's path of travel) to be an effective indicator of a potential hazard, the driver's attention must be directed to the relevant location or feature in

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25 Krauss, 2015b

26 Krauss, 2015c

27 Krauss 2015b; Barragan et al., 2021

28 Krauss 2015b; Barragan et al., 2021

29 Krauss, 2015c

30 Krauss, 2015c

31 Olson & Farber, 2003

32 Olson & Farber, 2003

33 Olson & Sivak, 1986

34 Triggs & Harris, 1982; Summala, 1981; Muttart, 2003

35 Olson & Farber, 2003, Krauss et al., 2015a; Alexander & Lunenfeld, 1986; Krauss et al., 2015b

the roadway.[36] The ability to discern potential roadway obstacles such as pedestrians, animals, or other vehicles is significantly reduced at night (i.e., in conditions with reduced luminance).[37] Conspicuity, which is defined as "those characteristics of an object or condition that determine the likelihood that it will come to the attention of an observer," can also significantly impact a driver's ability to detect roadway obstacles.[38] Conspicuity depends on many factors, including, but not limited to, contrast, stimulus size, uniqueness, and location within the visual field.[39] For example, glare from oncoming headlights has been shown to impair detection of pedestrian motion.[40] Low conspicuity can increase the time it takes a driver to detect a potential hazard, thus increasing PRT and shortening the time available to avoid a potential accident.[41]

In the context of driving, expectancy relates to a driver's "readiness to respond to situations, events, and information in predictable and successful ways."[42] This "readiness to respond" manifests as quicker responses to potentially hazardous stimuli.[43] For example, drivers can detect an expected hazard from farther away and respond faster than when the hazard is unexpected, such as while driving on a highway or interstate.[44] Violations of driver expectancies can cause considerable delays or failures in detection of an event or obstacle.[45] In addition to unexpected objects or events in the vehicle's path, pedestrians can exhibit unpredictable behavior due to their ability to quickly change trajectories without external indication.[46] According to hazard-perception frameworks, if a perceived hazard is merely a potential hazard, then a change in behavior is likely unnecessary, whereas if the perceived hazard is an actual hazard (i.e., the hazard is "materializing and will interact with the driver if no action is taken"), then action must be taken.[47]

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36 e.g., Falkmer & Gregersen, 2005; Krauss, 2015a

37 Krauss, 2015a; Owens & Sivak, 1993

38 Olson & Farber, 2003; Krauss et al., 2015a

39 Krauss et al., 2015a

40 Incident Video; Wood 2019; Theeuwes et al., 2002

41 e.g., Triggs & Harris, 1982

42 Alexander & Lunenfeld, 1986; Krauss et al., 2015b

43 Alexander & Lunenfeld, 1986; Krauss et al., 2015b

44 Shinar, 1985; Alexander & Lunenfeld, 1986; Krauss et al., 2015b

45 Langham & Moberly, 2003; Rumar, 1990; Olson & Sivak, 1986; Krauss, 2015c

46 AVSC Best Practice for Interactions Between ADS-DVs and Vulnerable Road Users (VRUs), 2022

47 Barragan et al. 2021

3 Root Cause Analysis

3.1 Incident Sequence Assessment

The sequence of salient events prior to, during, and following the collision between the AV and the pedestrian will be described in the following sections. The timing of each event is normalized to the point at which the AV first contacts the pedestrian (t=0), [redacted]. This will herein be referred to as the 'AV-pedestrian collision'. As a convention, time information is given in relative time to the nearest 0.1s. However, a greater number of salient events are identified immediately prior to and after the AV-pedestrian collision. Therefore, Exponent has provided time data to the nearest 0.01s for events that occur within 2 seconds of the AV-pedestrian collision, so as to provide a higher level of granularity. Events that occurred prior to the initial collision of the pedestrian with the AV will be referenced by negative time, and events that occurred following 'AV-pedestrian collision' will be referenced by positive time. The timeline of salient events is outlined in Table 6. A subset of these salient events is shown alongside the AV velocity, acceleration, and steering wheel angle in Figure 15.

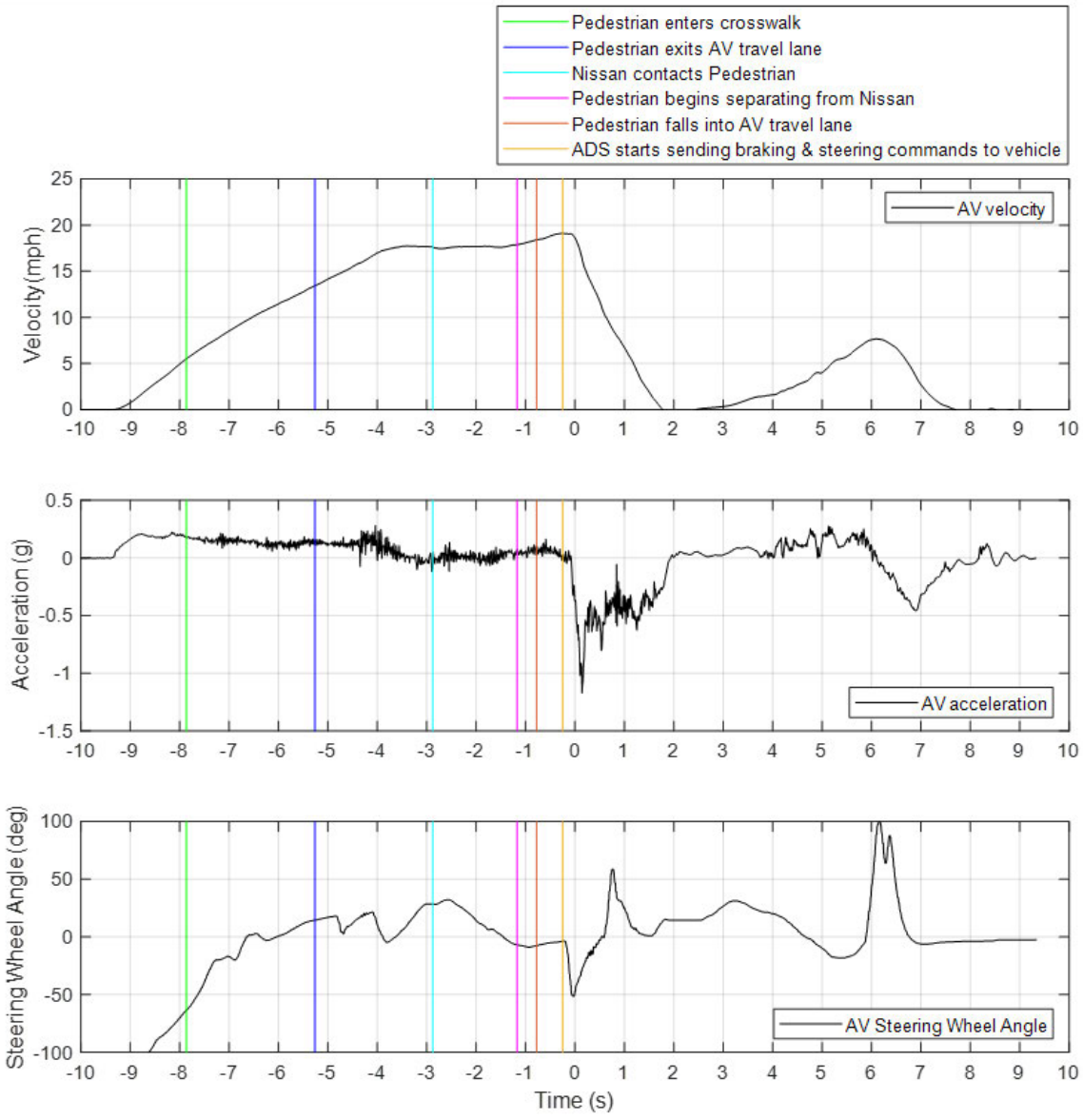


Figure 15. Timeline of certain events overlaid on AV velocity (top), acceleration (middle), and steering wheel angle (bottom). Time is normalized such that contact between the pedestrian and AV occurs at t = 0 s.

Table 6. Timeline of salient events

Event	Unix Time (s)	Relative Time (s)
Pedestrian first classified as pedestrian and 'tracked' with ID [redacted] at approximately 21:28:34 PDT	1696307313.4	-38.3
AV becomes static due to red traffic light	1696307324.8	-26.9
Traffic light changes to green	1696307341.7	-10.0
Nissan begins moving after light change	1696307342.4	-9.3
AV begins moving after light change	1696307342.4	-9.2
Pedestrian appears (visually) to enter 5th Street crosswalk	1696307343.8	-7.9
Prediction output shows pedestrian path crossing AV travel lane[48]	1696307344.0	-7.7
Pedestrian leaves AV's travel lane	1696307346.4	-5.3
Pedestrian stops/pauses in crosswalk	1696307347.0	-4.7
Contact between pedestrian and Nissan occurs	1696307348.8	-2.9
Pedestrian track (ID [redacted]) is dropped	1696307349.7	-2.0
Pedestrian begins separating from Nissan (visually)	1696307350.49	-1.17
[redacted]	1696307350.85	-0.81
Pedestrian lands in AV's travel lane	1696307350.89	-0.78
An imminent collision is predicted by the 'collision checker'[49]	1696307351.25	-0.41
AV begins sending commands for steering & braking[50]	1696307351.41	-0.25
Initial contact between pedestrian and AV occurs	1696307351.66	0.00
Collison checker node outputs that a collision has occurred	1696307351.87	0.21
ABS status change	1696307351.89	0.23
AV velocity initially becomes zero post impact[51]	1696307353.44	1.78
AV begins sending commands to begin accelerating post impact	1696307353.49	1.83
TCS status change	1696307355.5	3.8
DS4 triggered	1696307357.5	5.8
AV reaches its final point of rest	1696307360.4	8.8

[48] At all times, the highest confidence predicted path associated with pedestrian track ID [redacted] does not conflict with the planned path for the AV. The system correctly estimates that the pedestrian will fully traverse the AV's travel lane prior to the AV occupying this region.

[49] [redacted]

[50] [redacted]

[51] It was determined through review of the video footage as well as vehicle kinematics and [redacted] that the vehicle did not become static after the AV collided with the pedestrian and prior to accelerating again. However, the vehicle's longitudinal velocity did reach zero, and subsequently became negative as the sprung mass of the vehicle translated rearward. As the sprung mass translated in the forward direction, the vehicle began to accelerate. Therefore, the point at which the AV velocity initially became zero was determined to be the moment when the longitudinal velocity of the vehicle's sprung mass reached zero.

3.2 Nissan-Pedestrian Collision

This section describes the sequence of events that led to the initial collision of the pedestrian with the Nissan. A timeline of salient events prior to the Nissan-Pedestrian collision is depicted in Figure 16.

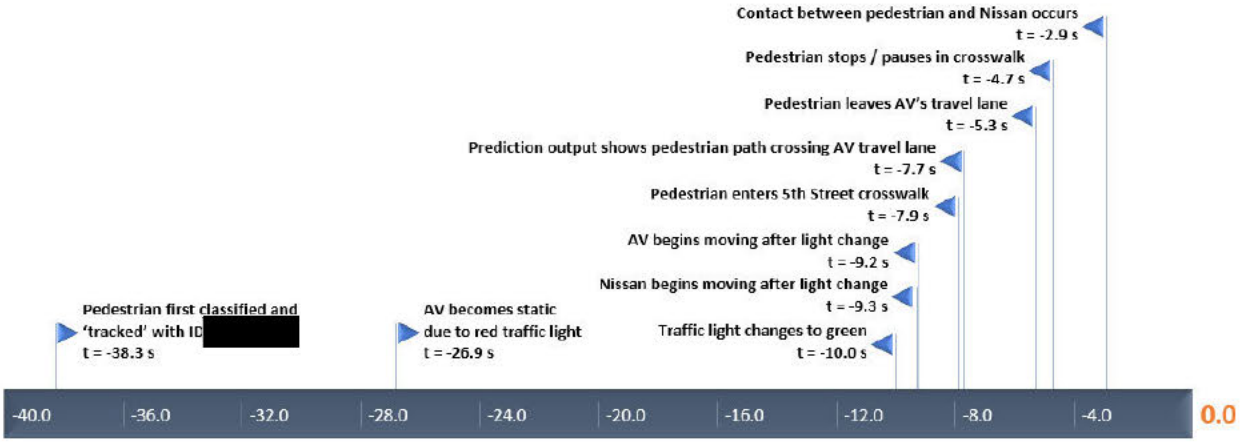


Figure 16. Timeline of salient events prior to Nissan-Pedestrian collision.

3.2.1 Accident Reconstruction Video Analysis –Nissan-Pedestrian Collision

Review of the video indicated the Nissan and AV were traveling in the southbound direction on Cyril Magnin Street before stopping for a red traffic signal at the intersection with Market Street. The Nissan was positioned in the inner through lane to the left of the AV over the stop bar. As presented in Figure 17, Camera 4 captured a left side view from the AV and depicted the location of the Nissan, while Camera 5 depicted a wide-angle view to the front of the AV providing information regarding the relative position of the Nissan with respect to the AV. Pre-existing damage to the passenger side of the Nissan included a fractured front hubcap and deformed fender, and the side-view mirror housing was separated from its attachment and dislodged, as observed in the Camera 4 image.



Figure 17. Select frames from AV [redacted] depicting vehicle positions as signal for southbound traffic towards 5th Street turned green.

An additional data/video compilation was provided by Cruise, combining [redacted] camera views with a [redacted]. From this data, the relative positions of the Nissan and AV could be further defined, and other objects tracked by the AV could be observed during the incident sequence (Figure 18). [redacted]



Figure 18. Example frame from data/video compilation, combining camera views with [redacted] for the AV as the vehicles began to accelerate from a stop.

Approximately 0.7 seconds after the traffic signal changed to green, the Nissan and AV began to accelerate and move to the south. As the AV started to accelerate, it moved rightward in its travel lane to align with a shift in its travel lane. Moments later, the pedestrian on the southwest corner proceeded to the east, entering 5th Street within the crosswalk perpendicular to the travel direction of the approaching vehicles. Over approximately 2.6 seconds, the pedestrian entered the 5th Street crosswalk, fully traversed the AV's

travel lane, and entered the Nissan's travel lane. Approximately 0.6 seconds later, prior to reaching traffic traveling in the northbound direction, the pedestrian paused in the Nissan's lane of travel. As captured by the video, the Nissan and AV proceeded forward having a green traffic signal. However, a *Do Not Walk* signal was illuminated for the crossing pedestrian. The AV reached a travel speed of approximately 15.0 mph by the time the pedestrian paused within the crosswalk in front of the approaching Nissan. As the adjacent Nissan remained in a similar longitudinal position relative to the AV through the midpoint of the intersection, the two vehicles were traveling at comparable speeds during this segment.



Figure 19. Frames from AV [redacted] depicting the relative positions of the Nissan and AV as the pedestrian paused within the 5th Street crosswalk of the inside traffic lane.

Based on Exponent's evaluation of the provided video, the pedestrian was struck by the Nissan approximately 2.4 seconds after leaving the AV's travel lane. During this time, the pedestrian did not appear to look to the left and instead can be seen waving or signaling, possibly towards northbound traffic. The AV's onboard video documented the positions of the Nissan, AV, and pedestrian at the time the Nissan and pedestrian made contact (Figure 20). At the time of impact between the Nissan and pedestrian, the AV was traveling at a speed of approximately 17.6 mph. The frame from Camera 4 shows the Nissan had advanced forward with respect to the AV, indicating that it accelerated and was traveling faster than the AV during this segment.



Figure 20. Key frames from AV onboard [redacted] depicting relative positions at the approximate time of the Nissan-pedestrian contact.

Figure 21 depicts a frame from the data/video compilation, including [redacted] In this figure, the time at which the Nissan first made contact with the pedestrian is depicted. [redacted]



Figure 21. Frame from data/video compilation providing [redacted] at the approximate time of the Nissan-pedestrian contact.

3.2.2 AV Interpretation of Nissan-Pedestrian Collision

The pedestrian was first detected by one of the AV's onboard lidars, was correctly classified as a pedestrian, and was tracked with ID [redacted] approximately 38.3 seconds prior to the initial collision with the AV. At this time, the AV was traveling southbound on Cyril Magnin Street approaching the intersection with Market Street and was slowing in response to a red traffic signal. The pedestrian was traversing the sidewalk on the west side of Cyril Magnin Street and was approaching the adjacent crosswalk that crosses Market Street. The Nissan adjacent to the AV was classified as a "Car" and was tracked by the AV. The AV came to a stop approximately 26.9 seconds prior to the initial collision with the pedestrian, at which time the pedestrian was still in the adjacent crosswalk, traversing Market Street against a "*Do Not Walk*" pedestrian signal.



Figure 22. Webviz visualization of the scene as the AV came to a stop at the intersection. The pedestrian was detected and tracked (with track ID) as the pedestrian crossed from the north side of Market Street (left) towards the south side of market street (right). North direction towards bottom right corner in the illustrations.

As mentioned in Section 1.3, The pedestrian was consistently detected, classified as a pedestrian, and tracked by the AV as the pedestrian traversed the adjacent crosswalk (across Market St.), waited at the south corner of the intersection, and traversed the travel lane of the AV in the opposite crosswalk (across 5th St.) until shortly after the pedestrian was struck by the Nissan.

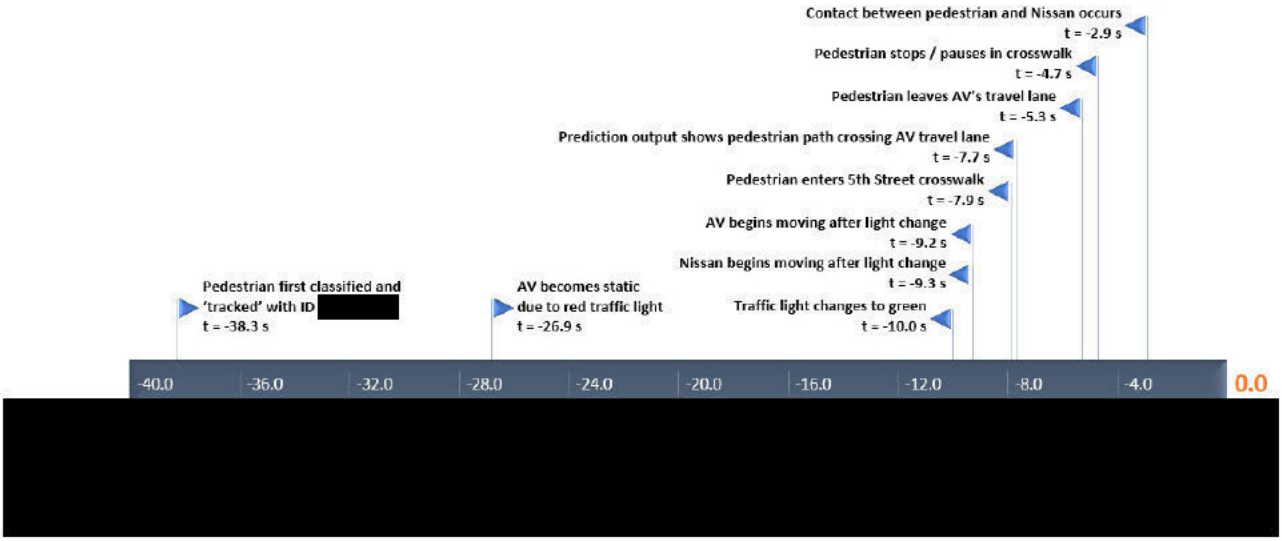


Figure 23. Timeline depicting which contributed to the tracking of the pedestrian while it had an associated track ID of are represented in the legend as denoted in Webviz (refer to Section 1.3.2).

As the pedestrian entered the 5th street crosswalk, the ADS prediction system generated path predictions for both the pedestrian and the Nissan, which were traveling approximately perpendicular to each other. As the Nissan approached the pedestrian, the highest probability paths predicted for the pedestrian and Nissan became consistent with a potential collision (Figure 24).



Figure 24. Prediction of intersecting paths for the Nissan (track ID [redacted] and the pedestrian (track ID [redacted]) ~4.8 s prior to AV-pedestrian contact. [redacted]

Prior to the collision between the Nissan and the pedestrian, [redacted] for the AV to bias rightward in response to a lateral constraint in the AV's path approximately 4.6 seconds before the AV-pedestrian collision. The exact cause of the rightward bias is not clear from the reviewed data, but it could be due to the presence of the pedestrian as it is the closest obstacle in the proximity of the planned rightward bias. [redacted] with less rightward bias, [redacted] Approximately 0.3 seconds later, [redacted] reduces the amount of rightward bias (right image of Figure 25). It is not clear from the reviewed data if this response is because a lateral constraint due to the pedestrian was no longer present.



Figure 25. Image depicting the moment when [redacted] rightward bias approximately 4.6 seconds prior to the AV-pedestrian collision (left). Image depicting the moment when rightward bias is reduced approximately 4.3 seconds prior to the AV-pedestrian collision (right).

The Nissan was traveling at an estimated velocity of approximately 21.7 mph, according to the AV, when it collided with the pedestrian in the lane adjacent to the AV, approximately 2.9 seconds prior to the AV-pedestrian collision. At the time of collision between the Nissan and the pedestrian, the pedestrian was classified as a pedestrian ([redacted]) and had an associated track (with track ID [redacted]). The pedestrian had a predicted velocity (by the ADS) of approximately 2.6 mph (Figure 26) when the Nissan-pedestrian collision occurred. Camera images captured at the approximate time of Nissan-pedestrian contact are shown in Figure 27.



Figure 26. [redacted] depicting the moment of impact between the Nissan and pedestrian, approximately 2.9 s prior to AV-pedestrian collision. Nissan and AV travel directions are to the right.



Figure 27. AV onboard camera frame [redacted] showing the approximate moment of Nissan-pedestrian contact, ~2.9 s prior to AV-pedestrian collision. [redacted] the pedestrian as a "Human".

At the time of Nissan-pedestrian collision, the AV had a velocity of approximately 17.6 mph, and [redacted] the AV trajectory by either the pedestrian or the adjacent Nissan. [redacted] It is apparent that the AV considered the predicted paths of the Nissan and Pedestrian and whether those paths were likely to conflict with the AV's planned trajectory. However, in planning the AV's trajectory, the ADS did not consider the potential of a collision between the Nissan and the pedestrian.

3.2.3 Human Factors Analysis –Nissan-Pedestrian Collision

The relevant time period prior to the Nissan's contact with the pedestrian starts when the pedestrian first steps into the crosswalk against the signal phase (approximately 7.9 seconds prior to the AV's contact with

the pedestrian) and lasts for approximately 5.0 seconds until the Nissan contacts the pedestrian (approximately 2.9 seconds prior to the AV's contact with the pedestrian). While most reasonable human drivers would detect a pedestrian across the intersection stepping into their lane of travel under most conditions, the detection of a pedestrian in such circumstances can be diminished by aspects of the surrounding environment and lighting conditions. For example, as the behavior of the Nissan driver in this incident demonstrates, the presence of a pedestrian in the vehicle's path does not always result in drivers responding appropriately, or at all, prior to a collision. It is possible that a reasonable human driver, especially one accustomed to driving in an urban area where pedestrians enter the roadway while traffic is in motion, would proceed with caution at this stage, yet still proceed with the pedestrian continuing to move across that driver's lane of travel. Some reasonable drivers would determine that the pedestrian in the adjacent lane did not represent a hazard and therefore no reaction was necessary, while other reasonable drivers might determine that, given that pedestrian behavior can be unpredictable, a pedestrian at any position in the roadway could constitute a potential hazard and would warrant a response (e.g., slow or otherwise apply the brakes).

3.3 Cruise AV-Pedestrian Collision

This section describes the sequence of events that occurred after the Nissan-pedestrian collision and leading up to the time of the AV-pedestrian collision. A timeline of salient events prior to the AV-pedestrian collision is depicted in Figure 28. As mentioned previously, there are numerous salient events which occur in this period. provide a higher level of granularity, time data to the nearest 0.01s is provided for events that occur within 2 seconds of the AV-pedestrian collision.

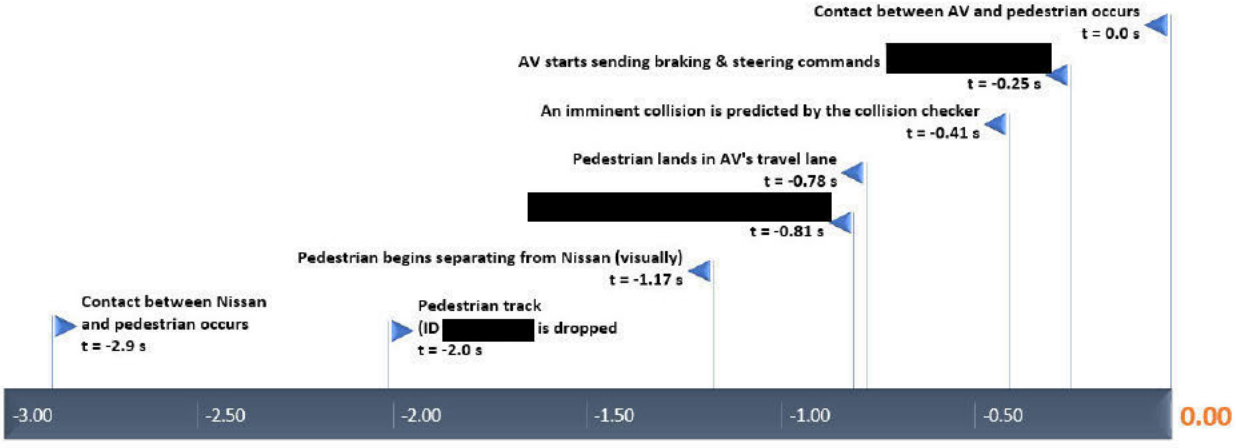


Figure 28. Timeline of salient events between pedestrian's collision with Nissan and subsequent collision with the AV.

3.3.1 Accident Reconstruction Video Analysis – AV-Pedestrian Collision

Exponent visually identified the time at first contact and time at separation between the pedestrian and the Nissan as approximately 2.9 seconds and 1.17 seconds prior to the AV-pedestrian collision, respectively. Shortly after separation, the pedestrian was thrown at an unknown velocity and landed in the AV lane of travel approximately 0.78 seconds prior to the AV-pedestrian collision. This sequence of events is described in more detail below.

Immediately following the contact with the pedestrian, the operator of the Nissan input a leftward steer and correspondingly, the vehicle moved to the left crossing the centerline and entering the northbound traffic lane. This movement created additional lateral separation between the Nissan and AV. Approximately 1.0 second after the Nissan moved left, the vehicle can be observed moving back towards the right, likely as a result of rightward steering by the operator[52] (Figure 29). As the Nissan moved forward and to the right, the pedestrian was carried by the vehicle in the same direction. During this time, the AV continued traveling to the south, slightly behind the Nissan. The AV reached a speed of approximately 17.6 mph at the time of collision between the Nissan and the pedestrian, and it maintained approximately this speed throughout this 1-second window.



Figure 29. Frame from AV [redacted] depicting the approximate location where the Nissan began to move towards the right.

[52] The rapid left and right movement of the Nissan is substantial and is, therefore, most likely the result of operator steering inputs.

The pedestrian separated from the Nissan approximately 1.17 seconds before the AV-pedestrian collision occurred.[53] Approximately 0.1 s after pedestrian separation from the Nissan (1.07 seconds prior to the AV-pedestrian collision), the Nissan's brake lights illuminated, indicating a brake application by the driver. Corresponding to the time of Nissan brake light illumination, the AV was traveling at a speed in the range of 18.0 mph and remained positioned approximately one car length behind the Nissan in the outside traffic lane. As the pedestrian separated from the Nissan, the video shows the continued rightward movement of the Nissan as the pedestrian was redirected into the outermost traffic lane occupied by the approaching AV. Images from the onboard video corresponding to the activation of the Nissan's brake lights are provided in Figure 30.



Figure 30. Frames from [redacted] depicting vehicle locations as the Nissan's brake lights illuminated (annotated with yellow arrow by Exponent).

Within approximately 1.5 s following the Nissan's brake application, the Nissan came to rest. The cameras documented the Nissan continuing its rightward movement as it slowed and came to rest at a small, clockwise angle relative to its lane of travel with the right front tire positioned near the white lane stripe (Figure 31). The pedestrian occupied the left region of the outside traffic lane.

[53] The timing of this event is determined visually based on camera data [redacted]



Figure 31. Frame from [redacted] depicting rest position of Nissan and location of AV when it initially came to a stop prior to advancing further south.

As the Nissan traveled rightward towards the AV lane of travel and the pedestrian separated from the Nissan, landing in the outside travel lane, the AV reached a speed of approximately 19.1 mph before braking was initiated by the AV approximately 0.25 s prior to AV-pedestrian contact. The initiated braking was coincident with initiated steering by the AV, which caused a slight rightward heading change in the vehicle. The application of the AV brakes resulted in slowing the AV to approximately 18.6 mph as contact with the pedestrian occurred. This contact between the AV and pedestrian occurred approximately 0.2 s after the Nissan came to a halt. Frames depicting the approximate position of the pedestrian prior to interacting with the AV are depicted in Figure 32 and Figure 33.



Figure 32. Views from [redacted] depicting position of the pedestrian in the right lane in front of the approaching AV.



Figure 33. View from [redacted] at its closest timestamp to the first interaction between the pedestrian and the AV, within 0.1 s post collision.

[redacted]

[redacted]

[redacted]

[redacted]

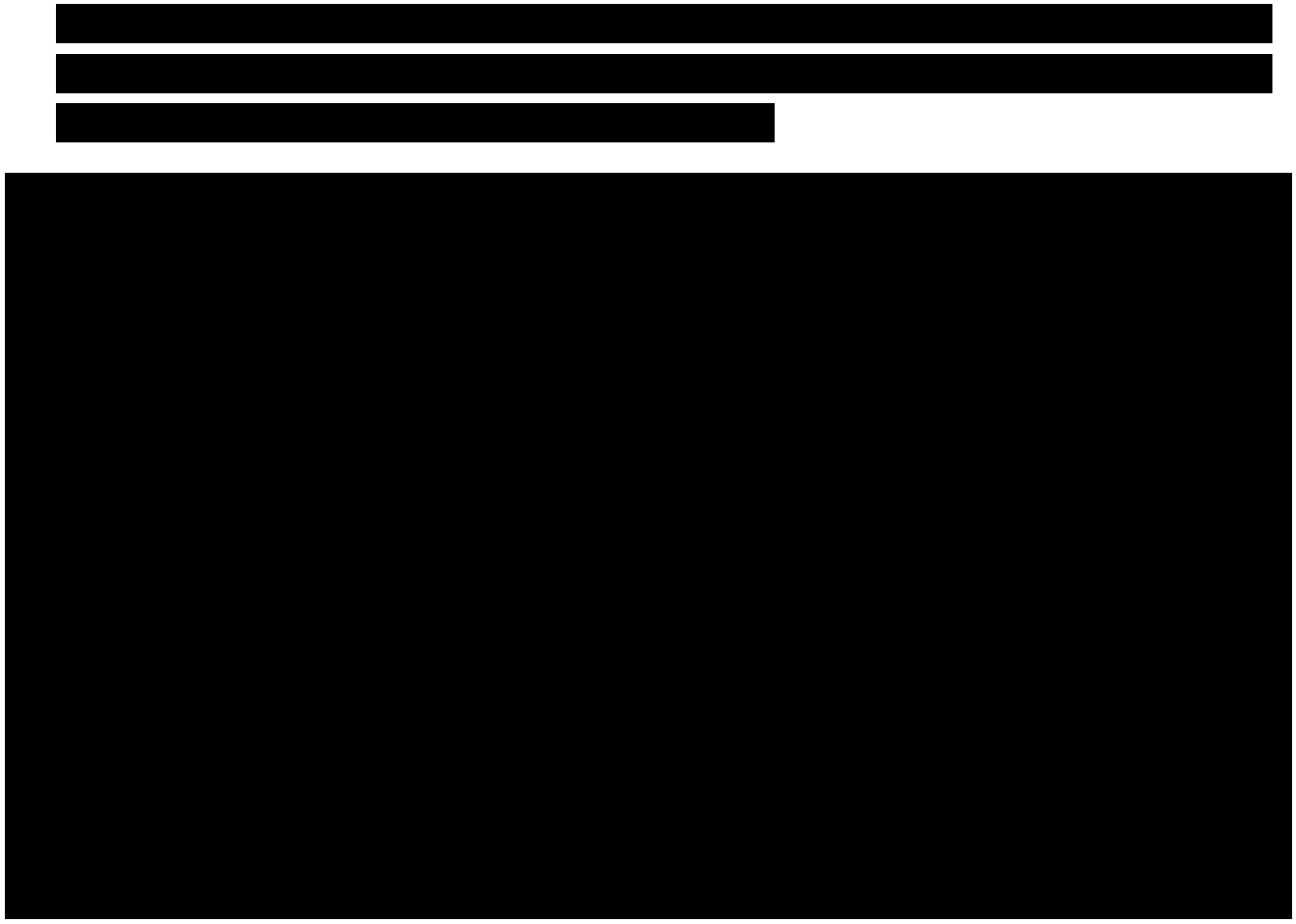
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54 [redacted]















3.3.3 Calculated stopping distance of the Cruise AV

The point at which the AV-pedestrian collision was unavoidable via braking (excluding any steering avoidance maneuver) was calculated based on performance limits of the AV planner system while also accounting for brake system latency[55]. The dynamic performance limits of the AV are shown in Table 9.

[redacted]

Using the parameters defined in Table 9, hypothetical brake activations are considered with varied initial velocity. The braking performance is idealized, assuming the maximum thresholds defined in Table 9 and discounting the impact of road gradient, road coefficient of friction, and lateral motion of the vehicle. Idealized braking for several different initial velocities is depicted in Figure 40.



Figure 40. Calculated stopping distance and time assuming idealized braking with varied initial velocity.

55 [redacted]

56 Provided by Cruise.

The point at which AV-pedestrian contact was unavoidable via braking was then determined by comparing minimum stopping distance for a range of initial velocities to a calculated relative displacement from the point at which the AV-pedestrian contact occurred (as determined by [redacted]). The brake system latency was considered to determine the last point at which contact between the AV and the pedestrian could have been avoided by the initiation of braking commands. Accounting for brake system latency, the system would have needed to initiate a brake request no later than 0.78 seconds prior to AV-pedestrian contact in order to completely avoid contact. At this relative time, the pedestrian had just fallen into the AV's travel lane, the AV was traveling at approximately 18.4 mph and the AV was approximately 6.55 m (21.5 ft) from the point at which AV-pedestrian contact occurred. It is noteworthy that a hypothetical brake activation occurring after this time (and prior to when the AV initiated braking at 0.25 s) would have potentially mitigated the severity of the initial collision between the AV and the pedestrian. The extent of this potential mitigation was not determined in this analysis.

3.3.4 Human Factors Analysis – AV-Pedestrian Collision

Nissan Contact with the Pedestrian

The Nissan made contact with the pedestrian approximately 2.9 s before the AV-pedestrian collision. Some reasonable drivers would perceive the impact between the Nissan and the pedestrian happening in the adjacent lane and recognize the impact as a situation that they would need to respond to,[57] while others may not predict or detect the impact due to factors such as violations of expectancy, glare, or A-pillar occlusion.[58] Some drivers (that would notice the impact) would respond by braking or other evasive maneuvers,[59] while others would not react. The AV's speed at the time of the Nissan-pedestrian collision was approximately 17.6 mph. Considering a typical PRT range of 2.0 to 3.0 s for an unexpected hazard at night,[60] and a braking time range of 1.1 to 1.2 s,[61] a reasonable human driver would likely not have been able to avoid the collision under similar circumstances.

[57] Crundall et al., 2012; Barragan et al., 2021

[58] Krauss, 2015c; Wood, 2019; Theeuwes et al., 2002; Reed, 2008

[59] Crundall et al., 2012; Barragan et al., 2021

[60] Triggs & Harris, 1982; Summala, 1981; Muttart, 2003

[61] Figure 40, Based on a vehicle speed range of 16.8 to 19.0 mph at the moment of brake initiation.

Pedestrian Separates from the Nissan

The pedestrian can be seen separating from the Nissan vehicle in the inside lane approximately 1.17 s before interacting with the AV. Some reasonable human drivers would perceive this event as a potential hazard in the adjacent lane and react, while others would predict no reaction was needed. The AV's speed at this time was approximately 17.9 mph. Considering a typical PRT range of 2.0 to 3.0 s for an unexpected hazard at night, and a braking time range of 1.1 to 1.2 s, a reasonable human driver would likely not have been able to avoid the collision under similar circumstances.

Pedestrian Crosses into AV's Lane

The pedestrian landed in the AV's travel lane approximately 0.78 s before interacting with the AV. Most reasonable human drivers would react to a pedestrian landing in the lane with a braking response or avoidance maneuver.[62] The AV's speed at this time as approximately 18.4 mph. Considering a PRT range of 1.1 to 1.6 s typical of expected hazards,[63] and the braking time range of 1.1 to 1.2 s, a reasonable human driver would likely not have been able to avoid the collision under similar circumstances.

3.4 Cruise AV Post-Collision Response

This section describes the sequence of events that occur after the AV makes initial contact with the pedestrian, including drive over, and subsequent actions by the AV. A timeline of salient events after the AV-Pedestrian collision is depicted in Figure 41. As mentioned previously, there are numerous salient events which occur in this period. So as to provide a higher level of granularity, time data to the nearest 0.01 s is provided for events that occur within 2 s of the AV-pedestrian collision. A subset of these salient events is shown alongside the AV velocity, acceleration, and steering wheel angle in Figure 42.

[62] e.g., Crundall et al., 2012

[63] Olson & Sivak, 1986

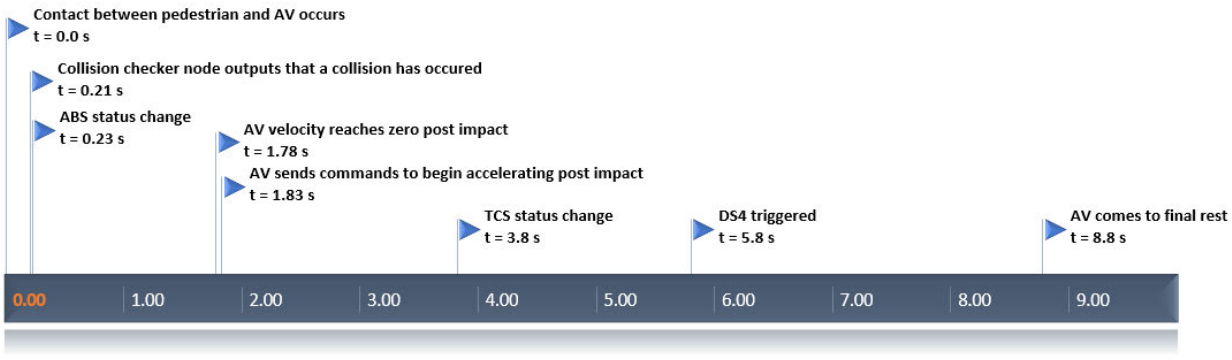


Figure 41. Timeline and event sequence of post collision.

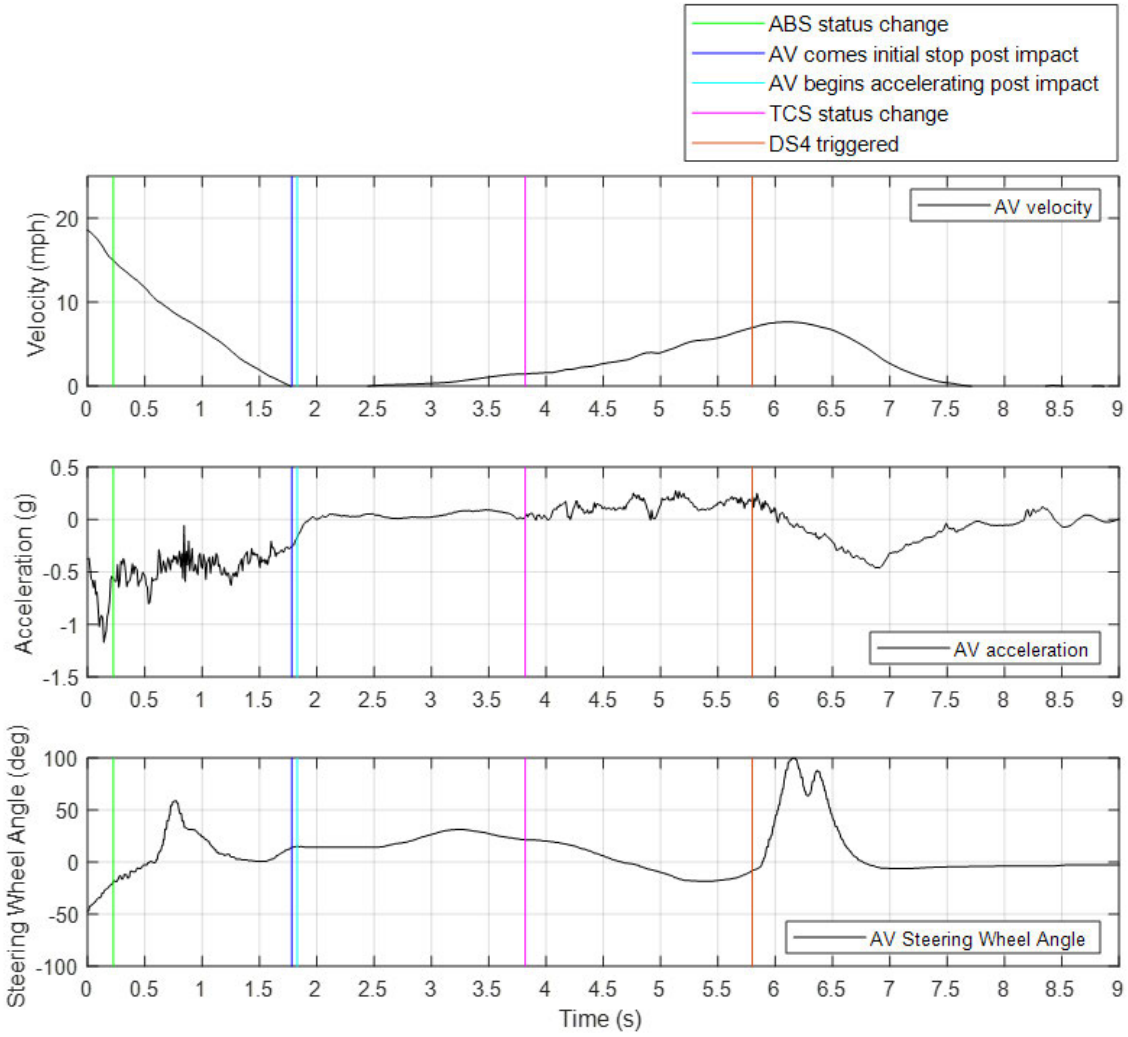


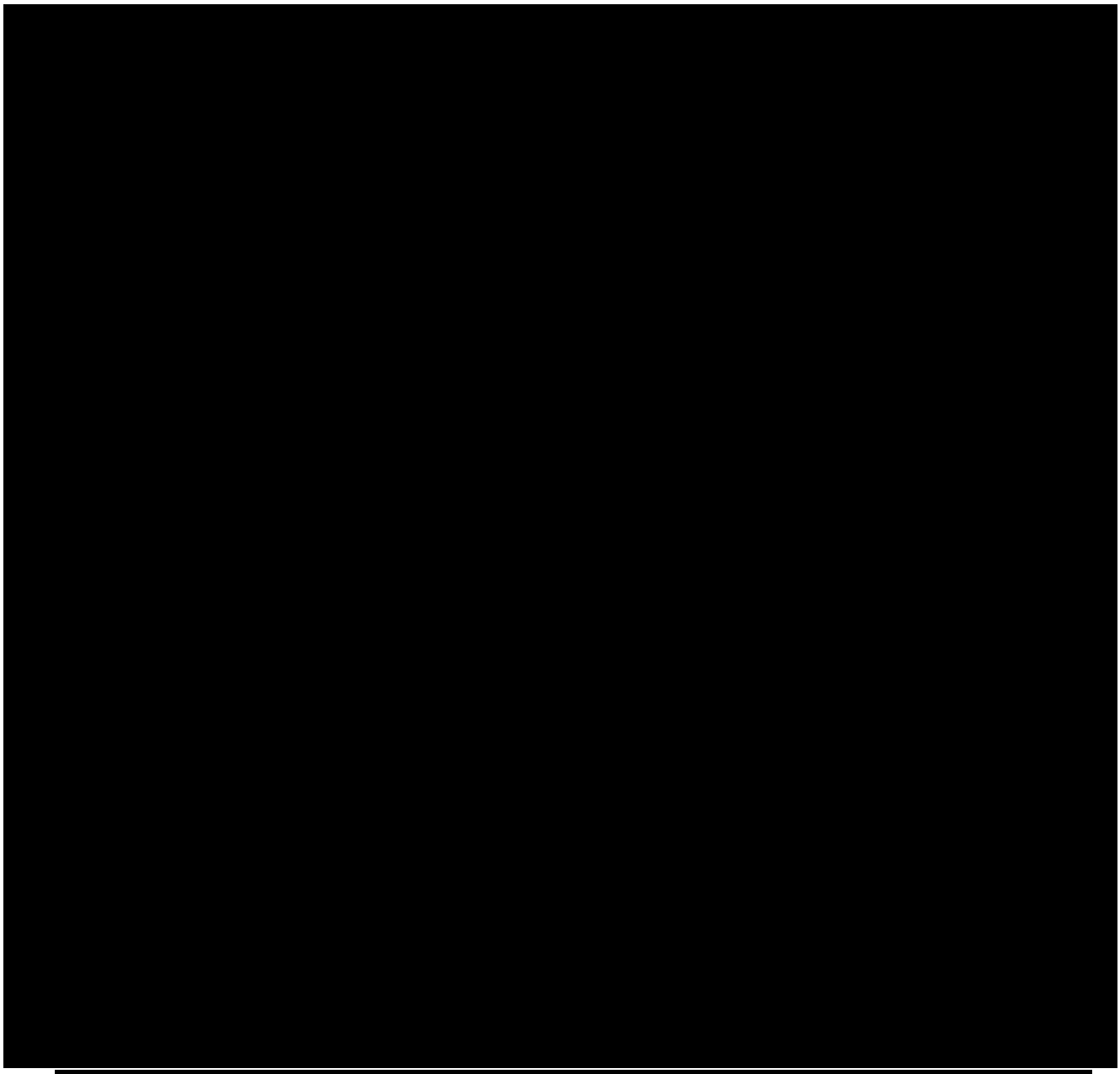
Figure 42. Timeline of post AV-pedestrian collision salient events overlaid on AV velocity, acceleration, and steering wheel angle. Time is normalized such that contact between the pedestrian and AV occurs at t = 0 s.

3.4.1 Accident Reconstruction Video Analysis – Post-Collision Response

After contacting the pedestrian, the AV continued forward movement while decelerating for approximately 1.78 seconds, coming to an initial stop with its front bumper positioned ahead of the Nissan. The average and peak deceleration of the AV (recorded by onboard accelerometers) was 0.44 g and 1.17 g, respectively. At initial rest, the AV was located between the adjacent Nissan on its left and a dedicated bike lane on its right, separated from traffic by flexible vertical markers (Figure 43). From this position, the AV then moved to the south approximately 20 feet reaching a maximum speed of approximately 7.7 mph before reaching its final rest position.



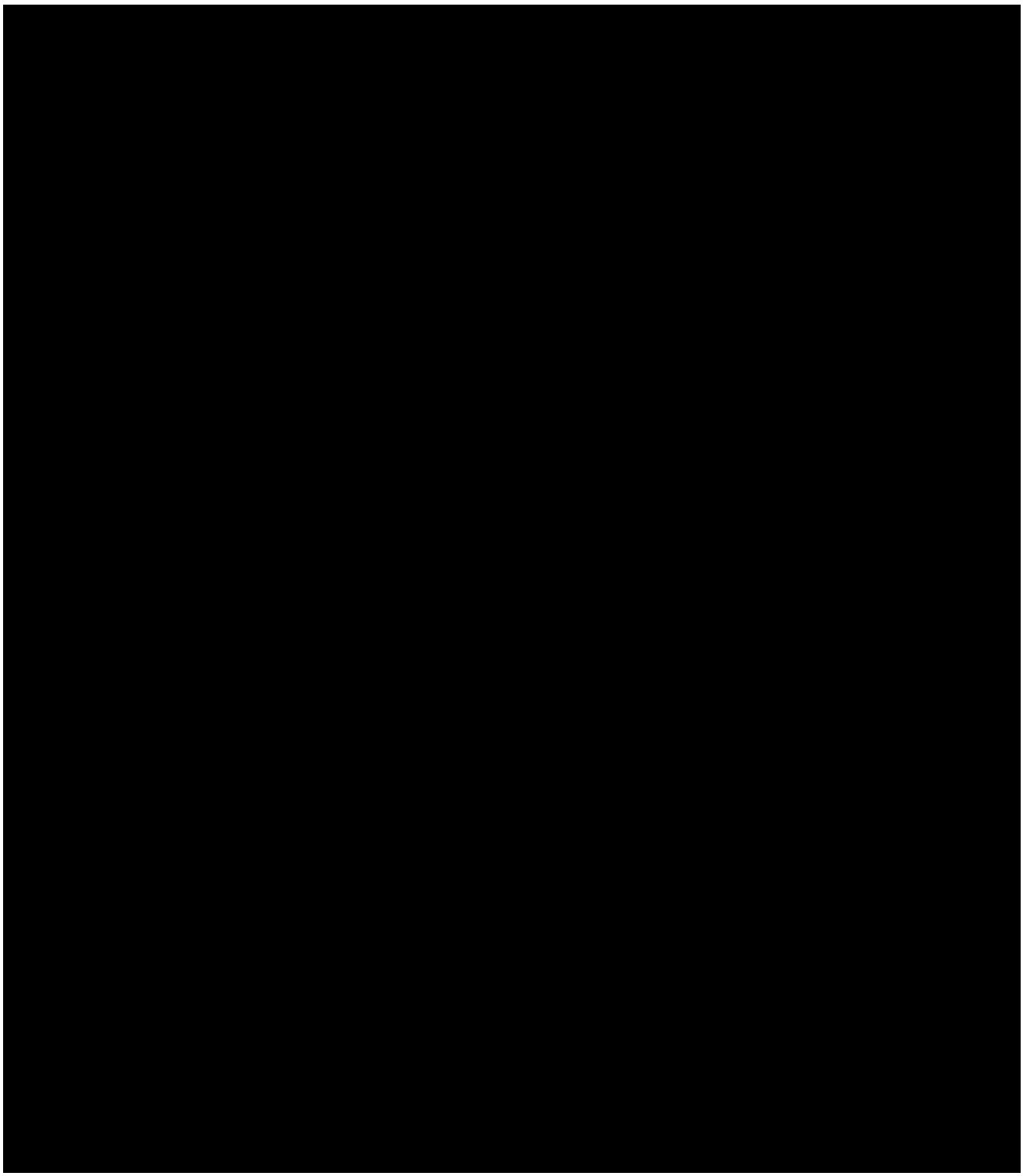
Figure 43. Frames from [redacted] depicting rest position of the Nissan and location of the AV when the Nissan initially came to a stop prior to advancing further south.



[redacted]

[redacted]

[redacted]

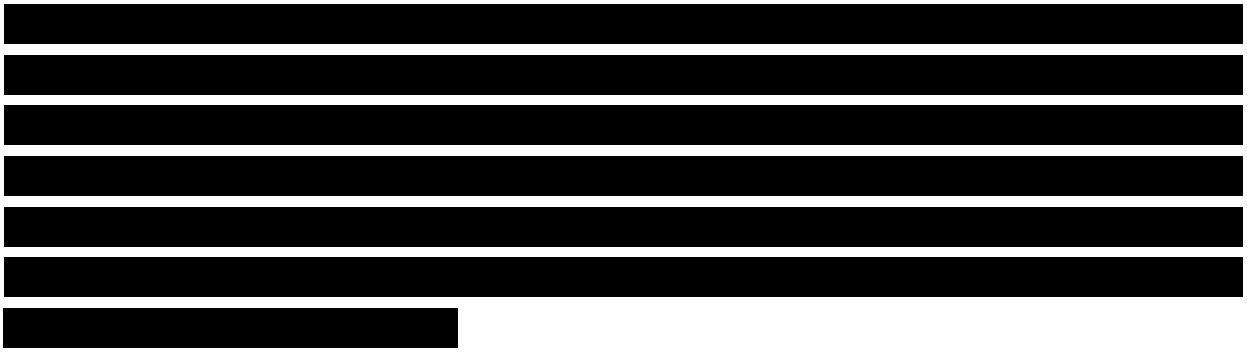


[redacted]



[redacted]







[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3.4.3 Human Factors Analysis – Post-Collision Response

After the AV contacted the pedestrian, an alert and attentive driver would be aware that an impact of some sort had occurred and would not have continued driving without further investigating the situation.

4 Findings and Conclusions

Leading up to the collision between the Nissan and the pedestrian, the AV accurately detected, classified, and tracked both the pedestrian and the Nissan. As the Nissan approached the in-path pedestrian, who was first crossing and then paused in lane, the AV's predicted paths for the pedestrian and Nissan became consistent with a potential collision as shown in Figure 54.



Figure 54. Prediction of intersecting paths for the Nissan (track ID and the pedestrian (track ID ~4.8 s prior to AV-pedestrian contact.

The Nissan was traveling at a speed of approximately 21.7 mph when it struck the pedestrian without braking. At the same time as the collision between the Nissan and the pedestrian, the AV was traveling at a speed of approximately 17.6 mph and was not predicting that either the Nissan or the pedestrian would enter the AV's travel path. The collision between the Nissan and pedestrian occurred approximately 2.9 s before the collision between the AV and the pedestrian as shown in Figure 55 and Figure 56.



Figure 55. [redacted] depicting the moment of impact between the Nissan and pedestrian, approximately 2.9 s prior to AV-pedestrian collision. Nissan and AV travel directions are to the right.



Figure 56. AV onboard camera frame from [redacted] showing the approximate moment of Nissan-pedestrian contact, ~2.9 s prior to AV-pedestrian collision. [redacted] of the pedestrian as a "Human".

Following the collision between the Nissan and the pedestrian, the pedestrian remained engaged with the Nissan for approximately 1.7 s, first at the vehicle hood and then tumbling to the roof. During this time, the Nissan moved left, crossing the centerline into the lane of oncoming traffic. Approximately 1.0 s after contact between the Nissan and the pedestrian, the Nissan moved right toward the AV travel lane. The pedestrian then separated from the Nissan approximately 1.17 s prior to the collision between the AV and the pedestrian. At this separation time, the AV was traveling at a speed of approximately 17.9 mph and was approximately one car length behind the Nissan in the adjacent right lane. The brake lights on the Nissan illuminated approximately 0.1 s after the Nissan struck the pedestrian. The AV was traveling at approximately 18.4 mph when the tumbling pedestrian was thrown at an unknown velocity and landed face down in the left region of the traffic lane occupied by the approaching AV, approximately 0.78 s prior

to being struck by the AV. The Nissan came to rest at a small, clockwise angle relative to its lane of travel with the right front tire positioned near the white lane stripe.

As evidenced by the video and sensor data, the classification and tracking of the pedestrian became intermittent within 1.0 s after the initial contact between the pedestrian and the Nissan until the last correct object classification occurred at approximately 0.3 s prior to the collision between the AV and the pedestrian. This intermittent classification and tracking of the pedestrian led to an unknown object being detected (Figure 57) but not accurately tracked by the Automated Driving Dystem (ADS) of the AV and the AV detected occupied space in front of the AV.



Figure 57. [redacted] showing the moment the pedestrian was tracked and classified as a "Dynamic_unknown" object with an ID of [redacted]

The ADS started sending steering and braking commands to the vehicle at approximately 0.25 s prior to the collision between the AV and the pedestrian (Figure 58) due to the detection of occupied space in front of the AV. Consequently, just prior to the collision with the pedestrian, the AV's heading momentarily changed rightward, and the vehicle began decelerating.



Figure 58. 

This deceleration resulted in a vehicle speed reduction from approximately 19.1 mph, prior to the onset of braking, to approximately 18.6 mph at the time of impact with the pedestrian. After the AV's front bumper first contacted the pedestrian, the ADS collision detection system detected a collision (Figure 59).



Figure 59. View from the [redacted] at its closest timestamp to the first interaction between the pedestrian and the AV, within 0.1 seconds post collision.

In order to determine the location of impact, the collision detection system refers to available object tracking information immediately prior to the detected impact. In the time immediately prior to impact, the pedestrian was substantially occluded from view of the lidar sensors, which facilitate object detection

and tracking for the collision detection system. Only the pedestrian's raised leg, which was bent up and out toward the adjacent lane, was in view of these lidar sensors immediately prior to collision. Due to a lack of consistent detections in this time frame, the tracking information considered by the collision detection system did not reflect the actual position of the pedestrian as shown in Figure 60. Consequently, the collision detection system incorrectly identified the pedestrian as being located on the side of the AV at the time of impact instead of in front of the AV and thus determined the collision to be a side impact.



Figure 60.

After contacting the pedestrian, the AV continued decelerating for approximately 1.78 s before coming to its initial stop with its bumper position located forward of the Nissan. The AV's left front wheel ran over the pedestrian and triggered an anti-lock braking system event approximately 0.23 s after the initial contact between the pedestrian and the AV's front bumper (Figure 61).



Figure 61. Variance of the readings

The determination by the ADS that a side collision occurred, and not a frontal collision, led to a less severe collision response being executed and resulted in the AV performing the subsequent outermost lane stop maneuver instead of an emergency stop. After coming to its initial stop, the AV began moving again, approximately 1.83 s after the initial contact between the pedestrian and the AV, to accomplish its outermost lane stopping maneuver.

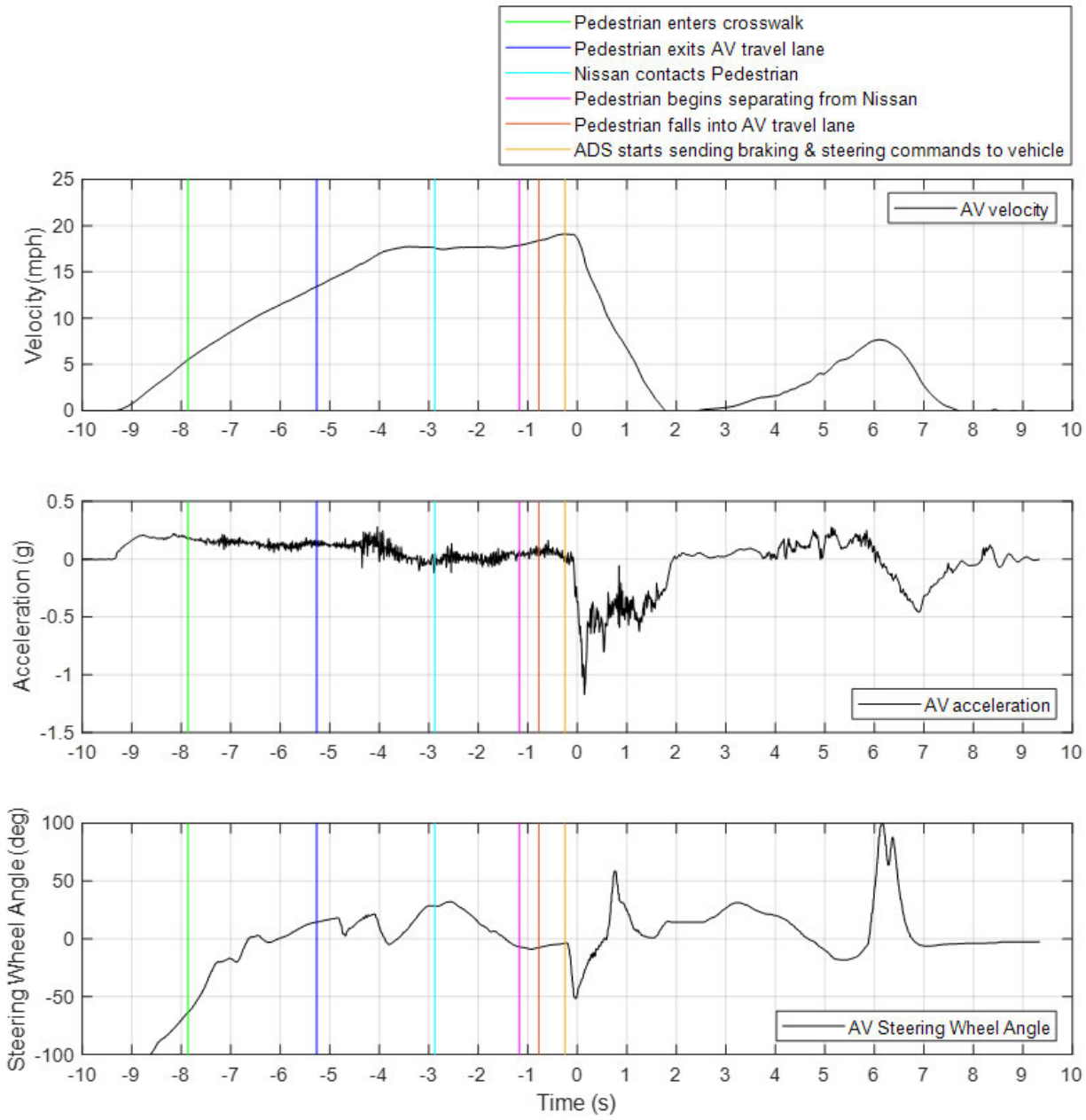


Figure 62. Timeline of events. Time is normalized such that contact between the pedestrian and AV occurs at t = 0 s.

During this maneuver, the AV reached a speed of 7.7 mph (Figure 62) and traveled approximately 20 feet while dragging the pedestrian before reaching its final rest position. As shown in Figure 63, the pedestrian's feet and lower legs were visible in the wide-angle left side camera view from the time of the collision between the pedestrian and the AV through to the final rest position of the AV. The ADS briefly detected the legs of the pedestrian while the pedestrian was under the vehicle, but neither the pedestrian nor the pedestrian's legs were classified or tracked by the ADS after the AV contacted the pedestrian.



Figure 63. View of the pedestrian's leg around the left rear wheel of the AV (white dashed circle annotation added by Exponent) approximately 3.4 s after the AV-pedestrian collision.

A traction control system event was recorded at approximately 3.8 s after the initial contact between the pedestrian and the AV due to the pedestrian physically resisting the motion of the vehicle. An accumulated offset between the wheel rotation of the left-rear wheel relative to the others from the wheel speed sensors led to the AV entering a degraded state approximately 5.8 s after the initial contact between the pedestrian and the AV. This degraded state caused the vehicle to initiate an immediate stop, and the vehicle reached its final point of rest approximately 8.8 s after the initial contact between the pedestrian and the AV (Figure 64).

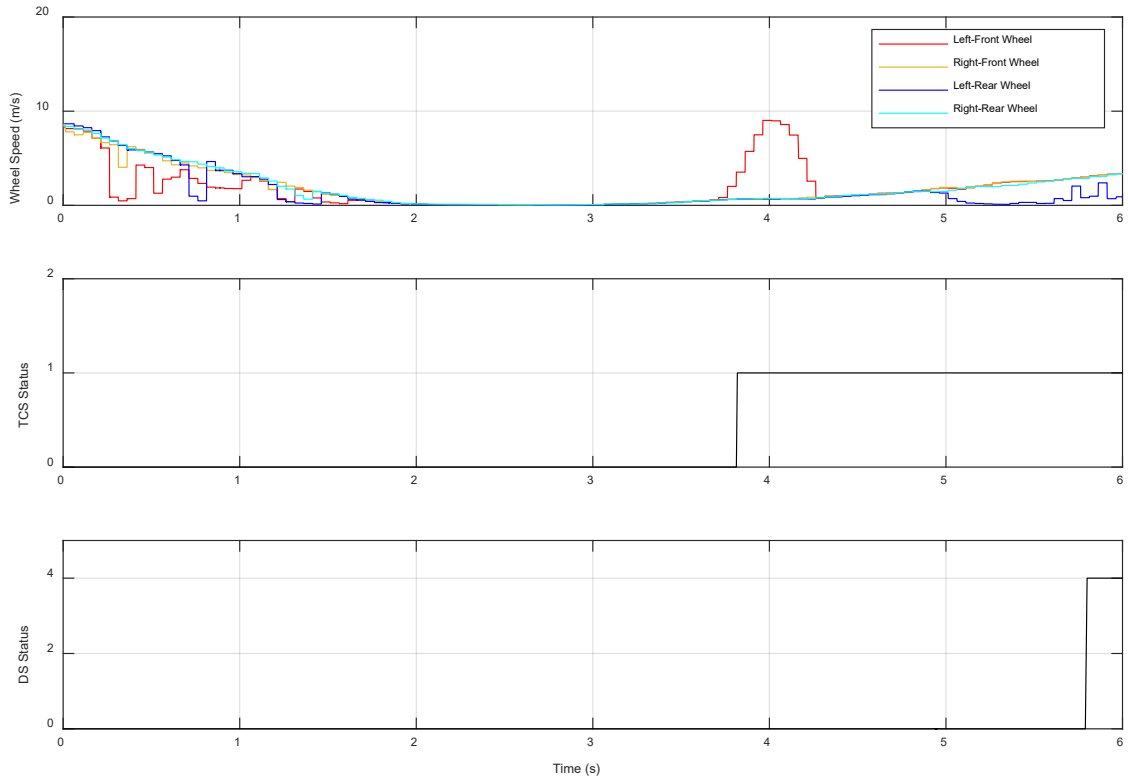


Figure 64. The AV's recorded wheel speeds (top), TCS status (middle), and Degraded State status (bottom) in the 6 seconds after the AV-pedestrian collision occurred.

The AV's collision with the pedestrian was caused by the pedestrian being projected in the AV's path of travel due to the collision with the Nissan Calculations of potential AV stopping distance and human factors analyses indicate that a collision of the AV with the pedestrian may not have been avoidable, even if the ADS had reacted to the collision between the Nissan and the pedestrian. The AV's lack of anticipation of a potential future incursion of the pedestrian into its travel lane was a contributing factor to this incident. Reasonable human drivers would face challenges reacting to the pedestrian being projected into their lane of travel and would likely not have been able to avoid the collision under similar circumstances. This difficulty could be due to violations of expectancy, glare, or A-pillar obstruction, or a combination of these, as well as to a failure to predict the collision of the Nissan with the pedestrian in the adjacent lane and/or the resulting redirection of the pedestrian into their lane of travel. Moreover, reasonable human drivers would not likely have had adequate time to avoid the collision once the pedestrian was struck by the Nissan.

The root cause of the AV's post-collision movement, after the initial brief stop, was the inaccurate determination by the ADS that a side collision had occurred, which led to the triggering of an outermost

lane stop maneuver instead of an emergency stop. Because all non-vehicles are treated in the same manner as a pedestrian with respect to a post-collision response, the intermittent classification of the pedestrian was not a contributing factor to the post-collision response. However, due to the inaccuracy of the object track considered by the collision detection system and the resulting disparity between this track and the pedestrian's actual position, the ADS failed to accurately determine the location of the pedestrian at the time of impact and while the pedestrian was underneath the vehicle. This contributed to the inaccurate side collision determination and the post-collision movement of the AV. When the AV came to an initial stop after the AV-pedestrian collision, the AV was already occupying the outermost lane and therefore, satisfied the location requirement for an outermost lane stop. However, the ADS did not consider this location as an acceptable stopping location because the outermost lane edge was mislabeled in the semantic map. This inaccurate determination by the ADS that it was not already in an acceptable stopping location was a contributing factor to the post-collision movement of the AV. After the AV contacted the pedestrian, an alert and attentive human driver would be aware that an impact of some sort had occurred and would not have continued driving without further investigating the situation.

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