Guardrail Height Safety Requirements Given Recent Crash History and Evolution of Vehicle Design

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16. Abstract

Over the past several decades, the U.S. vehicle fleet has shifted toward larger, taller, and heavier vehicles, raising questions about whether roadside safety systems remain aligned with real-world vehicle characteristics. This study evaluated the adequacy of the Florida Department of Transportation’s current 31-inch guardrail height standard relative to the previous 27¾-inch standard and recent guardrail failure outcomes in Florida. The research included a review of guardrail height practices, analysis of vehicle center of gravity, weight, and fleet composition trends, identification and classification of confirmed guardrail failure crashes, statistical comparison of failure patterns by guardrail height and vehicle characteristics, and an Annual Average Daily Traffic-normalized hot-spot analysis. Confirmed failures with known guardrail height were distributed in proportions consistent with statewide inventory prevalence, indicating no evidence that either height standard was overrepresented in the failure dataset overall. Vehicle center of gravity was significantly higher in Over failures than in Through failures, while vehicle weight was not a significant predictor of failure mode. Over failures were directionally less common at 31-inch installations than expected based on inventory proportions, but the difference was not statistically significant. The hot-spot analysis identified locations where repeated failures may warrant additional field or engineering review. Overall, the findings support continued use of the 31-inch standard while emphasizing continued monitoring of vehicle fleet trends, guardrail performance, site-specific failure conditions, and potential future design adaptations as the vehicle fleet continues to evolve.

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Executive Summary

Roadside guardrails are a critical component of Florida's highway safety system because they are intended to contain and redirect errant vehicles before those vehicles reach more hazardous roadside conditions. In 2016, the Florida Department of Transportation (FDOT) adopted the 31-inch Midwest Guardrail System (MGS) as the standard guardrail height, replacing the previous 27¾-inch standard. This change reflected national roadside safety guidance and the need to better accommodate a vehicle fleet that has shifted toward taller, heavier vehicles, including sport utility vehicles, pickup trucks, and crossovers. As these vehicle trends continue, it is important to evaluate whether current guardrail height standards remain appropriate under real-world crash conditions.

The purpose of this research was to evaluate the adequacy of FDOT's current 31-inch guardrail height standard in relation to recent vehicle design trends and confirmed guardrail failure outcomes in Florida. The study compared the 31-inch standard with the previous 27¾-inch standard, examined the role of vehicle center of gravity and vehicle weight in guardrail failure modes, and identified locations where repeated guardrail failures may warrant additional engineering review.

The research was completed through a series of related tasks. The first task reviewed guardrail height practices, failure-mode terminology, national crash-testing guidance, Florida's guardrail height history, and guardrail height standards used by other states. The second task examined vehicle fleet trends, including changes in vehicle center of gravity, vehicle weight, and fleet composition. The third task developed a confirmed guardrail failure dataset from nearly 5 years of statewide Florida crash data. The fourth task evaluated failure patterns by guardrail height and vehicle characteristics. The fifth task conducted an Annual Average Daily Traffic (AADT)-normalized hot-spot analysis to identify locations or corridors where confirmed failures appeared elevated relative to traffic exposure.

The literature and practice review confirmed that the move from the older 27¾-inch guardrail height to the 31-inch MGS was consistent with the broader national shift toward roadside safety systems designed for a more modern vehicle fleet. The review also showed that guardrail failure is not defined by height alone. Failure outcomes can include vehicles passing over the rail, passing through the rail, passing under the rail, snagging, or otherwise failing to be redirected as intended. These outcomes can be influenced by guardrail height, system condition, roadway geometry, impact angle, operating speed, vehicle geometry, roadside conditions, and installation details.

The vehicle trend analysis showed that the U.S. vehicle fleet has changed substantially over time. Passenger cars no longer dominate the fleet to the same degree as in earlier decades, while light trucks, sport utility vehicles, crossovers, and pickup trucks now represent a much larger share of registered vehicles and new vehicle sales. These vehicles are generally taller and heavier than the lower-profile passenger cars that informed many older roadside safety design assumptions. The analysis also showed that the tallest segment of the fleet has experienced meaningful increases in center of

gravity height, while vehicle weights have generally trended upward. These findings support the need for continued monitoring of roadside safety hardware in relation to changing vehicle characteristics.

The crash data collection task screened a nearly 5-year statewide crash dataset from January 1, 2021, through August 26, 2025. The initial dataset included 3,073,696 reported crashes. Using the harmful event sequence from the Florida long-form crash report, the research team identified 28,321 crashes in which a guardrail face was coded as one of the first three harmful events. A secondary screening process identified 3,135 potential guardrail failure or breach crashes. Each of these potential failures was manually reviewed using police report narratives and diagrams. Manual review confirmed 811 guardrail failures to redirect, consisting of 407 Through failures and 404 Over failures. This dataset provided the foundation for evaluating guardrail height performance and vehicle characteristics in confirmed failure events.

The statistical analysis found that confirmed failures with known guardrail height were distributed in proportions consistent with the available statewide guardrail height inventory. Among confirmed failures with known guardrail height, 159 occurred at 27¾-inch installations and 50 occurred at 31-inch installations. These proportions were similar to the inventory distribution used in the study, which indicated that approximately 77 percent of known installations were 27¾-inch and approximately 23 percent were 31-inch. The chi-square test did not show a statistically significant overrepresentation or underrepresentation of either height standard in the confirmed failure dataset overall.

When Over failures were examined separately, 31-inch installations had a lower observed share of Over failures than would be expected based on inventory proportions. This pattern is consistent with the engineering purpose of the higher guardrail height and suggests a possible directional benefit of the 31-inch standard for reducing Over failures. However, the difference was not statistically significant. Therefore, the analysis does not provide conclusive evidence that the 31-inch standard statistically outperforms the 27¾-inch standard in the available confirmed failure data.

The clearest statistical finding was the relationship between vehicle center of gravity and failure mode. Vehicles involved in Over failures had significantly higher centers of gravity than vehicles involved in Through failures. This finding is consistent with expected guardrail impact mechanics because vehicles with higher centers of gravity are more likely to interact with the rail in a way that contributes to override-type outcomes. Vehicle weight, by contrast, was not a statistically significant predictor of failure mode in the available data. Although heavier vehicles may increase impact energy, the results suggest that vehicle geometry, particularly center of gravity height, may be more important than weight alone in distinguishing Over and Through failures.

The AADT-normalized hot-spot analysis identified locations where repeated guardrail failures remained visible after accounting for traffic exposure. This indicates that the observed patterns were not explained by traffic volume alone. Over failures tended to appear as more localized hot-spots, while Through failures were more often associated with roadway segments, ramps, or interchange areas. Four locations were selected for more detailed review: the Florida's Turnpike westbound exit ramp to NW 27th Avenue in Miramar, northbound I-95 in Jacksonville, the I-75 and I-10 interchange area near Lake City, and I-75 Alligator Alley near the Broward-Collier County line. These reviews suggested that repeated failures may reflect site-specific conditions such as ramp curvature, advisory speed, superelevation, shoulder slope, impact angle, interchange geometry, roadside context, and vehicle characteristics rather than guardrail height alone.

Overall, the findings support the continued use of the 31-inch guardrail height standard as an appropriate and defensible improvement over the older 27¾-inch standard. The study did not find evidence that 31-inch installations were overrepresented in confirmed failures, and the directional reduction in Over failures at 31-inch locations is consistent with the intended safety benefit of the higher rail height. At the same time, the findings do not show that guardrail height alone explains confirmed failure outcomes. Guardrail performance in the field appears to reflect a combination of vehicle characteristics, roadway geometry, impact conditions, roadside conditions, barrier placement, and site-specific installation context.

The results of this study have practical significance for FDOT because they provide a data-driven baseline for monitoring guardrail performance as the vehicle fleet continues to evolve. The research also demonstrates the value of combining crash report review, guardrail inventory information, vehicle specifications, statistical analysis, and spatial screening to evaluate roadside safety performance. This approach can help FDOT identify locations where additional field review or engineering evaluation may be more useful than relying on crash counts alone.

The primary recommendation is to continue using the 31-inch guardrail height standard while maintaining a program of continued monitoring and targeted review. The 31-inch standard did not appear to underperform relative to the older 27¾-inch standard in the available confirmed-failure dataset, and the observed pattern of Over failures was directionally consistent with the intended benefit of the higher rail height. However, confirmed failures continued to occur at 31-inch installations, and vehicle center of gravity remained an important factor in Over failure outcomes. Prior research indicates that higher top-rail heights may be feasible under certain crash-test conditions, including 34-inch and 36-inch MGS configurations; however, additional testing and evaluation would be needed before such heights could be considered for broader application (Stolle et al., 2012; Asadollahi Pajouh et al., 2018). As the vehicle fleet continues to shift toward taller vehicles with higher centers of gravity, FDOT should continue tracking confirmed guardrail failure outcomes, particularly Over failures involving taller vehicles, and consider future evaluation of potential design adaptations if vehicle fleet trends continue.

Table of Contents

List of Figures

List of Tables

1 Introduction

Guardrails are a critical component of Florida's roadside safety system. They are designed to contain and redirect errant vehicles, reduce the severity of roadway departure crashes, and prevent vehicles from reaching more hazardous roadside conditions such as fixed objects, steep slopes, bodies of water, or opposing traffic. Because guardrails are intended to function as a last line of protection, their performance must remain compatible with the vehicles using the roadway system.

In 2016, the FDOT adopted the 31-inch MGS as the standard guardrail height for W-beam guardrail installations. This change replaced the previous 27¾-inch standard and reflected a broader national shift toward roadside safety systems better suited to the modern vehicle fleet. The earlier 27¾-inch standard was developed during a period when the vehicle fleet was more heavily represented by lower-profile passenger cars. Since then, the vehicle fleet has shifted toward sport utility vehicles, pickup trucks, crossovers, and other vehicles that are generally taller, heavier, and characterized by higher centers of gravity.

These changes in vehicle design can affect how vehicles interact with guardrail systems during crashes. A higher center of gravity can influence the likelihood of override-type failures, while increased vehicle weight can affect impact energy and barrier loading. At the same time, real-world guardrail performance is influenced by many factors beyond height alone, including impact angle, vehicle speed, roadway geometry, shoulder slope, barrier offset, installation condition, and roadside context. As a result, field performance data are needed to complement crash-testing results and better understand how guardrail systems are performing under actual Florida crash conditions.

The purpose of this research was to evaluate the adequacy of FDOT's current 31-inch guardrail height standard in relation to recent changes in vehicle design and confirmed guardrail failure outcomes. The study compared the current 31-inch standard with the previous 27¾-inch standard, examined whether vehicle characteristics such as center of gravity and weight were associated with different failure modes, and identified locations where repeated guardrail failures may warrant additional engineering or field review.

The project was completed through a series of related tasks. The first task reviewed guardrail height practices, national crash-testing guidance, guardrail failure terminology, Florida's guardrail height history, and guardrail height standards used by other states. The second task analyzed vehicle fleet trends, including changes in center of gravity, weight, and fleet composition. The third task developed a confirmed guardrail failure dataset using nearly 5 years of statewide Florida crash data. The fourth task evaluated the distribution of confirmed failures by guardrail height and vehicle characteristics. The fifth task used an AADT-normalized hot-spot analysis to identify locations or corridors where repeated failures appeared elevated relative to traffic exposure.

The crash data collection effort used statewide crash records from January 1, 2021, through August 26, 2025. Crashes were screened using harmful event sequence information from the Florida long-form crash report, followed by manual review of police report narratives and diagrams to identify confirmed guardrail failures. Confirmed failures were then classified by failure mode, including Over and Through failures, and were linked where possible to guardrail height information and vehicle specification data. This process provided a curated dataset for evaluating the relationship between guardrail height, vehicle characteristics, and observed failure outcomes.

This report presents the results of the full research effort. The findings are intended to help FDOT determine whether the 31-inch standard remains appropriate for Florida's evolving vehicle fleet, whether the previous 27¾-inch and current 31-inch standards show different patterns in confirmed failure outcomes, and whether certain vehicle or site characteristics are associated with repeated guardrail failures. The results also provide a framework for continued monitoring of guardrail performance and for identifying locations where targeted field review or engineering evaluation may be appropriate.

The remainder of this report is organized as follows. Chapter 2 reviews guardrail failure terminology, guardrail height standards, national guidance, Florida's guardrail height history, state practices, and prior guardrail performance research. Chapter 3 summarizes vehicle fleet trends related to center of gravity, weight, and fleet composition and discusses the implications of those trends for guardrail performance. Chapter 4 describes the methodology used to identify and classify confirmed guardrail failure crashes. Chapter 5 presents the final dataset and preliminary data distributions. Chapter 6 evaluates guardrail height, vehicle characteristics, and failure mode relationships. Chapter 7 presents the AADT-normalized hot-spot analysis and selected location reviews. Chapter 8 summarizes the conclusions, limitations, and issues that may be of interest to FDOT.

2 Guardrail Standards, Failure Modes, and Prior Research

This chapter presents a review of national and state-level guardrail height standards, historical evolution of FDOT's design criteria, and technical literature surrounding guardrail performance. It establishes a foundational understanding of key definitions, failure mechanisms, and the progression of test standards such as National Cooperative Highway Research Program (NCHRP) Report 350 and the American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH).

The objective of this chapter is to identify best practices across states, analyze relevant studies conducted through national research programs, and assess how past changes in guardrail height have influenced performance outcomes. This review provides the context for the subsequent chapters, which evaluate vehicle fleet characteristics, confirmed guardrail failures, statistical relationships, and spatial patterns.

By thoroughly examining current practices and research, this chapter contributes essential insights into the performance of guardrails in an evolving transportation landscape. The findings will support FDOT's broader effort to ensure that guardrail infrastructure remains aligned with modern vehicle characteristics and effectively protects roadway users.

2.1 Defining Guardrail Breach and Failure Modes

This section defines Breach and failure modes based on relevant literature. These concepts are critical to evaluating the performance of guardrails. A breach refers to the failure of a guardrail to contain a vehicle, potentially leading to serious injury and damage. Failure modes discussed include override, underride, and snagging. These failure modes will later be used to analyze various ways a guardrail can fail, often with height being a factor.

2.1.1 Breach

A guardrail breach occurs when a guardrail fails to adequately contain and redirect an impacting vehicle, resulting in a failure of the barrier's intended safety function. Guardrail performance is commonly evaluated using the crash-testing and evaluation criteria set forth in the AASHTO's MASH and the NCHRP Report 350. These documents evaluate roadside safety hardware in terms of structural adequacy, occupant risk, and vehicle trajectory, including whether the barrier safely contains and redirects the vehicle without unacceptable override, underride, or rollover related outcomes. In this study, a breach is used to describe a real world guardrail failure in which the barrier did not successfully contain or redirect the vehicle as intended.

The performance of guardrails is evaluated based on guidelines set forth by the NCHRP Report 350 and MASH, which define acceptable crash performance as the ability to control vehicle deceleration, redirect the vehicle without causing rollover, prevent underride or override during an impact. The ability of a guardrail to prevent these two critical forms of failure is vital to ensuring roadside safety and reducing the severity of injuries in crash events.

2.1.2 Override

Override occurs when an impacting vehicle travels over the top of the guardrail, bypassing the intended redirection mechanism and continuing into hazardous areas, such as opposing traffic lanes and surrounding fixed objects such as trees and light poles. This failure mode is particularly concerning because it leads to significant risks of injury or fatality, as the vehicle can collide with other obstacles or vehicles in the path of travel.

Teng et al. (2015) showed that rail height plays an important role in W-beam guardrail performance. Their study noted that low rail heights may increase the risk of vehicle rollover or truck override, while excessively high rails may increase the risk of underride for smaller vehicles. These findings reinforce the importance of selecting a rail height that allows the guardrail to properly engage the vehicle and safely redirect it during impact. If rail height is not sufficient to properly engage the vehicle during impact, the risk of override or other penetration outcomes may increase. Manchas and Olson (2009) evaluated whether guardrails measuring 27 inches or lower experienced more through, over, or under penetrations than installations measuring 28 inches or greater. Their study did not identify a clear trend in penetration performance across the 27 to 31-inch height range, but it reinforced the importance of rail height as one factor in overall guardrail behavior. A properly functioning guardrail system must therefore provide a rail height that allows effective vehicle engagement and safe redirection during impact.

2.1.3 Underride

Underride, on the other hand, occurs when the vehicle slides beneath the guardrail, bypassing the systems protective barrier. This failure mode is often observed in incidents involving smaller passenger vehicles, particularly those with lower ground clearance. Asadollahi Pajouh et al. (2018) found that 34-inch and 36-inch rail heights remained successful for the tested 1100C small-car condition, while taller heights raised concern for underride. When underride takes place, vehicles can become wedged under the rail or potentially continue their path into more hazardous situations, causing significant injury to the occupant.

Underride failures typically result from inadequate lower rail height or insufficient structural stiffness of the barrier. FDOT specifically calls out the consideration of a Thrie-Beam guardrail in areas with a higher potential of underride due to the additional rail depth over the W-beam (FDOT Plans Preparation Manual). If the guardrail does not maintain its position during impact, either due to improper installation, wear and tear, or substandard design, the vehicle can slide underneath the rail rather than being redirected. To prevent this type of failure, guardrails must be designed to have sufficient height at the lower section of the rail and be able to withstand the forces generated during a collision to maintain their structural integrity. This ensures that the guardrail will effectively contain the vehicle without allowing it to slip underneath.

2.1.4 Snagging

According to the Federal Highway Administration's (FHWA) ET-Plus review, snagging is an undesirable interaction of vehicle components with a barrier face or posts during impact due to deflection and/or surface irregularities in the barrier (FHWA ET-Plus). Parts of the vehicle may be sheared off, or the vehicle may decelerate abruptly, spin-out, or rollover. Severe snagging during impact with a w-beam barrier or terminal may lead to rail separation and failure of the barrier to contain the vehicle. Snagging is often seen in areas where a guardrail connects to a rigid barrier or rigid object (Kentucky Transportation Cabinet, 2023).

Both override and underride are considered critical failure modes in modern guardrail design, as they significantly increase the risk of severe occupant injury. Snagging is another failure mode that heightens the potential of vehicle damage and rollover. Understanding and preventing these breach mechanisms is essential to improving roadside safety.

2.2 Guardrail Height Literature Review

This section presents a review of existing research and historical documentation relevant to guardrail height standards, with a focus on how these standards have evolved to improve roadside safety. The literature is organized into several primary areas. Section 2.2.1 reviews the history of test standards as well as current national test procedures. Section 2.2.2 explores current guardrail types in use across the United States. Section 2.2.3 focuses on federal standards for guardrail height. Section 2.2.4 examines the evolution of guardrail height standards in Florida, tracing changes over time and the justifications behind them. Section 2.2.5 focuses on studies supported by the NCHRP, which have influenced national policy and design guidance. Section 2.2.6 reviews FDOT funded studies, highlighting state-level research and its contributions to safety hardware improvements.

2.2.1 Test Standards

Early recommendations on test procedure came from the Highway Research Correlation Services Circular 482, published in 1962. This was the first published procedures on full-scale crash testing that specified vehicle mass, impact speed, and approach angle. This laid the foundation for uniformity, including minimum rail length, test vehicle speed, impact angle, and vehicle weight.

NCHRP Project 22-2 was initiated in 1973 and published as Report 153 in 1975 to address the finite uniformity provided in Circular 482. This report included input from 50 individuals and agencies to provide a more comprehensive set of testing procedures for longitudinal barriers. Updates were made to standardize the testing facility, testing article, test vehicle, as well as test conditions (Transportation Research Board, 1975).

This guidance was followed by NCHRP Report 230 in 1981, which provided recommended procedures for crash testing highway appurtenances. Report 230 used a standard passenger-vehicle test matrix that included an 1800-lb minicompact, 2250-lb subcompact, and 4500-lb passenger car. While this represented an improvement in testing consistency, later changes in the vehicle fleet led to updates in the crash-testing criteria. In particular, NCHRP Report 350 later replaced the 4500-lb passenger sedan with a 3/4-ton pickup truck, reflecting the growing importance of taller and heavier vehicles in roadside safety evaluations.

NCHRP Report 350 was published in 1993 providing a comprehensive set of standards including improvements to Report 230. Speed was increased from 97 km/hr to 100 km/hr. A ¾ ton pickup truck became the standard test vehicle, replacing the 4500lb passenger car, reflecting the shift in vehicle fleet. The previous Minicompact Sedan weight was redefined to 700 kg, single-unit cargo trucks (8000 kg), and tractor-trailer vehicles (36,000 kg) (Ross et al, 1993). Critical impact point was redefined to include redirecting type safety hardware. Additionally, six test levels are defined.

AASHTO's MASH is the current crash testing and evaluation framework for roadside safety hardware, with the first version published in 2009, succeeding NCHRP Report 350. This document reflected modern vehicle fleet, with a passenger car increasing in weight from a 820C to 1100C, Pickup Truck from 2000P to 2270P, and a revised Single Unit Truck (AASHTO, 2009). These updates represented modern cars in the 2000s. The core of the documents remains the same, however MASH provided explicit test matrices for each barrier device.

The 2016 edition of MASH is the update and most current test standards for all roadway hardware, improving on the 2009 version. This update included more explicit procedures and guidance for hardware. The test vehicles remained the same, however, greater importance was placed on stability metrics. Vehicle roll, pitch, and yaw were highlighted including new definitions of failure (AASHTO, 2016).

Within MASH 2016 there are six test level standards this document may refer to as TL-1 to TL-6. These are demonstrated in Table 2-1.

Table 2-1: 2016 AASHTO MASH test levels (AASHTO, 2016)

Test Level (TL)	Vehicle Type	Vehicle Weight (lb)	Speed (MPH)
TL-1	Passenger Car	2420	31
	Pick-up truck	5000	31
TL-2	Passenger Car	2420	44
	Pick-up truck	5000	44
TL-3	Passenger Car	2420	62
	Pick-up truck	5000	62
TL-4	Passenger Car	2420	62
	Pick-up truck	5000	62
	Single unit trucks	22,000	56
TL-5	Passenger Car	2420	62
	Pick-up truck	5000	62
	Tractor Van Trailer	79,000	50
TL-6	Passenger Car	2420	62
	Pick-up truck	5000	62
	Tractor Tank Trailer	79,000	50

2.2.2 Current Guardrail Types

The MGS is a widely used, FHWA-accepted 31-inch W-beam guardrail system (FHWA). This design was originally published in 2002, incorporates a 31-inch top of rail height. Prior to that, the design of the strong-post W-beam guardrail had not been updated since the 1960's. This followed a study conducted by Sicking et al. (2002) with the Midwest Roadside Safety Facility to investigate the effects of guardrail height, spacing, and attachment methods.

It was found that with this design, light trucks were contained, however heavier trucks were not. Raising the guardrail height from the previous 27 ¾ inch, allowed for improved containment of vehicles with a higher center of gravity, while also allowing for tolerance on installation height (Sicking et al., 2002). Full-scale crash test and computer simulations were used to examine the new guardrail performance in comparison to that of prior designs. Through these methods it was determined that most trucks and smaller cars could be safely contained.

A 2007 paper by Faller et al. reviewed the performance of the W-beam guardrail system. The objective of this study was to conduct safety performance evaluations and make comparisons between light and heavy pickup trucks. Five full-scale crash tests were conducted to evaluate the performance of the MGS. Three vehicle types were used including two 5,000 lb. pickup trucks, two 4,400 lb. pickup trucks, and one 2,425 lb. passenger car. The tests compared the 27 ¾ inch to the new 31-inch MGS design. The 27 ¾ inch guardrail height did not provide adequate safety performance, noting that the pickup trucks with higher center of gravity were not contained (Faller et al., 2007). Raising the height to 31inch top of rail allowed for successful containment, meeting NCHRP Report 350 test criteria.

2.2.3 Federal Standards for Guardrail Height

National guidance related to guardrail height comes primarily through AASHTO design guidance, such as the Roadside Design Guide, together with FHWA policy, eligibility determinations, and crashworthiness guidance. General recommendations are provided with the aim of improving roadside safety across the United States. While each state has the authority to set its own guardrail standards based on local conditions and needs, national guidance helps to ensure these systems meet minimum safety requirements.

FHWA provides national guidance for roadside safety through documents like the AASHTO Roadside Design Guide. These guidelines emphasize effective barrier design to reduce crash severity, while allowing for flexibility based on local conditions. It is important to note, the Roadside Design Guide does not set required standards, it is intended to be used as national guidance.

The 2011 AASHTO Roadside Design Guide provides guidance for both the traditional blocked-out Strong-Post W-beam and the MGS. The Roadside Design Guide recommends a nominal installation height of 29 inches for new Strong-Post W-beam installations, with a tolerance of 1 inch up or down. For the MGS, the Roadside Design Guide recommends a 31-inch rail height, an increase from the historic 27¾-inch and the 29-inch Strong-Post configuration. The MGS demonstrated improved redirection performance for modern vehicle fleets and allows a tolerance of +1 inch and −3 inches.

FHWA does not prescribe a single national guardrail mounting height, but rather, provides crashworthiness criteria and eligibility determinations. The 31inch MGS is recommended by the AASHTO Roadside Design Guide and is FHWA accepted under current crash testing criteria, as it offers improved performance for a broader range of vehicles, but states retain discretion and some continue to use legacy Strong-Post configurations in certain applications.

Guardrails historically centered around the 27¾-inch Strong-Post system until the 1990s and 2000s. These years saw continued updates, with taller rail heights being tested for modern vehicles and improve safety.

2.2.4 Evolution of Guardrail Height Standards in Florida

Florida's guardrail height standards have evolved significantly over the past few decades in response to changes in vehicle design, crash performance data, and updated federal safety requirements. The following timeline outlines the key developments in the state's approach to guardrail height and the research or guidance that supported each change.

Prior to widespread federal updates, Florida's standard guardrail height was 27¾ inches, based on NCHRP Report 350 crash-testing criteria, which were the prevailing federal guidelines at the time. This height was primarily designed for smaller passenger vehicles and was widely used across the U.S. The NCHRP 350 guidelines introduced additional crash-test vehicles, including the ¾-ton pickup truck, alongside the full-size passenger sedan, to better evaluate performance against higher-center-of-gravity vehicles.

In 2009, AASHTO released the first edition of the MASH, which established updated crash-testing procedures for roadside safety hardware. Around this same period, the 31-inch MGS gained wider acceptance because testing and related design guidance indicated improved compatibility with modern vehicles when compared with older lower-height systems. FHWA and AASHTO established phased implementation deadlines for MASH-compliant roadside safety hardware, with full implementation targeted by December 31, 2019 (FHWA, 2016). The 31-inch height was shown to provide better compatibility with modern vehicles in crash testing.

In response to these changes the FDOT updated its standard plans and design criteria to reflect the 31-inch guardrail height for W-beam systems. These changes were gradually implemented across new construction and retrofit projects starting around 2012, with full adoption in subsequent standard updates (FDOT, 2016).

By 2016, FDOT standards reflected use of 31-inch W-beam guardrail systems aligned with national guidance. All new installations must comply with MASH 2016, and FDOT continues to phase out the outdated systems through regular maintenance, resurfacing, and reconstruction projects (FDOT, 2022).

2.2.5 NCHRP Studies

The NCHRP Report 350, published in 1993, was the main guide for testing how well roadside safety devices like guardrails, crash cushions, and barriers worked. Although it strongly influenced the design and acceptance of guardrail systems used during that period, it is more accurate to describe it as a crashworthiness standard than as a document that directly established a single universal guardrail mounting height. It helped states decide what safety equipment to use and how it should be designed. The report set rules for crash testing using different types of vehicles, at different speeds and angles. This included W-beam guardrail systems that were commonly installed at a top-of-rail height near 27 3/4 inches (Ross et al., 1993).

Faller et al. explored the gap between crash-tested barrier performance and how traffic barriers perform in real world conditions (2007). The authors also make a point to the wear of real-world conditions may lead to barrier degradation, height mismatches, and their contribution to overriding the guardrail during impact. It is noted that in-service performance evaluations that do exist are often limited to anecdotal or case-specific studies, with little consistency in how failures, such as guardrail breaches, are defined or tracked.

Combating this lack of data, in a 2011 study, Ferdous et al. used LS-DYNA, a crash simulation software, to analyze how common roadside and median barriers perform during vehicle impacts. The goal was to identify the performance limits of these barriers under different crash conditions, such as vehicle size, speed, and angle of impact. The study showed that barrier height and design are critical to effectively containing and redirecting vehicles, particularly where vehicle trajectory changes the effective impact height relative to the barrier (Ferdous et al., 2011).

2.2.6 State Department of Transportation-Funded Studies

The evolution of guardrail height standards in Florida has been strongly influenced by performance, safety compliance, and alignment with national guidelines such as the MASH. A study prepared by Florida International University Transportation Research and published by FDOT (2012) evaluates performance of roadside safety systems, including the W-beam guardrail. Barrier failures are identified in 21 crash reports from Florida Highway Patrol, where W-beam guardrails failed to contain or redirect the impacting vehicle. In these cases, vehicles either penetrated, overrode, or went under the barriers. These results are attributed to highspeed impacts, steep angles, or vehicle size exceeding the design capacity of the system. The barriers often met older crash testing standards like NCHRP 350, however their performance did not align with AASHTO MASH criteria. The report recommends prioritizing the replacement of outdated hardware, addressing common failure modes, and using crash data to inform future roadside safety system design and placement.

Virginia Highway and Transportation Research Council analyzed the low guardrail height in Virginia in 1981. Two sites were tested with different guardrail heights for the same length of 1,000 feet. Site one tested a 22-inch guardrail on a two-lane highway, while site two tested a 25-inch guardrail height on a straight section of an interstate highway. Through testing, it was determined that site one with the lower guardrail height was more hazardous than that of site two. It also created methods for locating low guardrails, proposed six remedial treatments, and created a numerical scoring system to prioritize corrections (Hargroves, 1981).

Washington State Department of Transportation Design Policy, Standards, and Research Team evaluates the correlation between guardrail height and penetration of the guardrail in Washington State. Guardrail collision date collected between 1999 and 2009 was categorized into three collision types. These include strike of the guardrail face, strike of the guardrail leading end, and Through, Over, and Under (TOU). The W-beam guardrail was the only model selected for testing. Out of the 1,806 chosen crashes, the 28-inch guardrail had the most TOU collision type at 30, followed by 26-inch at 20 TOU collisions. It is noted that the large variety of heights looked at may contribute to the average of 5.0 percent penetration crashes (Manchas & Olson, 2009).

2.2.7 Additional Guardrail Studies

In a study by Hawkins et al. (1987), the impact of barrier height on guardrail performance was found to be significant in determining the success of roadside safety barriers. The research analyzed 1,686 traffic barrier accidents and identified that guardrail failure rates were notably higher for lower barrier heights, particularly when older guardrail designs were involved. The study indicated that vehicle override was more likely when guardrails were insufficient in height, especially with larger vehicles such as trucks and vans, which have higher centers of gravity. The authors concluded that inadequate barrier height, whether due to design limitations or the elevation changes from road resurfacing, was a major factor contributing to guardrail breaches.

Bligh et al. conducted MASH test 3-10 and 3-11on 31-inch W-beam guardrail systems with offset blocks (2011) using the 1100C small vehicle in collisions. The design vehicle passed with the 31-inch height, remaining upright and deemed acceptable. Impact led to deflection of the guardrail itself; however, no breach was recorded, safely redirecting the test vehicle without any underride of the vehicle.

A key study by Marzougui et al. (2007) directly evaluated how different W-beam guardrail heights affect vehicle containment and redirection during crash scenarios. Using full-scale crash tests and simulation data, the research demonstrated that increasing the guardrail height improves performance, particularly for larger, higher-riding vehicles such as SUVs and trucks. The study found that lower rail heights (around 27 ¾ inches) were more likely to allow vehicle override or cause wheel snagging, compromising the safety of both vehicle occupants and surrounding traffic. Increasing the rail height to approximately 31 inches significantly reduced these risks, aligning with recommendations from FHWA. This study provides technical justification for modernizing existing infrastructure to match the evolving vehicle fleet and crash test protocols like those outlined in MASH.

Similarly, Fang et al. (2017) examined how different rail heights affected the safety performance of the MGS**.** The study used full-scale crash testing to assess whether small variations in height above or below the standard 31-inch rail altered the barrier's ability to safely contain and redirect impacting vehicles. The findings confirmed that the Strong Post W-beam maintains acceptable performance within a limited tolerance range at the 31-inch standard with small cars under MASH impact conditions. However, the system's effectiveness significantly decreased below 29 inches, increasing the likelihood of override or wheel snagging, especially in crashes involving higher-profile vehicles like SUVs and pickups. These results reinforce the rationale behind updating older 27 ¾-inch systems and maintaining strict height specifications in both installation and maintenance practices. It was concluded that the wood post Thrie-beam guardrails provide safer redirection in terms of exit angle than the steel-blockout.

Asadollahi Pajouh et al. evaluated the performance of increased rail heights for the 31-inch MGS through full-scale crash testing and computer simulation. It was concluded that heights up to 36 inches continued to meet MASH TL-3 requirements for 1100C small passenger cars. The study confirmed that top-rail heights of 34 and 36 inches continued to meet MASH TL-3 criteria for 1100C passenger cars. These results indicate that rail heights up to 36 inches can be safely used without risking underride or excessive post snagging, compromising vehicle redirection, or containment. It is noted, however, that heights above 36-inches, such as 37-inches, would likely result in small car underride.

Similarly, a study by Stolle et al. in 2012 evaluated the potential for increasing mounting height of the MGS. Two full-scale crashes with Kia Rio passenger cars were conducted on a 34-inch and 36-inch top rail mounting height. Both heights were found to satisfy MASH evaluation criteria. It is recommended that the tests be run for pickup trucks before the increased heights be deemed crashworthy (Stolle et al., 2012).

A Swedish study by Fredriksson & Holmen focuses on the lack of tests on the standard guardrails with sport utility vehicles (SUVs) and sports cars. It was found that a W-beam guardrail ceases to function below 17 inches from ground to centerline, specifically in relation to sports car impacts. Higher installation tolerances are also recommended based on geography and the typical vehicles found on specific roadways.

Driver behavior is an element considered by Lloi et al. in their study on the impact of guardrail heights with a limited sight distance on driver behavior. The study included 54 participants, each of whom drove 4 of the 18 possible simulations involving no guardrail, a 29½-inch guardrail, or a 37-inch guardrail in both driving directions. It was concluded that with the lower guardrail height, drivers tend to stay close to the roadside, while the higher height results in increased lateral distance. It was also noted that males increased their speed with the increased guardrail height and decreased sight distance, while females did not. It is proposed that increased speeds be tested in the design stage of taller guardrails.

2.3 Guardrail Height Standards, by State

This section examines guardrail height standards across all 50 U.S. states to provide a comprehensive understanding of current practices, identify inconsistencies, and evaluate their practical impacts. By analyzing each state's approach, a broad comparison of standards can be made to help identify trends, outliers, or areas where alignment with national guidelines may be lacking. This wide scope is essential for assessing the potential need for greater consistency in safety practices and infrastructure planning. The objectives are to document and compare existing guardrail height standards while identifying trends and variations. Additionally, this section seeks to evaluate how closely state standards align with federal recommendations.

2.3.1 Applicability to States

While the FHWA and AASHTO provide national guidance on guardrail standards, the implementation and regulation of guardrail height is ultimately the responsibility of individual states. Each state transportation agency has the authority to adopt, modify, or expand upon federal recommendations based on local needs, roadway conditions, climate, vehicle trends, and crash history. The flexibility means that while many states use FHWA and AASHTO guidelines as a baseline, guardrail height standards can vary from state to state. Some may adhere closely to national guidance, while others develop more specific design criteria to address unique regional factors.

The variation in state-level practices underscores the importance of examining and comparing guardrail height standards nationwide. It also highlights the potential benefits of aligning more closely with evolving federal research and crash testing protocols to ensure consistent safety outcomes across the country.

2.3.2 Guardrail Data Collection and Evaluation Methodology

This section collected data on guardrail height standards from all 50 U.S. state departments of transportation. The primary sources included official state DOT design manuals, standard plans, roadside safety policies, and publicly available construction specifications.

To ensure accuracy and consistency, each state's most current specifications for guardrail systems, including height requirements for common systems like W-beam guardrails, were collected and reviewed. When multiple height values were listed, the standard, default height for typical installations was recorded. Special attention was given to whether the values were explicitly defined in inches, presented in ranges, or referenced national standards such as MASH or NCHRP 350.

In some cases, state documents were outdated, incomplete, or unclear. When this occurred, the most recent and most widely used values were assumed to reflect current practice. For specifications the nominal top of rail value was recorded for comparison purposes. While every effort was made to verify and standardize the data, variations in document structure and update frequency may have introduced minor inconsistencies.

2.3.3 State-by-State Guardrail Height Standards

The collected data is presented in two tables listing each found standard guardrail height and the abiding states. The tables are organized alphabetically by state for ease of reference. Table 2-2 includes states that follow a standard or typical guardrail height, generally aligning with nationally recommended values such as the 31-inches MGS including tolerances. Table 2-3 highlights states that show variation from typical standards.

Table 2-2: Guardrail height standard by U.S. state and territory

Guardrail Height Standard 31 (in)		
Alabama	Louisiana	North Dakota
Alaska	Maine	Ohio
Arizona	Maryland	Oklahoma
Arkansas	Massachusetts	Oregon
California	Minnesota	Pennsylvania
Colorado	Missouri	Rhode Island
FHWA	Montana	South Carolina
Florida	Nebraska	Tennessee
Georgia	Nevada	Texas
Hawaii	New Hampshire	Utah
Idaho	New Jersey	Washington
Indiana	New Mexico	Wisconsin
Iowa	New York	Wyoming
Kansas	North Carolina	Vermont
Kentucky		

Table 2-3: Other guardrail height standards by U.S. state and territory

Other Height Standards (in)	
Virginia	32 3/4 "
Mississippi	32"
Delaware	31" to 32"
Illinois	31 7/8”
District of Columbia	30-1/8"
Connecticut	30’’
Michigan	29"
Puerto Rico	28-3/4"
West Virginia	28-1/2" or 31"
South Dakota	27-3/4" to 29-1/2"

The standard guardrail height across most U.S. states falls between 27 ¾ and 32-inches, with 31-inches being the most commonly adopted values. While the 31-inch heights reflect general consistency nationwide, several states allow for slight deviations. For instance, Delaware permits heights ranging from 31 to 32 inches, while South Dakota allows installations between 27-3/4 and 29-1/2 inches, reflecting flexibility in application or existing installations. These measurements are typically associated with both the Strong-Post W-beam guardrail system at 27 ¾-inch and MGS, which has been engineered for optimal performance at a height of 31-inches.

Some states diverge from the typical FHWA's 27 3/4 -inch and 31-inch recommendation in notable ways. Virginia and South Dakota both remain with the Strong-Post W-beam system in variation. Both states have their standards around the 27 ¾-inch recommendation, while adhering to the ±1-inch set forth by the Roadside Design Guide. West Virginia allows for either the 28 ½-inch or 31-inch guardrail height, as both are listed as of 2018 in their design standards.

Regional patterns in guardrail height standards reveal small, but notable geographic trends. For example, the area containing West Virginia, Virginia, Connecticut, and Delaware all have standard heights other than the typical 31-inches. Virgina and Delaware have heights above, Connecticut has a height of 30-inches, while West Virginia has the option of 31-inch or 28 ½-inch.

FHWA recommends a standard guardrail height of 29-inches for Strong Post W-beam installations and 31-inches for use with the MGS, which is designed to perform optimally at this height. Most states adhere closely to this guidance, with many matching the 31-inch recommendation precisely. Others fall within a tolerance of ±1 inch, indicating widespread alignment with national standards. However, a few states, including West Virginia and South Dakota remain using the older 27 ¾-inch W-beam standard with tolerances. Conversely, states like Mississippi, Delaware, and Virginia have slightly higher standards, exceeding 31 inches, yet still remaining within tolerances. These elevated heights may be influenced by factors such as regional climate conditions, anticipated roadway settling, or an added safety buffer in design specifications.

2.4 Summary of Guardrail Height Standards and Prior Research

The review highlights the evolution of guardrail height standards and their critical role in roadside safety amid changes in vehicle design. The shift in FDOT's standard from 27¾ inches to 31 inches reflects a broader national trend, driven by updated crash test protocols and the increasing prevalence of vehicles with higher centers of gravity, such as SUVs and light trucks. These vehicles present greater risks of override and ineffective redirection, prompting a need to reassess the performance of legacy guardrail systems.

This report has defined and examined key failure modes, breach, override, underride, and snagging, and reviewed national safety testing standards, including NCHRP Report 350 and the MASH. It also evaluated current guardrail systems and synthesized findings from major national and state-funded research efforts. The evidence strongly supports the 31-inch MGS as a more effective solution for modern crash conditions.

A 50-state review of current practices revealed that while many states have adopted the 31-inch standard, others still use varied heights ranging from 27¾ to over 32 inches. This variation underscores the importance of aligning state practices with evolving federal guidance to ensure consistent and effective roadside safety.

The results of this review provide the necessary foundation for the next phases of the research project. The following chapters use this foundation to evaluate vehicle fleet characteristics, confirmed guardrail failure data, statistical relationships among failure mode, vehicle characteristics, and guardrail height, and spatial patterns in confirmed failures.

3 Vehicle Fleet Characteristics and Guardrail Implications

Chapter 3 is focused on analyzing how vehicle characteristics have changed over time and whether Florida's current guardrail height standards have adequately adapted in response. Specifically, this chapter investigates trends in three key areas: vehicle center of gravity, vehicle weight, and fleet composition. In parallel, the evolution of guardrail height standards in Florida is documented and analyzed in the context of these vehicle changes. This chapter summarizes how vehicle characteristics have changed over time and discusses the implications of those trends for guardrail performance. The chapter focuses on vehicle center of gravity, vehicle weight, and fleet composition.

3.1 Review of Historic Trends and Relevant Datasets

The National Highway Traffic Safety Administration (NHTSA), in its 2005 report on trends in static stability factors of passenger cars, light trucks, and vans, covers the importance of analyzing vehicle weight, center of gravity, and static stability factor (SSF) on rollover crashes. Rollover crashes were noted as the most severe traffic crashes, despite only amounting for 3 percent of total crashes in 2003. SUVs had the highest reported rollover fatality rate at 59 percent.

SSF is defined as the at- rest calculation of a vehicle's rollover resistance, based on the geometric properties. This is defined as T/2H, where T is the track width of the vehicle, and H is the center of gravity height for the vehicle (NHTSA, 2005). This is an important factor when looking at a vehicle's possibility for rollover. A lower SSF indicates a higher probability for rollover in certain vehicle maneuvers. Typically, SUVs and pickup trucks range from 1.00 to 1.30 in SSF, compared to the 1.30 to 1.50 range of passenger cars. In reference to guardrail impact, a lower SSF would lead to more frequent override incidents.

A recent study, (Tse, 2022) analyzed trends in vehicle center of gravity height and SSF using data from the Light Vehicle Inertia Properties Database (LVIPD) and the New Car Assessment Program (NCAP) rollover testing. It was found that there was a steady upward trend in center of gravity height from 1971 to 2020, especially pronounced after 2000. Results showed that while early passenger cars had an average center of gravity height of about 19 to 21 inches, current light trucks and SUVs frequently exceeded 26 inches, in some cases reaching 30 inches or more. These findings are critical because a higher center of gravity increases rollover propensity override of roadside barriers. That same study also found that while vehicle designs have become more crashworthy in general, SSF declined slightly due to these higher centers of gravity, indicating increased rollover risk despite improved occupant protection. This article highlights the importance of updating roadside infrastructure, particularly guardrails, to better match the physical profiles and dynamics of today's vehicles.

According to the NCHRP Research Report 1033, light trucks and SUVs now make up the majority of new vehicle sales, which has led to a general increase in fleet height and weight (Riexinger et al., 2023). These changes have raised concerns about the adequacy of earlier guardrail systems, which were primarily designed and tested for lower-profile vehicles typical of the 1970s and 1980s.

NCHRP Research Report 1061 notes that as of 2017, approximately 92 percent of the vehicles on U.S. roads were classified as passenger vehicles, making up most of the national vehicle fleet (Harwood et al. 2023). Within this group, the distribution reveals a notable shift in consumer preference and vehicle design over recent decades. Of these passenger vehicles, about 45 percent were traditional passenger automobiles, such as sedans, coupes, and hatchbacks, which have historically represented the majority of personal transportation. However, the remaining 55 percent consisted of vans, light trucks, and SUVs, a category that has grown significantly. This trend reflects a broader movement away from low-profile passenger cars toward higher-riding vehicles that can serve multiple roles for consumers. Heavy trucks accounted for roughly 4.5 percent of the vehicle population. These are typically commercial vehicles, such as tractor-trailers, delivery trucks, and other high-capacity transport vehicles. Motorcycles, buses, and other specialized vehicles make up 3.5 percent of vehicles.   This information is summarized in Table 3-1 (Harwood et al., 2023).

Table 3-1: Summary of U.S. vehicle registration data (Harwood et al., 2023)

Vehicle type	Number of registered vehicles	Percentage of registered vehicles
Passenger vehicles	248,840,000	91.9
Automobiles	111,180,000	41
Pickup trucks	47,860,000	17.7
Sport utility vehicles	73,580,000	27.2
Vans	16,220,000	6
Motorcycles	8,720,000	3.2
Heavy trucks	12,230,000	4.5
Single-unit trucks	9,340,000	3.4
Truck tractors for combination trucks	2,890,000	1.1
Buses[a]	980,000	0.4
School buses	480,000[b]	0.2
Transit buses	60,000[c]	0.02
Other buses (including intercity buses and motor coaches)	440,000[d]	0.2
TOTAL	270,770,000	100

Sources: Adapted from FHWA (2004), the Federal Motor Carrier Safety Administration, the Bureau of Transportation Statistics (BTS) (2016, 2017), and other cited sources.

[a] Total number of registered buses is based on BTS data (www.bts.gov/content/bus-profile).

Vehicle type	Number of registered vehicles	Percentage of registered vehicles
Passenger vehicles	248,840,000	91.9
Automobiles	111,180,000	41
Pickup trucks	47,860,000	17.7
Sport utility vehicles	73,580,000	27.2
Vans	16,220,000	6
Motorcycles	8,720,000	3.2
Heavy trucks	12,230,000	4.5
Single-unit trucks	9,340,000	3.4
Truck tractors for combination trucks	2,890,000	1.1
Buses[a]	980,000	0.4
School buses	480,000[b]	0.2
Transit buses	60,000[c]	0.02
Other buses (including intercity buses and motor coaches)	440,000[d]	0.2
TOTAL	270,770,000	100

[b] Based on National School Transportation Association data for 2013 (https://s3-us-west-2.amazonaws.com/nsta/6571/Yellow-School-Bus-Industry-White-Paper.pdf).
[c] Number of transit buses based on BTS data (www.bts.gov/content/transit-profile). d Computed from the preceding three values."

FHWA's article on the vehicle fleet and motor-vehicle registration highlights the changes in vehicle fleet from 1970 to 2000 (FHWA, 2000). During the 1990s, light single-unit truck registrations increased by 61.1 percent, accounting for 39.1 percent of the vehicle fleet by 1990, showing the early stages of the transition away from traditional passenger cars. Automobile registration dropped from 80 percent in 1977 to 62.9 percent in 2000. Minivans remained relatively stable during this time, with a slight increase from 7.8 percent in 1995 to 8.2 percent in 2000. The SUV segment showed a notable rise, growing from 6.9 percent to 10.2 percent between 1995 and 2000. This shift marked the beginning of a long-term trend that continues today, where light trucks and SUVs now make up the majority of the passenger car fleet.

Figure 3-1 compiles vehicle registration from 1970 to 2000 (FHWA, 2000). Seen in this graph are the early changes in fleet composition, where automobiles began to decrease, and trucks and buses began to rise in its place. This trend continues in Figure 3-4.

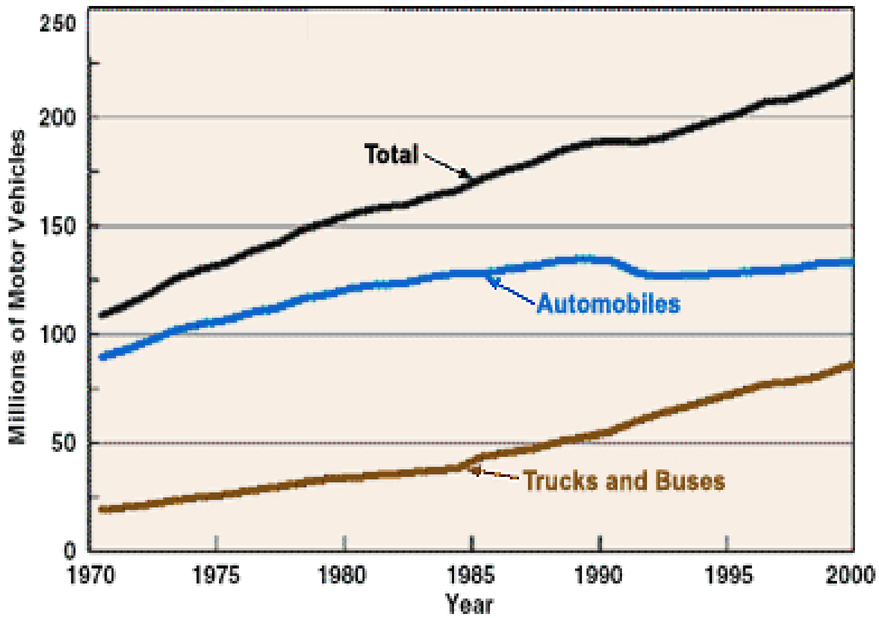

Figure 3-1: FHWA fleet composition from 1970 to 2000 (FHWA, 2000)

3.2 Relevant Datasets

Vehicles are constantly changing and evolving, with new models every year. The NHTSA publishes a record of measured vehicle inertial parameters for new models per calendar year based on data collected by the NHTSA New Car Assessment Program (NCAP). These parameters include vehicle make and model, track width, weight, and center of gravity height. Four major publications have been made of this data including groupings of prior to 1992 (Garrott, 1992), 1992 through 1998 (Heydinger et al., 1999), 2001 through 2008 (Bixel et al., 2010), and the latest of 2009 through 2020 (Zagorski, 2021).

The NCAP conducts laboratory tests for rollover stability measurement, including calculations for SSF. Tests are conducted at the Vehicle Inertial Measurement Facility (VIMF), where a stable pendulum method is observed. For the test, the vehicle is loaded onto a rigid platform at trim height, with a pivot point above the combined center of gravity. The trim height is the vertical distance from either the ground or wheel hub, to the vehicle frame when the vehicle is at rest and loaded under specified conditions. The trim height typically represents normal ride conditions with no additional passengers or load. The platform is then tilted by applying weight to either end, assuring the tilt test can be done in a stable and controlled manner. This test allows for a correct measurement of center of gravity height.

There are two test categories conducted on every vehicle, driver-only loading, and fully loaded. The driver-only loading, however, is the most commonly used for calculation of the SSF, where center of gravity is derived from. This is the configuration that is published in the NCAP consumer information. Fully loaded configuration test results are often used in engineering evaluations, but less commonly reported to the public.

FHWA publishes state motor-vehicle registrations in their yearly publication of the Highway Statistic Series. This is a compiled list of all motor-vehicle registrations reported by the states, organized into categories of automobiles, buses, trucks, motorcycles, and all-motor vehicles. Yearly reports were compiled to analyze changes over time. The FHWA dataset was used as the source information for the analysis of fleet composition, presented in section 3.3 of this report.

3.2.1 Vehicle Center of Gravity

From the 1970s through the 1990s, vehicles generally exhibited a lower center of gravity height due to their smaller size and lower ground clearance (Tse, 2022). Sedans dominated the market, with body styles typically favoring improved SSF and reduced rollover risk. However, starting in the late 1990s and into the 2000s, vehicle popularity trends toward SUVs, crossovers, and light trucks. These vehicles have a higher height, larger weight, and elevated suspensions, which contribute to an increase in center of gravity height. Because of this, the average center of gravity height across the vehicle fleet began to rise.

Changes in vehicle center of gravity can be tracked through yearly publications by NHTSA’s Measured Vehicle Inertial Parameters. These data points are represented in Figure 3-2. This includes data from 1999 to 2020. This chart displays the changes in vehicle center of gravity height. Q1–Q4 represent Quartiles 1–4, respectively. Throughout the given years, the height changes approximately 0.022 inches (0.55 mm) per year on average. This indicates a steady trend towards taller vehicle designs. This can largely be attributed to the growing number of light trucks, SUVs, and crossovers which all typically have higher ride heights than automobiles, including sedans.

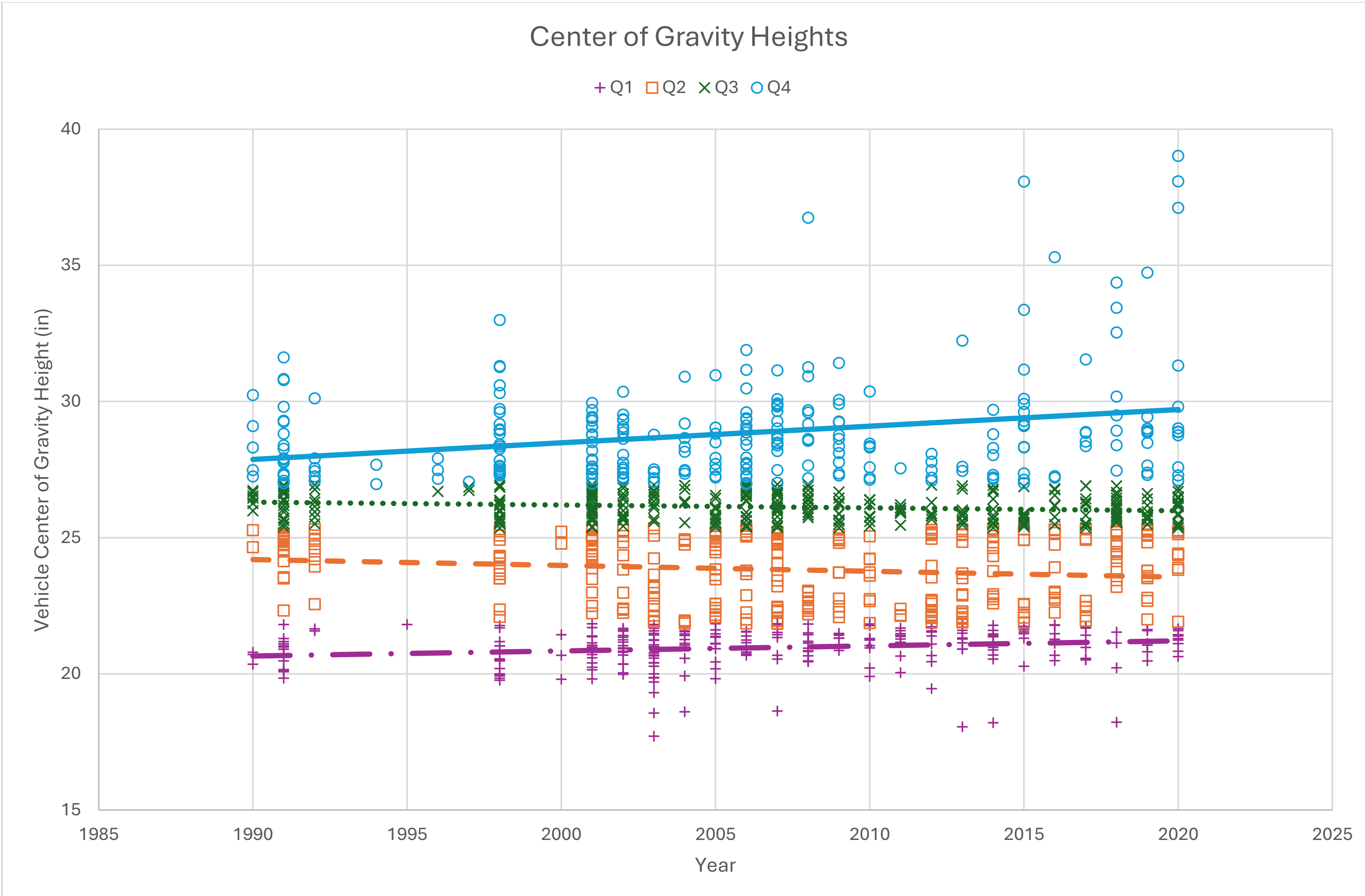

Figure 3-2: Center of gravity change

Figure 3-2 breaks down this data by quartile for a more detailed view of how center of gravity height is changing across the fleet:

- Quartile 4 represents vehicles with the highest 25 percent of center of gravity heights. These are taller vehicles such as light trucks, SUVs, and vans. Roughly, this category sees an approximated 0.02 inch average growth in height per year.
- Quartile 3 displays the upper-middle 25 percent of center of gravity heights. These vehicles likely include crossovers, midsize SUVs, and taller sedans. This saw an average decrease of about 0.01 inch per year.
- Quartile 2 covers the lower-middle 25 percent of center of gravity heights. This category likely consists of standard sedans, hatchbacks, and smaller crossovers, representing a mix of conventional passenger cars and more compact utility vehicles. On average, center of gravity height for this quartile decreases roughly 0.001 inch per year.
- Quartile 1 includes vehicles with the lowest 25 percent of center of gravity heights, typically low-profile passenger cars such as coupes, sports cars, and compact sedans. These vehicles prioritize handling and stability, which benefit from a lower center of gravity. This group saw the highest average annual increase of 0.008 inch per year.

This quartile-based breakdown provides a clearer understanding of how the average fleet-wide rise in center of gravity height varies within different vehicle types. While the overall trend shows an increase, Quartiles 2 and 3 demonstrate slight annual decreases, indicating that midsize vehicles and crossovers have generally become lower over time. In contrast, both the shortest vehicles (Quartile 1) and the tallest vehicles (Quartile 4) have increased in center of gravity height, with the tallest vehicles growing the fastest. Specifically, vehicles in Quartile 1 are increasing about 0.02 inches per year more than midsize vehicles and 0.01 inches more than the smallest vehicles like sedans and sport cars. This shows that while the smallest vehicles continue to get taller, higher-profile passenger cars are seeing a relatively greater upward shift in center of gravity height.

Table 3-2 displays the overall change in a 30-year period, as well as by quartile. Initial and final center of gravity height were averaged of data collected from 1990 and 2020 per quartile.

Quartile 1, representing the vehicles with the lowest center of gravity, saw a slight increase from 20.6 inches to 21.3 inches. In total, there is an absolute change of 0.7 inches, or 3.29 percent, showing the lowest 25 percent of cars are getting taller, yet at a slow rate.

The middle 50 percent saw a decrease in center of gravity height in both the second and third quartiles. Quartile 2 decreases from 25.0 inches in 1990 to 24.3 inches in 2020. This group had a absolute decrease of 0.7 inches, or 2.78 percent. Quartile 3 had an initial center of gravity of 26.4 in 1990, which fell to 26.0 inches in 2020. This quartile showed an absolute change of 0.4 inches, or 1.58 percent. Both quartiles do decrease over the 30-year period, however remaining under a 1-inch differential.

Quartile 4 represents the vehicles with the highest center of gravity since 1990. In the initial year, the height was averaged at 28.5 inches. The final height was 31.1 inches in 2020, for an absolute change of 2.6, or an increase of 9.12 percent. This quartile indicates the tall cars are increasingly getting taller.

Table 3-2: Center of gravity summary

Quartile	Initial Year	Initial Center of Gravity Height (in)	Final Year	Final Center of Gravity Height (in)	Absolute Change (in)	Percent Change (%)
1st Quartile	1990	20.6	2020	21.3	0.7	3.29%
2nd Quartile	1990	25.0	2020	24.3	-0.7	-2.78%
3rd Quartile	1990	26.4	2020	26.0	-0.4	-1.58%
4th Quartile	1990	28.5	2020	31.1	2.6	9.12%
Total	1990	25.8	2020	25.9	0.1	0.31%

In total, the average center of gravity increased from 25.8 inches in 1990 to 25.9 inches in 2020. This is an overall increase of 0.1 inches, or 0.31 percent, when looking at total fleet.

3.2.2 Vehicle Weight

Changes in vehicle design and customer preferences have led to steady increases in the overall vehicle height and weight. Understanding how these evolving vehicle dimensions affect crash dynamics is essential for ensuring that roadside barriers, such as guardrails, remain effective in safely containing and redirecting vehicles.

According to the data provided on vehicle weight from NHTSA, vehicle weight is trending upwards, increasing each model year. On average, the average new vehicle weighs 10.8 pounds more than the previous year. When broken down into quartiles, three out of four follow this trajectory, reinforcing the overall trend of increasing vehicle weight as shown in Figure 3-3.

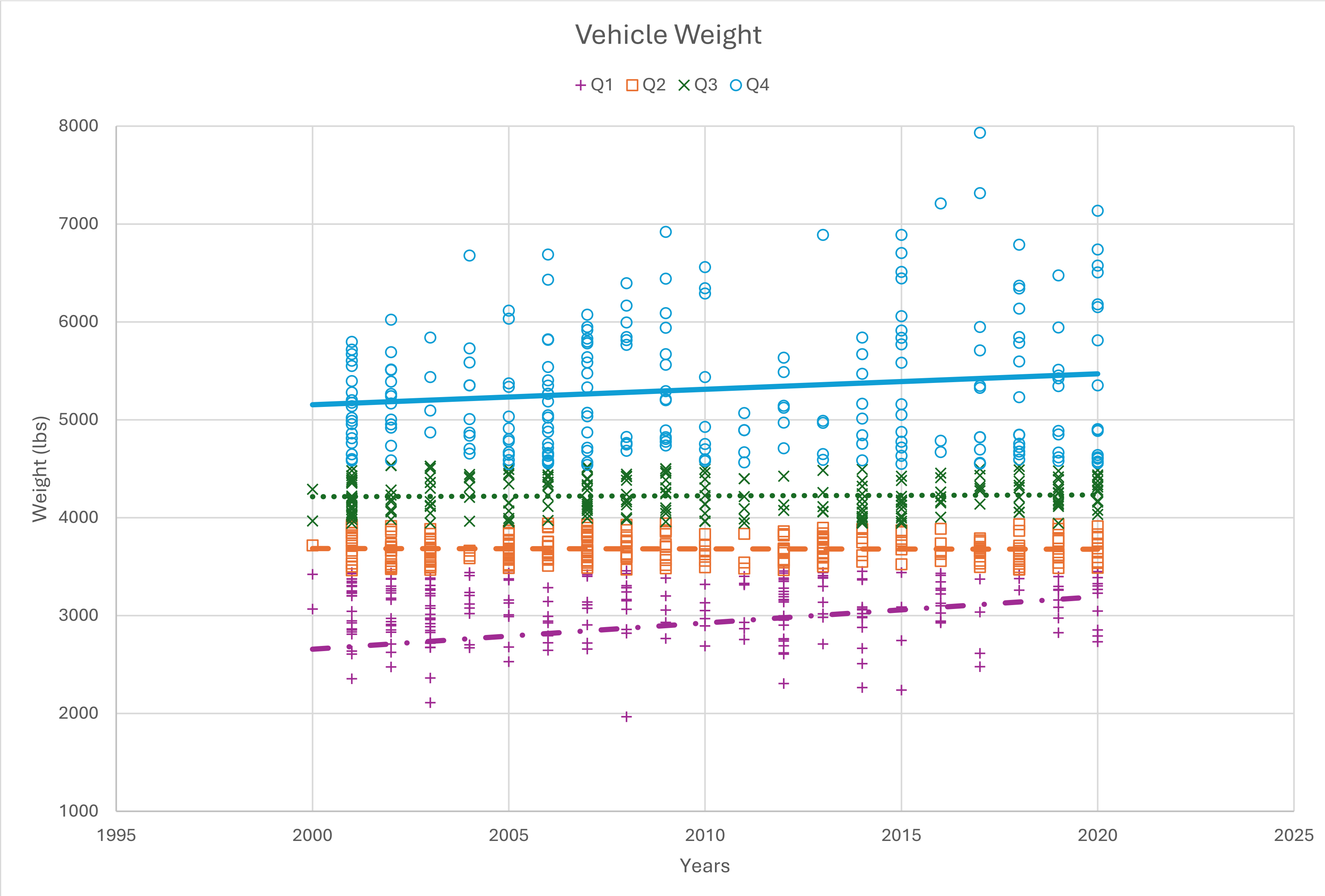

Figure 3-3: Vehicle weight changes

Over time, vehicles have become both taller and heavier. Vehicles in Quartile 1, representing the lightest segment of the fleet, are increasing in weight by an average of 26.82 pounds per year. In contrast, vehicles in Quartile 3 show a slight average decrease of 0.33 pounds per year, while Quartile 2 exhibits an annual increase of approximately 0.88 pounds. Notably, the heaviest vehicles in Quartile 4, which include large trucks and SUVs, have experienced an average annual weight gain of 15.80 pounds. This figure indicates that while midsize vehicles have remained relatively stable or slightly lighter, both the lightest passenger cars and the largest vehicles are steadily gaining weight. This trend contributes to an overall rise in the average weight of the vehicle fleet. Table 3-3 summarizes the changes in vehicle weight from 2000 to 2020.

Table 3-3: Vehicle weight summary

Quartile	Initial Year	Initial Weight (lb)	Final Year	Final Weight (lb)	Absolute Change (lb)	Percent Change (%)
1st Quartile	2000	3047.3	2020	3165.8	118.5	3.89%
2nd Quartile	2000	3666.1	2020	3683.2	17.1	0.47%
3rd Quartile	2000	4211.1	2020	4290.4	79.3	1.88%
4th Quartile	2001	5182.3	2020	5508.0	325.6	6.28%
Total	2000	3770.9	2020	4289.5	518.6	13.75%

The first quartile represents the lightest vehicles. This group showed an increase in weight from 3047.3 lbs. to 3165.8 lbs. for an absolute change of 118.5 lbs., or 3.89 percent. The light vehicles in this quartile are increasingly getting heavier.

The second quartile shows a 0.47 percent increase from 2000 to 2020, with a total increase of 17.1 lbs. The weight changes from 3666.1 lbs. to 3683.2 lbs. This differs from Figure 3-3, in which the trendline shows a slight negative change for that quartile. This is due to a spike in weight from the years of 2007 to 2008, then again in 2013. This summary table, however, shows the overall change for this quartile is increasing.

Quartile 3 sees a 1.88 percent increase from 2000 to 2020. The weight increases from 4211.1 lbs. to 4290.4 lbs., for an absolute change of 79.3 lbs. Quartile 4, the group with the heaviest vehicles, saw the largest increase in weight from 5182.3 lbs. to 5508.0 lbs. This is a 6.28 percent change, or 325.6 lb. increase.

In total, vehicles are increasing in weight when averaging all quartiles. There is an absolute change of 518.6 lbs., at a 13.75 percent increase. This reveals a consistent upward shift in vehicle weight, suggesting vehicles are increasingly becoming heavier by year.

Combined with increases in vehicle height and center of gravity, this added weight has important implications for crash dynamics and the effectiveness of roadside safety features. Heavier and taller vehicles produce greater impact forces during collisions and are more prone to overriding guardrails if barrier systems are not properly designed and tested for these loads. This can lead to reduced containment performance, higher risks of severe vehicle rollovers, and increased danger to occupants and other road users.

As a result, modern guardrail standards must not only address changes in vehicle height but also account for these increases in vehicle mass. Ensuring that guardrails can withstand higher impact energies and provide reliable redirection for a wider variety of vehicle sizes and weights is critical to maintaining effective roadside safety. This underscores the need for continuous evaluation of both fleet trends and guardrail performance, so that design standards can evolve alongside the vehicles they are meant to protect.

3.2.3 Vehicle Fleet Composition

Vehicle fleet composition is an important factor when looking at the guardrail design height evolution. Through vehicle registration publicly provided by the U.S. Department of Transportation, overall trends are able to be seen of vehicle fleet composition over time. This can be seen in Figure 3-4, which includes data from 1994 to 2020.

Prior to 1985 passenger vans, passenger minivans, and utility-type vehicles were classified as automobile registrations. For all data beginning in 1985, these vehicles were considered in the truck category for registration.

Important to note, while the FHWA provides the broad vehicle characteristics of automobiles, trucks, and buses, the detailed classification and registration of these vehicles is often carried out by each individual state's Department of Motor Vehicles. States follow federal guidance for reporting to the FHWA but may apply their own criteria for delineating specific vehicle types such as SUVs and crossovers.

Automobiles usually correspond to the Passenger Cars category in FHWA terms. This includes standard cars such as sedans, hatchbacks, coupes, and smaller crossovers. Trucks encompass all vehicles designed primarily for carrying capacity or performing work functions. This broad category includes light trucks, such as pickup trucks, many SUVs, and minivans, as well as heavy single-unit trucks and combination trucks like tractor-trailers.

Figure 3-4 shows the overall number of vehicles registered in the United States continues to grow each year, reflecting sustained demand for personal and commercial transportation. Within this expanding fleet, trucks are experiencing an average annual increase of approximately 4 million new registrations. In contrast, registrations of traditional automobiles are declining by about 1 million vehicles per year on average. This shift in fleet composition illustrates a clear consumer preference for larger, more versatile vehicles that can serve multiple roles, from daily commuting to hauling and recreation.

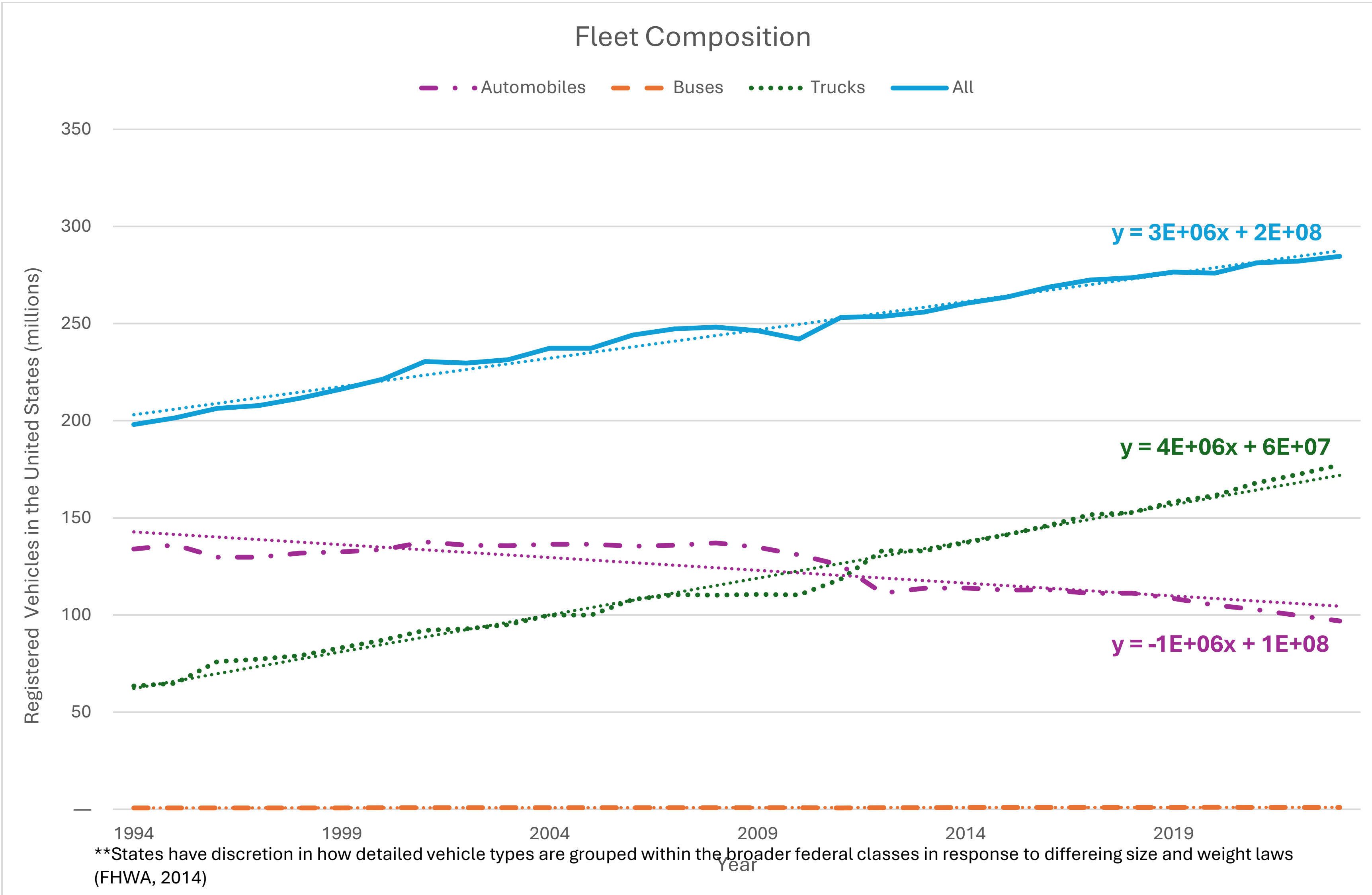

Figure 3-4: Fleet composition

Table 3-4 summarizes the changes in fleet composition from 1994 to 2023, as shown in

Figure 3-4. Overall, there is a 65.32 percent increase in number of vehicles on the road since 1994. Automobiles have a 27.65 percent decrease, with an overall decrease of 37,028,099 vehicles being registered. Buses increased by 44.32 percent, with 297,102 new registrations since 1994. Trucks have the highest increase at 179.30 percent. This means 113,772,991 additional trucks were registered as of 2023. These numbers highlight the significant shift in fleet composition and the growing dominance of trucks in the vehicle population.

Table 3-4: Fleet composition summary

Fleet Type	Initial Year	Initial Count	Final Year	Final Count	Absolute Change	Percent Change (%)
Automobiles	1994	133,929,662	2023	96,901,563	-37,028,099	-27.65%
Buses	1994	670,423	2023	967,525	297,102	44.32%
Trucks	1994	63,455,280	2023	177,228,271	113,772,991	179.30%
Summary	1994	198,045,365	2023	284,614,269	86,568,904	65.32%

Automobiles outnumbered the number of trucks on the road from 1970 to 2011, when the two were equal. Ever since, automobile numbers have steadily decreased, while the number of trucks has trended upward. This ongoing shift toward larger vehicles has reshaped the composition of the vehicle fleet. Over time, this transition has contributed to a fleet that is not only larger in number but also heavier and taller on average, which has direct implications for the performance of guardrails. Understanding these trends is critical for adapting infrastructure to meet the demands of an evolving vehicle population. With an increasing percentage of vehicles classified as heavier and taller, it will eventually become necessary to adjust guardrail heights and performance standards to maintain effective protection for the modern fleet.

3.3 Guardrail Performance Implications of Vehicle Fleet Trends

The results of this analysis reveal important trends that directly inform considerations for the adequacy and future evolution of Florida's guardrail height standards. The findings collectively illustrate how shifts in vehicle design, mass, and fleet composition over the past several decades are creating new challenges for roadside safety infrastructure.

3.3.1 Increasing Vehicle Center of Gravity and Implications for Containment

The steady increase in average vehicle center of gravity height, particularly among the tallest vehicles such as SUVs and light trucks, has clear implications for guardrail performance. A higher center of gravity increases the likelihood of vehicle rollover and raises the potential for override failures when interacting with guardrails originally designed for a fleet dominated by lower-profile passenger cars. Even small annual increases, when compounded over decades, result in a meaningful divergence from the design assumptions underpinning older guardrail systems.

The disproportionate growth in center of gravity height among both the tallest (Quartile 4) and lowest (Quartile 1) segments of the fleet suggests that the issue is not confined to a niche subset of vehicles but rather reflects a broad market-wide shift toward taller vehicle designs. This trend reinforces the need for continued monitoring and may warrant future adjustments to guardrail height and design specifications to ensure containment performance remains effective.

3.3.2 Vehicle Weight Growth and Impact Energy Considerations

The analysis also highlights a consistent upward trend in vehicle weight across much of the fleet. Heavier vehicles impart greater kinetic energy during crashes, increasing demands on the structural performance of roadside barriers. Notably, the heaviest vehicles (Quartile 4) gained an average of 15.8 pounds annually, while even the lightest vehicles (Quartile 1) added approximately 26.8 pounds per year. This combination of increasing vehicle mass and elevated center of gravity amplifies the forces exerted on guardrails during crashes, raising questions about whether current guardrail systems are adequately tested and rated for these evolving crash dynamics.

As a result, future updates to testing protocols and design standards may need to reflect these trends to ensure that guardrails continue to provide reliable redirection and containment for the modern fleet. Considerations for increased post strength, anchorage performance, and system stiffness may become increasingly relevant as vehicle masses continue to rise.

3.3.3 Fleet Composition Shift and Broader Exposure

Since 2011, trucks and SUVs have surpassed traditional automobiles in registrations, representing a structural shift in the composition of Florida’s, and the nation’s, vehicle fleet. As these vehicles dominate new sales and registrations, the exposure of guardrails to higher, heavier vehicles has become the norm rather than the exception. The rising prevalence of these vehicles increases the probability that guardrails will encounter impact conditions that differ substantially from those anticipated during the development of older standards.

This ongoing transition underscores the importance of aligning roadside safety features with real-world vehicle profiles. Infrastructure that was once calibrated for a passenger car-dominated fleet must now be evaluated and possibly recalibrated for a fleet where SUVs, crossovers, and light trucks are dominant.

3.4 Summary of Vehicle Trends and Guardrail Implications

Over the past several decades, the U.S. vehicle fleet has undergone substantial transformation, characterized by changes in average vehicle height, weight, center of gravity, and fleet composition. Driven largely by the growing prevalence of SUVs, pickup trucks, light trucks, and crossovers, these trends have produced a vehicle fleet that differs from the lower-profile passenger car fleet that influenced many earlier guardrail design assumptions.

The analysis showed that the tallest segment of the vehicle fleet has experienced the greatest increase in center of gravity height. Although fleetwide average center of gravity changed only modestly, the upper quartile increased more substantially, indicating that the vehicles most relevant to override potential have continued to become taller. Vehicle weight also increased over time, particularly among the heaviest vehicles, which may increase impact energy and place greater demand on roadside safety systems.

These vehicle trends help explain why guardrail height standards have evolved. Older 27¾-inch guardrail systems were developed during a period when lower-profile passenger cars were more dominant. As taller and heavier vehicles became more common, the 31-inch MGS was introduced to provide improved compatibility with the modern vehicle fleet and better engagement with higher-profile vehicles. This change reflects an important adaptation in roadside safety design, but it does not eliminate the need for continued monitoring.

Overall, the findings in this chapter reinforce the importance of evaluating guardrail performance in relation to changing vehicle characteristics. The 31-inch standard is better aligned with the current fleet than the older 27¾-inch standard, but continued increases in vehicle height, center of gravity, and weight may challenge existing roadside safety systems over time. These trends provide the basis for the following chapters, which evaluate confirmed guardrail failure data, compare failure outcomes by height standard and vehicle characteristics, and identify locations where repeated failures may warrant additional review.

4 Guardrail Failure Data Collection and Analysis Methodology

This chapter describes the methodology used to identify, review, classify, and prepare guardrail failure records for analysis. The purpose of this process was to develop a curated dataset of real-world guardrail failure events in Florida that could support evaluation of guardrail height standards, vehicle characteristics, failure modes, and spatial patterns.

The analysis began with a nearly 5-year statewide crash dataset from Signal 4 Analytics covering January 1, 2021, through August 26, 2025. Because a prefiltered statewide dataset of guardrail failures was not available, the research team used the harmful event sequence from the Florida long-form crash report to identify crashes in which a guardrail face was coded as one of the first three harmful events. Crashes were then screened for subsequent harmful events involving roadside objects or conditions that would typically indicate that the vehicle passed through, over, under, or beyond the guardrail system.

All crashes flagged through this screening process were manually reviewed using available police report narratives, diagrams, and supporting crash information. This review was necessary because harmful event coding alone cannot reliably determine whether a guardrail failed to contain or redirect a vehicle. The manual review process distinguished confirmed guardrail failures from crashes in which the guardrail appeared to perform as intended or where the available information was too ambiguous to support a failure classification.

Confirmed failures were classified by failure mode, including Over and Through failures, and were linked where possible to vehicle characteristics and guardrail height information. Vehicle make, model, and model year were used to compile center of gravity height and vehicle weight from available vehicle specification sources. Crash locations were also mapped and compared with FDOT eMaintenance end treatment inventory data, supplemented by manual review of aerial imagery and available site information, to identify whether the associated guardrail height was 27¾ inches or 31 inches.

The resulting dataset provided the foundation for the subsequent statistical and spatial analyses in this report. These data were used to evaluate the distribution of confirmed failures by guardrail height, compare vehicle characteristics by failure mode, and support the AADT-normalized hot-spot analysis used to identify locations where repeated guardrail failures may warrant additional review.

4.1 Screening Using Harmful Event Sequences

Florida uses a standardized long-form crash report that documents key details about each crash, including location, roadway and environmental conditions, involved vehicles, and the sequence of events leading to injury or property damage. As part of this record, the reporting officer must identify the “Harmful Event” sequence, typically coded as up to four ordered events (Harmful Event 1, Harmful Event 2, Harmful Event

3, and Harmful Event 4). The first harmful event represents the initial occurrence that produced injury or damage (for example, impact with a guardrail face, another vehicle, or a fixed object). Subsequent harmful events capture additional impacts or outcomes that occurred after the initial event, such as secondary collisions, rollovers, or departures from the roadway. In this study, the harmful event sequence is used to identify crashes in which a guardrail was struck and to distinguish cases where the guardrail may have failed to contain or redirect the vehicle from those in which it performed as intended.

A crash was initially flagged as a potential failure to redirect when at least one of the first three harmful events (Harmful Event 1, 2, or 3) was coded as "guardrail face" and a subsequent harmful event involved an object that would typically be located on the far side of the guardrail (e.g., culvert, ditch, embankment, tree, body of water, fence, utility pole, or similar roadside feature). The presence of these subsequent impacts suggests that the vehicle passed through, over, or beyond the guardrail, potentially resulting in a more severe crash outcome.

To ensure thorough and accurate identification of guardrail failures, all crashes flagged by this screening process underwent manual review of the official police report narratives and diagrams to determine whether the guardrail in fact failed to contain or redirect the vehicle. This manual review step is essential, as some crashes may be incorrectly flagged due to miscoding, incomplete reporting, or crash sequences in which the guardrail performed as intended.

Between January 1, 2021, and August 26, 2025, a total of 3,073,696 crashes were reported statewide. Applying the harmful event screen identified 28,321 crashes in which a guardrail face was coded as Harmful Event 1, 2, or 3. Of these, 3,135 were further flagged as potential failures to redirect based on the presence of a subsequent harmful event involving an object beyond the guardrail. All 3,135 potential failures were manually reviewed, and 811 crashes were ultimately verified as failures to redirect. Because the statewide dataset is too large to permit narrative review of all crashes, only crashes meeting the harmful event screening criteria were flagged for detailed review. This two-step approach uses the coded harmful event sequence as an efficient filter while keeping the intensive manual review process targeted and practical.

4.2 Limitations and Error Management

The crash identification and screening approach used in Chapter 4 is subject to several important limitations that should be considered when interpreting the results. The methodology relies on the harmful event sequence coded in the Florida long-form crash report as the primary filter for identifying potential guardrail failures and breaches. Crashes were selected when at least one of the first three harmful events was coded as "guardrail face," and a subsequent harmful event involved an object typically located on the far side of the barrier. While this coding structure provides an efficient way to isolate crashes of interest from a very large statewide dataset, it also introduces opportunities for misclassification.

Type I errors (false positives), cases in which a vehicle was successfully contained or redirected by the guardrail but subsequently struck an object inside the protected zone (e.g., curb, mailbox, sign support), or cases in which roadside objects were miscoded as being beyond the rail; were managed through a manual review process. All 3,135 crashes flagged as potential failures to redirect underwent manual review of the official police report narratives and diagrams. This review allowed the research team to confirm the crash sequence, assess the location of secondary impacts relative to the guardrail, and determine whether the guardrail in fact failed to contain or redirect the vehicle. Through this process, 811 crashes were verified as failures to redirect and retained for further analysis, while the remaining flagged cases were excluded as non-failures or ambiguous events. This two-step procedure, automated screening followed by targeted manual review, was necessary to maintain both practicality and quality control given the size of the dataset.

Type II errors (false negatives) are more difficult to detect and correct. Some true failures to redirect may not generate a coded secondary harmful event that indicates contact with an object beyond the guardrail. These include partial breaches where a vehicle penetrates or rides up the rail without striking another coded object, as well as override or underride events where a vehicle crosses the guardrail and overturns or comes to rest without an additional harmful event being recorded. In addition, some crashes may not be captured by the screening criteria if the guardrail impact is miscoded (e.g., recorded as a “guardrail end” or a generic “fixed object” rather than “guardrail face”) or if the harmful event sequence does not accurately reflect the crash sequence. As a result, the 811 confirmed failures to redirect likely represent a conservative subset of all guardrail failures that occurred during the study period.

Additional limitations stem from the quality and completeness of supporting data. Police narratives and diagrams vary in detail and clarity, which can make it challenging to interpret crash dynamics or resolve conflicting information. Guardrail height data, collected through separate field and inventory efforts, may be subject to measurement or coding errors, geolocation inaccuracies, or temporal mismatches between the crash date and the height observation. These factors can introduce uncertainty into the assignment of specific height categories (e.g., legacy versus current standards) and may lead to the exclusion of cases with insufficient or ambiguous information. Despite these challenges, the combination of a structured harmful event based screen, a clearly defined failure-to-redirect criterion, and comprehensive manual review of all flagged crashes provides a transparent and defensible framework for identifying guardrail failure events while managing the most critical sources of error.

4.3 Guardrail Failure Dataset

This section presents the results of the guardrail failure screening and classification process. This section first documents the structure and content of the compiled breach dataset, including the organization of the crash records, key variables, and the classification of crashes into through, over, and non-breach categories. It then summarizes the preliminary findings from the 5-year analysis period, highlighting the frequency of guardrail strikes, the subset of crashes flagged as potential failures to redirect, and the number and distribution of confirmed breach failures by year and breach type. These results provide the empirical foundation for subsequent assessments of guardrail performance and height standards.

4.3.1 Breach Dataset Metadata

Florida long-form crash report data was used for all crashes in which a guardrail face was coded as one of the first three harmful events. The data was sorted by four categories to support efficient filtering and review of potential guardrail breach cases:

- ALL – Contains all crashes for the year in which a guardrail face was coded as Harmful Event 1, 2, or 3. This serves as the master dataset and includes both potential and confirmed breach cases.
- Harmful Event 1 – Subset of crashes where “Guardrail Face” is coded as Harmful Event 1.
- Harmful Event 2 – Subset of crashes where “Guardrail Face” is coded as Harmful Event 2.
- Harmful Event 3 – Subset of crashes where “Guardrail Face” is coded as Harmful Event 3.

Each crash record includes a unique report identification number (ID) which serves as the primary identifier for classification, cross-referencing, and mapping. Crashes were classified based on information contained in the official police report narratives and accompanying illustrations and categorized as shown in Table 4-1.

Table 4-1: Data coding

Type	Notation
Through	Report ID
Over	Report ID
Non-breach	

“Through” crashes were typically identified when the narrative explicitly described the vehicle as traveling *through* the guardrail, or when the description indicated that the vehicle struck the guardrail and continued beyond it to another object or to a location outside the protected area. In cases where the narrative was ambiguous, the corresponding diagram was reviewed to determine whether the vehicle appeared to penetrate through the guardrail.

“Over” crashes were identified when the narrative described the vehicle as rolling over, vaulting, or traveling on top of the guardrail after impact. If the narrative did not clearly indicate an override, airborne movement, or travel along the top of the rail, the case was re-examined for evidence of a potential through breach.

This dual review process, combining narrative assessment with examination of crash illustrations, helped ensure that crashes were classified as Through or Over as accurately as possible, given the available data and the study's limitations.

4.3.2 Preliminary Results

Table 4-2 summarizes the crash screening results by year. Across the study period, 3,073,696 crashes were reported statewide, including 28,321 crashes in which a guardrail strike was identified. Of these guardrail strike crashes, 3,135 were flagged as potential breach failures and reviewed in greater detail using crash narratives and diagrams.

Table 4-2: Statewide guardrail crash screening results by year

Year	2021	2022	2023	2024	2025	Total
Total Crashes	549,421	710,689	717,009	702,346	394,231	3,073,696
Guardrail Strikes	5,728	7,406	7,134	6,001	2,052	28,321
Potential Breach Failures	627	888	792	556	272	3,135
Failure to Redirect (Percent of Guardrail Strikes)	183 (3.19%)	202 (2.73%)	192 (2.69%)	175 (2.92%)	59 (2.88%)	811 (2.86%)

Confirmed failures to redirect represented a small share of all guardrail strikes. Across the full study period, 811 crashes were confirmed as failures to redirect, representing 2.86 percent of guardrail strikes. The annual percentage remained relatively consistent, ranging from 2.69 percent to 3.19 percent. This suggests that confirmed guardrail failures were uncommon relative to all guardrail strikes but occurred consistently enough to support further review by failure mode, vehicle characteristics, guardrail height, and location.

Identified failures were further categorized by breach type, including Through and Over failures. This classification is summarized by year in Table 4-3.

Table 4-3: Confirmed Over and Through guardrail failures by year

Year	2021	2022	2023	2024	2025	Total
Through	79	98	99	96	35	407
Over	104	104	93	79	24	404

Across the study period, the retained Over and Through failure dataset included 407 Through failures and 404 Over failures. The annual distribution was relatively balanced between the two failure modes, although Through failures were slightly more common in

3 of the 5 study years. The highest annual count occurred in 2022, followed closely by 2023. The lower count in 2025 reflects the partial year of available data, which extended through August 26, 2025. These results show that both Over and Through failures occurred consistently during the study period and support separate evaluation of the two failure modes in the subsequent analysis.

4.4 Preparation of the Final Analysis Dataset

This section documents the procedures used to prepare the confirmed Over and Through failure dataset for the vehicle- and guardrail-height-based analyses. Vehicle characteristics, including center of gravity height and vehicle weight, were compiled where sufficient vehicle make, model, and model year information was available. Guardrail height was assigned where confirmed failure locations could be matched to FDOT eMaintenance end treatment inventory or verified through supporting spatial review. Because not all confirmed failures had sufficient vehicle information or guardrail height information, the final analysis dataset is smaller than the full set of confirmed failures to redirect.

4.4.1 Vehicle Specification Data

Following verification of Over and Through failures described in Section 4.3, vehicle characteristics were compiled for center of gravity height and vehicle weight. Each crash report provided the vehicle make, model, and model year, which were used to identify the corresponding vehicle specification record. Vehicle information was obtained primarily from NHTSA NCAP data when available. When a direct center-of-gravity height was unavailable, SSF was used to estimate center-of-gravity height based on published vehicle dimensions. SSF was calculated as:

$$SSF = \frac{T}{2H}$$

Where,

T is trackwidth, and

H is center of gravity height.

When the exact model year was not available, the vehicle model was reviewed for major design updates (generation changes) and body style consistency. The closest available year within the same generation and body style was selected to minimize differences in dimensions and stability characteristics.

4.4.2 Guardrail Height Assignment

All confirmed Over and Through failures were geolocated and mapped in ArcGIS based on location details from Signal4 and were compared against FDOT eMaintenance end treatment inventory data. Because comprehensive guardrail data for all locations could not be obtained, end treatment height data from the FDOT eMaintenance database were used as a proxy. FDOT design standards generally ensure that the terminal height is representative of the connected guardrail segment.

To ensure correct identification, each mapped failure was manually reviewed using a combination of ArcGIS satellite map and Google Street View. This verified the end-treatment type to confirm the correct guardrail height at the crash location.

Because FDOT eMaintenance end treatment inventory is concentrated on major highways, not all confirmed failures with usable vehicle information could be matched to an end treatment and assigned a guardrail height. In addition, semitrucks were excluded from the vehicle-based analyses, and some crash reports did not include sufficient vehicle descriptors, such as make, model, or model year, to support reliable vehicle identification. As a result, the full set of confirmed failures to redirect was reduced for the subsequent vehicle- and guardrail-height-based analyses. Table 4-4 summarizes the availability of vehicle and guardrail height data for the retained Over and Through failure dataset.

Table 4-4: Vehicle and guardrail height data for Over and Through failures

Failure mode	Has Guardrail and Vehicle Data	Vehicle Data, No Guardrail Data	No Vehicle Data, No Guardrail Data	Total
Through	102	115	200	407
Over	107	109	188	404

5 Confirmed Guardrail Failure Dataset and Data Distributions

Chapter 5 presents the data used for the statistical evaluation of guardrail failure modes in relation to guardrail height standard and vehicle characteristics. The chapter begins with a summary of the final distribution of confirmed failures by failure mode and guardrail height, followed by descriptive figures illustrating the distributions of vehicle center of gravity height and vehicle weight. It then evaluates the distributional form of these variables across relevant subgroups to determine whether the assumptions of parametric testing are met. Together, these summaries provide the basis for the statistical analyses presented in the following sections.

5.1 Data Distribution

Table 5-1 summarizes the final distribution of mapped and confirmed failures, reported as Over, Through, and Total counts and percentages for 27¾-inch and 31-inch guardrail height standards.

Table 5-1: Failures with known guardrail height by failure mode

Failure mode	27 3/4-in. guardrail, n (%)	31-in. guardrail, n (%)
Over	86 (54.1%)	21 (42.0%)
Through	73 (45.9%)	29 (58.0%)
Total	159 (100.0%)	50 (100.0%)

These percentages describe the composition of confirmed failures within each height standard and do not represent failure rates per installation. Because the dataset includes confirmed failures rather than all guardrail strikes, differences in percentages should be interpreted as descriptive.

Figure 5-1 and Figure 5-2 summarize the distribution of vehicle center of gravity height and weight for confirmed failures. Box plots were used to visualize differences in central tendency and spread between Over and Through crashes and to identify potential outliers and skewness prior to formal statistical testing.

Figure 5-1 is a box plot of vehicle center of gravity height by failure mode. The y-axis represents vehicle center of gravity height in inches, whereas the x-axis shows each failure mode studied. Figure 5-2 shows a box plot of vehicle weight by failure mode. The y-axis shows vehicle weight, with the x-axis showing failure mode.

In both figures, the line inside each box represents the median. The top of each box represents the 75th percentile and the bottom of each box represents the 25th percentile. The whiskers extend to the maximum and minimum values for each failure mode.

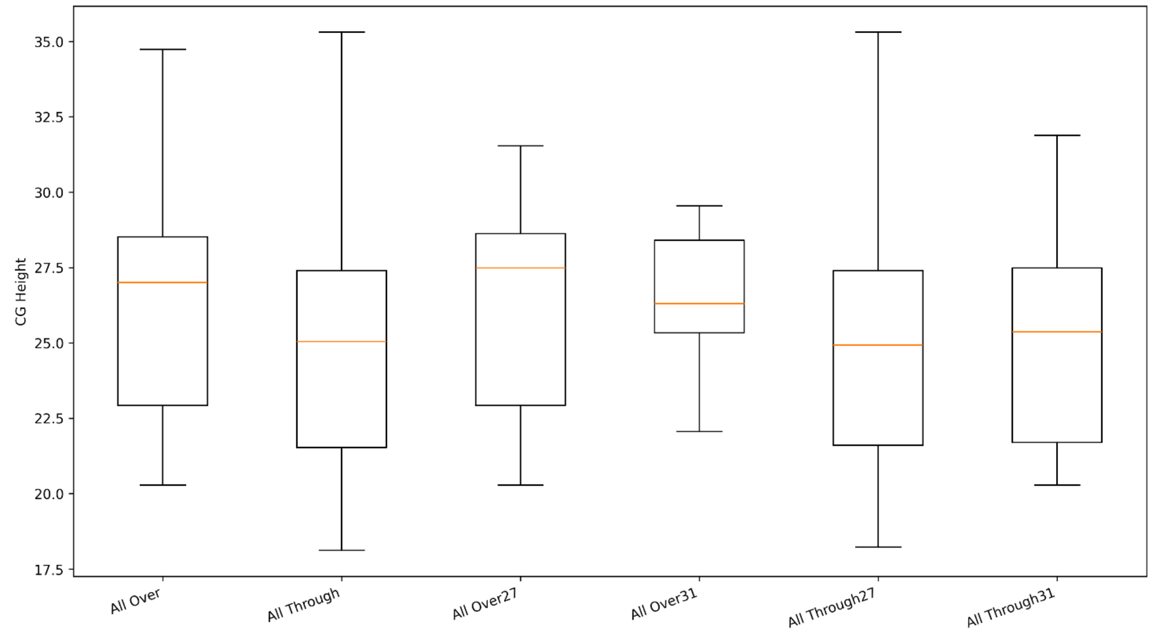

Figure 5-1: Vehicle center of gravity

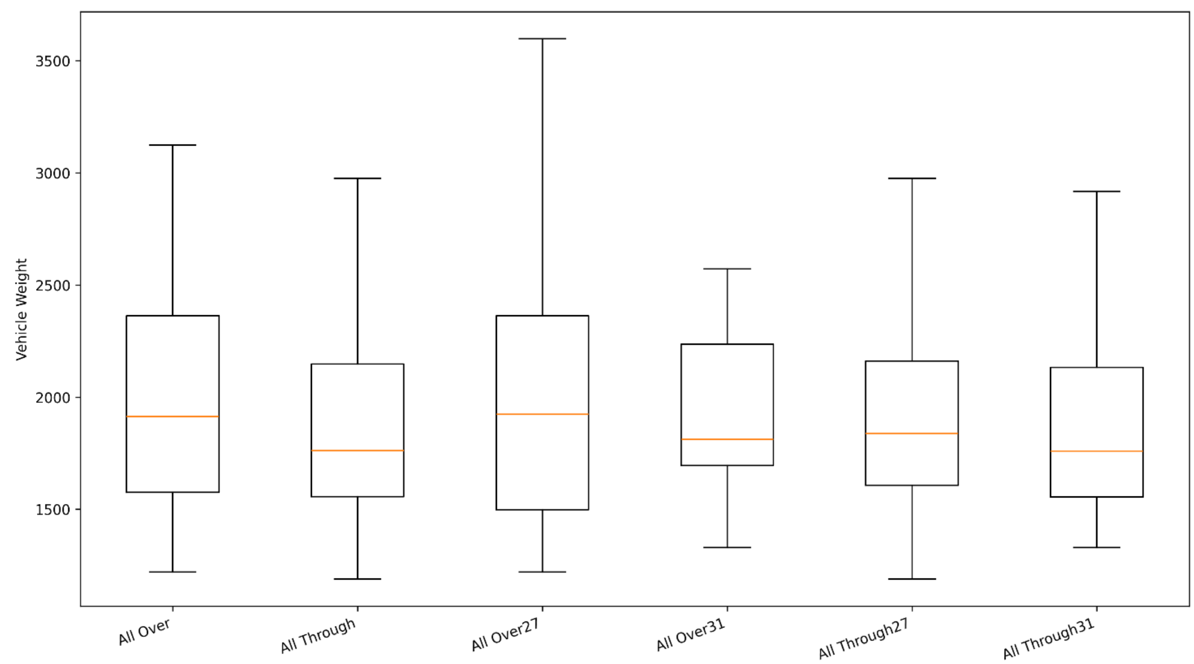

Figure 5-2: Vehicle weight

Figure 5-1 shows a clear difference between failure modes, with Over failures generally exhibiting higher center of gravity heights than Through failures. Across the studied groups, the median center of gravity height for the Over failures was visually greater than that of the Through failures, as the interquartile range was shifted upward relative to the Through group. The Over failures median values ranged from approximately 26 in. to 27.5 in., with Through failures had median values near 25 inches. The central tendencies and spread of the Over failure group were consistently positioned at higher center of gravity heights, indicating vehicles involved in Over failures typically are taller than those involved in Through failures. From the box plot, median center of gravity heights ranged approximately from 24 in. to 27.5 in., with observed values ranging from 18 in. to 35 in.

Figure 5-2 showed a considerably greater overlap among failure groups than observed with center of gravity height. All Over crashes displayed somewhat higher median weight than the total Through group, however the interquartile ranges overlapped and were not sharply separated. Median vehicle weight ranged from approximately 1,800 lb. to 2000 lb., with observed weights ranging from about 1,200 lb. to 3,700 lb. This suggests that vehicle weight did not distinguish between Over and Through failures as clearly as with center of gravity height.

5.2 Normality Test

Normality was evaluated before selecting the statistical tests used in the analysis. Because several planned analyses involved continuous variables, it was necessary to determine whether parametric methods that assume normality were appropriate or whether nonparametric alternatives were more suitable.

The research question that led this section is as follows: Are vehicle center of gravity height and vehicle weight normally distributed within the failure mode and guardrail height subgroups used in the analysis?

The Shapiro-Wilk procedure is a standard statistical test that evaluates whether a sample is consistent with a normally distributed population. It was selected for this section as normality would need to be assessed separately for vehicle center of gravity height and weight across failure mode and guardrail height standard. The test was applied to six subgroups:

1. All Over failures across all guardrail heights
2. All Through failures across all guardrail heights
3. Over failures at 27¾-inch
4. Over failures at 31-inch
5. Through failures at 27¾-inch
6. Through failures at 31-inch

The Shapiro-Wilk test statistic is given by:

$$W = \left(\left(\sum a_i x_i\right)^2\right) / \left(\sum (x_i - \bar{x})^2\right)$$

Where

x_i denotes the ordered sample values,

$\bar{x}$ represents the sampled mean, and

a_i are constants derived from expected normal order (Shapiro & Wilk, 1965)

Table 5-2 summarizes the test, sample size, and p-values for center of gravity height and weight across the six subgroups. Most subgroup-variable combinations showed statistically significant departures from normality.

Table 5-2: Shapiro-Wilk normality test results

Failure subgroup	**Variable**	**n**	**Shapiro-Wilk W**	**p-value**	**Normal at α = 0.05?**
All Over failures	Center of Gravity height	216	0.457	< 0.001	No
All Over failures	Vehicle weight	101	0.938	< 0.001	No
All Through failures	Center of Gravity height	216	0.788	< 0.001	No
All Through failures	Vehicle weight	149	0.228	< 0.001	No
Over failures, 27¾-inch	Center of Gravity height	86	0.639	< 0.001	No
Over failures, 27¾-inch	Vehicle weight	41	0.919	0.006	No
Over failures, 31-inch	Center of Gravity height	21	0.908	0.051	Yes
Over failures, 31-inch	Vehicle weight	7	0.887	0.258	Yes
Through failures, 27¾-inch	Center of Gravity height	73	0.772	< 0.001	No
Through failures, 27¾-inch	Vehicle weight	55	0.926	0.002	No
Through failures, 31-inch	Center of Gravity height	29	0.914	0.022	No
Through failures, 31-inch	Vehicle weight	22	0.905	0.037	No

The Shapiro-Wilk test results indicate that vehicle center of gravity height and vehicle weight were generally not normally distributed across the failure subgroups evaluated.

For nearly all subgroup-variable combinations, the null hypothesis of normality was rejected at $\alpha = 0.05$. The only exceptions were the Over failures, 31-inch subgroup, for which center of gravity height ($W = 0.908$, $p = 0.051$) and vehicle weight ($W = 0.887$, $p = 0.258$) did not show statistically significant departures from normality. However, these subgroups had relatively small sample sizes, particularly for vehicle weight ($n = 7$), which limits the power of the Shapiro-Wilk test to detect non-normality.

Overall, these results support treating vehicle center of gravity height and vehicle weight as generally non-normal variables in this study. Accordingly, comparisons involving these variables should rely on statistical methods that do not assume normality, such as the Mann-Whitney U test.

6 Evaluation of Data and Findings

This chapter uses the confirmed failure records assembled for this study to describe the vehicle and guardrail characteristics associated with these events and to provide context for evaluating the current 27¾-inch and 31-inch height standards. Using the finalized set of mapped and confirmed failures, vehicle make/model/year information was paired with available NHTSA sources to characterize center of gravity height and weight, and failures were linked where possible to FDOT eMaintenance end treatment records to identify the applicable height standard. The chapter summarizes how confirmed failures are distributed across 27¾-inch and 31-inch installations and how vehicle center of gravity and weight vary between Over and Through outcomes. Together, these results provide a data driven baseline for assessing whether failure patterns appear consistent with current height standards and for guiding the statistical analyses presented in the following sections.

The statistical evaluation of the collected data is organized around four primary research questions. Together these questions will support the overall goal of the study: to evaluate whether failure behavior differs between guardrail height standards and to determine if vehicle characteristics help explain differences between Over and Through failures. Each question addresses a component of the overall objective, with unique statistical analysis for each component of data studied.

Each subsection in this chapter follows the same format addressing a specific research question. The subsection begins by stating the research question, why it is being asked, and how it relates to the overall goal of this study. The statistical test used is then identified and explained. The subsection then concludes with results and interpretation of findings. This section is formatted this way to provide a clear link between each question's objective, the statistic reasoning, and conclusion.

6.1 Inventory-Proportional Distribution of Confirmed Failures by Guardrail Height

The research question that led this section is as follows: Are confirmed guardrail failures distributed across 27¾-inch and 31-inch installations in proportion to the statewide inventory of those guardrail heights?

This section examines confirmed guardrail face failures at each guardrail height standard and compares those counts to the statewide inventory distribution of guardrail heights. The FDOT End Treatment database indicates that 27¾-inch guardrails make up approximately 77 percent of the statewide inventory, while 31-inch systems make up approximately 23 percent. This analysis evaluates whether confirmed failures are represented at each height in proportion to their prevalence in the field, or whether failures at one height standard are overrepresented or underrepresented relative to statewide inventory expectations.

6.1.1 Statistical Test

The test selected for this question was a chi-square goodness of fit test. This test compares the observed confirmed failures by guardrail height against the expected counts derived from the statewide inventory proportions. This test was run with the goal of determining whether confirmed counts differ from expected counts under a hypothesized distribution.

Expected counts E_i were compared to observed confirmed failures using the total number of confirmed failures where the height is known n and statewide inventory p_i (Diez et. Al., 2019).

$$E_i = np_i$$

$$\chi^2 = \sum \left(\frac{(O_i - E_i)^2}{E_i} \right)$$

Null hypothesis: Confirmed failures are distributed across 27¾-inch and 31-inch installation heights proportional to statewide inventory.

Alternate hypothesis: Confirmed failures are not distributed across 27¾-inch and 31-inch installation heights proportional to statewide inventory.

6.1.2 Results and Interpretation

Table 6-1 displays the expected counts based on statewide inventory data and the known failures identified in this study. The chi-square goodness of fit test resulted in $\chi^2(1)$ =0.108, $p = $ 0.742.

Table 6-1: Observed and expected confirmed failures by guardrail height

Guardrail Height	Expected Failures	Known Failures
27¾-inch	161	159
31-inch	48	50

The observed distribution of confirmed failures (159 at 27¾ inches; 50 at 31 inches) was consistent with the distribution expected from statewide inventory proportions (161 and 48, respectively). The chi-square goodness-of-fit test was not statistically significant, $\chi^2(1) = 0.108$, $p = 0.742$, indicating no evidence that confirmed failures were overrepresented or underrepresented at either guardrail height. Because the observed counts were nearly identical to the expected counts, the analysis provides no evidence of a meaningful difference in confirmed failure frequency by guardrail height. In other words, confirmed failures occurred at rates consistent with the statewide distribution of 27¾-inch and 31-inch installations.

6.2 Vehicle Characteristics and Failure Mode

This section evaluates whether vehicle characteristics differ systematically by failure mode. Two research questions led this section: Is vehicle center of gravity height higher in crashes resulting in Over failures than in crashes resulting in Through failures? Does vehicle weight differ between crashes resulting in Over failures and crashes resulting in Through failures?

6.2.1 Statistical Test

The Shapiro-Wilk test indicated that vehicle center of gravity height and vehicle weight were generally not normally distributed within the Over and Through failure groups. Therefore, the Mann-Whitney U test was selected because it is a rank-based, two-sample test appropriate for comparing independent groups when the normality assumption is not met. For center of gravity height, a one-sided test was used because Over failures were expected to involve vehicles with higher centers of gravity. For vehicle weight, a two-sided test was used because no directional relationship between vehicle weight and failure mode was assumed.

For center of gravity, the hypothesis is as follows. $CG_{Over}$and $CG_{Through}$ denote the center of gravity height distributions for Over and Through failure crashes, respectively.

- H_0: $CG_{Over} \leq CG_{Through}$
- H_A: $CG_{Over} > CG_{Through}$

For vehicle weight the hypothesis is as follows. $W_{Over}$and $W_{Through}$ denote the weight distributions for Over and Through failure crashes, respectively.

- H_0: $W_{Over} = W_{Through}$
- H_A: $W_{Over} \neq W_{Through}$

The test was calculated as:

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1$$

Where,

$R_1$is the sum of ranks for group 1 and

$n_1$is the sample size of group 1 and

n_2 is the sample size of group 2 (Mann & Whitney, 1947).

6.2.2 Results and Interpretation

Table 6-2 presents the Mann–Whitney U test results for vehicle center-of-gravity (CG) height and vehicle weight. For each variable, the table reports the sample size, median, and interquartile range (IQR) for each failure mode, along with the Mann-Whitney U statistic, p value, and rank biserial correlation effect size.

Table 6-2: Mann-Whitney U test results

Outcome	n (Over)	Median (Over)	IQR (Over)	n (Through)	Median (Through)	IQR (Through)	Mann–Whitney U	p-value	Rank-biserial R
CG height	107	27.38	4.74	102	25.01	5.78	6867.5	0.0006	0.258
Vehicle weight	48	1862.5	859.75	77	1813.0	590.7	1987.5	0.4803	0.075

Vehicle center of gravity was significantly higher in Over failures than in Through failures. The median center of gravity height was 27.38 inches for Over failures (IQR = 4.74; n = 107) and 25.01 inches for Through failures (IQR = 5.78; n = 102). The Mann-Whitney U test showed a statistically significant difference in the hypothesized direction, with Over failure vehicles having a higher center of gravity than Through failure vehicles in approximately 63 percent of randomly paired comparisons.

For vehicle weight, the median weight was 1862.50 (IQR = 859.75) for Over failures (n = 48, weight available) and 1813.00 (IQR = 590.70) for Through failures (n=77, weight available). The results were consistent with a small, not statistically significant, tendency toward higher weights in Over failures.

This analysis provides evidence that center of gravity height differs by failure mode, with Over failures being associated with higher center of gravity heights than Through failures. This finding is consistent with the hypothesis that vehicles with higher center of gravity heights may be more susceptible to override when interacting with a guardrail face.

Vehicle weight, however, did not differ significantly between Over and Through failures. The lack of significant weight difference suggests that vehicle weight alone may not be a primary factor in Over or Through failure modes based on the sampled data. This interpretation should be considered in the context of limited data on vehicle weight within the data.

Both comparisons of vehicle center of gravity height and weight were conditioned on crashes that resulted in confirmed failures which guardrail height standard was known.

6.3 31-inch Standard Normalized to Inventory

This section focuses specifically on Over failures and evaluates whether 31-inch guardrail installations experience this failure mode less often than would be expected based on their prevalence in the statewide inventory. Unlike the previous analysis, which examined confirmed failures overall, this analysis isolates Over failures to determine whether they are underrepresented at 31-inch installations relative to 27¾-inch installations after accounting for the relative number of each installation height in the field. The research question guiding this section is: Assuming guardrail strike exposure is proportional to statewide end-treatment prevalence, are Over failures underrepresented at 31-inch installations relative to 27¾-inch installations, suggesting that 31-inch installations may be better positioned to reduce Over failures?

6.3.1 Statistical Test

Two tests were selected for this section, the chi-square goodness of fit test and a one-sided exact binomial test. The chi-square goodness of fit test was used to compare Over failures against the counts expected under the statewide inventory.

Letting $p_{31,0} = 0.2297$ represent the statewide 31-inch proportion and $p_{31,Over}$ be the proportion of Over failures that occur at 31-inch installations, the hypothesis is as follows:

- Null hypothesis (H_0): $p_{31,Over} = p_{31,0}$
- Alternative hypothesis (H_A): $p_{31,Over} < p_{31,0}$

Expected counts were computed as:

$$E_h = p_h \times n_{Over}$$

Where,

E_h is the expected number of Over failures in height category h,

p_h is the statewide inventory proportion for height category h, and

n_{Over} is the total number of observed Over failures.

The chi-square test statistic was computed as (Magnello, 2005):

$$\chi^2 = \Sigma((O_h - E_h)^2 / E_h)$$

Where,

O_h is the observed count and

$E_h$is the expected count.

The one-sided exact binomial test was chosen as a confirmatory test for the directional claim $p_{(31,Over)} < p_{31,0}$. This is an appropriate secondary test as the two-category outcome can be represented as the number of Over failures occurring at 31-inches out of n_{Over} trials with null probability $p_{31,0}$.

The exact binomial test statistics were computed as:

$$P(x; p, n) = \binom{n}{x} (p)^x (1 - p)^{(n-z)}$$

6.3.2 Results and Interpretation

A total of 107 Over failures with known guardrail height were observed with 86 at 27¾-inch installations and 21 at 31-inch installations. The observed proportion of Over failures occurring at 31-inch installations was 21 of 107 = 0.1963, or 19.6 percent.

Under the inventory-based exposure model, 82.43 Over failures would be expected at 27¾-inch installations and 24.57 Over failures would be expected at 31-inch installations. The observed count at 31-inch installations was 21, representing 19.6 percent of Over failures, compared with the expected inventory-based share of 22.97 percent. Table 6-3 displays these observed and expected values.

Table 6-3: Observed and expected Over failures by guardrail height

Guardrail height	Observed failures (n)	Observed share	Expected failures (n)	Expected share
27¾-inch	86	80.4%	82.43	77.03%
31-inch	21	19.6%	24.57	22.97%
Total	107	100%	107.00	100%

Table 6-4 summarizes inventory-proportionality results for confirmed Over and Through failures with known guardrail height. The “All” row combines the Over and Through records shown in Table 5-1. Observed 31-inch failure counts and percentages are compared with the expected values based on the statewide end-treatment inventory distribution, where 31-inch installations represent 22.97 percent of the inventory. The table also reports the observed-minus-expected difference at 31 inches and the corresponding goodness-of-fit test results for each failure set.

Table 6-4: Inventory proportionality results for failures by guardrail height

Failure Mode	n	Observed 31″ (n, %)	Expected 31″ (n, %)	Δ share at 31″ (pp)	O/E ratio at 31″	$\chi^2(1)$	p (χ^2 GOF)	p (binomial, one-sided)
All	209	50 (23.9%)	48.01 (23.0%)	+0.95	1.042	0.108	0.742	—
Over	107	21 (19.6%)	24.57 (23.0%)	−3.34	0.854	0.675	0.411	0.243
Through	102	29 (28.4%)	23.43 (23.0%)	+5.46	1.238	1.719	0.190	—

Note: pp = percentage points; O/E = observed-to-expected; GOF = goodness-of-fit.

The chi-square goodness-of-fit test compared the observed distribution of Over failures by guardrail height to the distribution expected under the statewide inventory-based exposure model. Although the observed number of Over failures at 31-inch installations was lower than expected, with 21 observed compared to 24.57 expected, this difference was not statistically significant, $\chi^2(1) = 0.675$, $p = 0.411$. Similarly, 86 Over failures were observed at 27¾-inch installations compared with 82.43 expected. These results indicate that the observed distribution of Over failures does not differ significantly from the distribution expected based on statewide end-treatment prevalence. Therefore, while the observed 31-inch share of Over failures was directionally lower than expected, the chi-square test does not provide sufficient evidence to conclude that Over failures are underrepresented at 31-inch installations relative to 27¾-inch installations under the inventory-proportional exposure assumption.

Under the exact binomial test, the expected probability of an Over failure occurring at a 31-inch installation is $p0 = 0.2297$, which corresponds to an expected 24.57 of 107 Over failures at 31 inches. The observed count was 21 of 107, or 19.6 percent, which is 3.34 percentage points below the expected 31-inch share of 22.97 percent and corresponds to an observed-to-expected ratio of 0.854. However, the one-sided exact binomial p value, $p = 0.243$, indicates that an outcome this low is plausible under the null hypothesis. Therefore, the apparent reduction is not statistically distinguishable from sampling variability. Taken together with the chi-square goodness-of-fit result in Table 6-4, the binomial findings support the same conclusion: while the point estimate trends toward fewer Over failures at 31 inches, the evidence is insufficient to claim a statistically significant reduction relative to statewide prevalence.

The data suggest a possible directional reduction in Over failures at 31-inch installations, but the difference was not statistically significant. Therefore, this result should be interpreted as an inventory-adjusted screening finding rather than conclusive evidence of a performance advantage. Within the available sample of confirmed Over failures with known guardrail height, the 31-inch installation height showed fewer Over failures than expected based on statewide inventory proportions, but the observed difference was small enough that it could plausibly reflect sampling variability.

6.4 Transition Region for Failure Mode and Center of Gravity

This section focuses on determining whether increasing center of gravity height is associated with a shift in failure mode, and whether the data supports the existence of a transition region where Over failures become more likely than through failures. The question that guided this section is: Within confirmed guardrail failures, is there a center of gravity height “threshold region” where the probability that a failure is an Over failure (vs a Through failure) increases?

6.4.1 Statistical Test

Logistic regression was selected as the outcome is binary (Over vs. Through) and the goal is to see how the chance of an Over failure changes as a continuous variable increase (like center of gravity height or weight). This is specified as (Hosmer et al., 2013):

$$log\left(\frac{p}{1-p}\right) = \beta_o + B_1(CG)$$

For the primary logistic model:

Null hypothesis (H_0):

$$\beta_1 = 0$$

Center of gravity height is not associated with the odds of an Over failure relative to a Through failure.

Alternative hypothesis (H_A):

$$\beta_1 > 0$$

Higher center of gravity height is associated with greater odds of an Over failure relative to a Through failure.

For the secondary threshold assessment:

Null hypothesis (H_0):

The relationship between center of gravity height and failure mode is adequately described by a linear logistic model.

Alternative hypothesis (H_A):

The relationship is nonlinear, suggesting a sharper threshold like transition.

6.4.2 Results and Interpretation

The binary logistic regression indicated that center of gravity height was a statistically significant positive predictor of Over failure status. The estimated coefficient for center of gravity height and standard error (SE) was:

$$\beta_1 = 0.0766$$

$$SE = 0.025$$

$$z = 3.043$$

$$p = 0.002$$

This corresponds to an odds ratio of 1.080 per unit increase in center of gravity height, with a 95 percent confidence interval of 1.028 to 1.134. Each 1-inch increase in center of gravity height was associated with an estimated 8.0 percent increase in the odds of an Over failure relative to a Through failure.

Using the fitted model, the estimated point at which the predicted probability of an Over failure reached 0.50 occurred at approximately:

$$CG_{0.50} = -\frac{\beta_0}{\beta_1} = 25.6$$

This value represents the approximate crossover region where Over and Through failures were equally likely according to the fitted model.

Predicted probabilities from the model showed a gradual shift in failure mode as center of gravity increased:

- CG = 24: predicted P(Over) ≈ 0.47
- CG = 25: predicted P(Over) ≈ 0.49
- CG = 26: predicted P(Over) ≈ 0.51
- CG = 28: predicted P(Over) ≈ 0.55
- CG = 30: predicted P(Over) ≈ 0.58

The secondary nonlinear assessment did not provide evidence of a sharp breakpoint. The nonlinear term was not statistically significant, and the comparison between the quadratic and linear models did not support a sharp breakpoint. The likelihood-ratio (LR) comparison between the quadratic and linear models was also nonsignificant:

$$LR\chi^2 = 1.116$$

$$p = 0.291$$

These findings indicate that higher center of gravity height is associated with a greater likelihood that a confirmed guardrail failure will occur as an Over failure rather than a Through failure. However, the data does not support the existence of a discrete or abrupt center of gravity cutoff above which Over failures suddenly become dominant. Instead, the results support the presence of a transition region, centered near CG ≈ 25.6, across which the probability of Over failure gradually increases.

Figure 6-1 shows the modeled relationship between center of gravity height and the predicted probability of an Over failure.

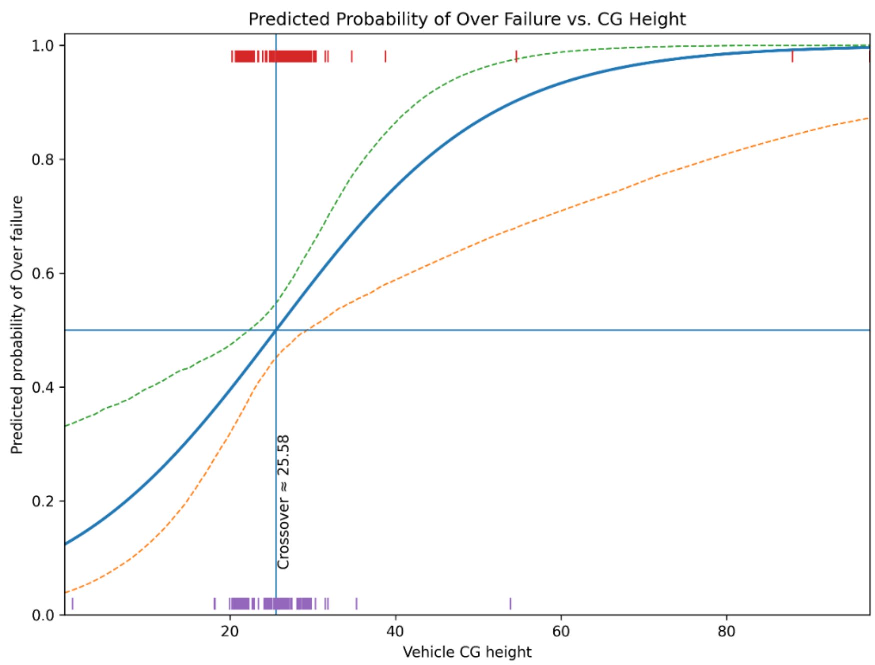

Figure 6-1: Predicted probability of Over failure by vehicle center of gravity height

6.5 Summary of Guardrail Height, Vehicle Characteristic, and Failure Mode Findings

This chapter evaluated confirmed guardrail face failures in Florida to examine whether guardrail height standard and vehicle characteristics help explain failure mode in breach crashes. Confirmed failures were classified as either Over or Through, vehicle center of gravity height and weight were compiled from available vehicle records, and guardrail height standard was assigned where possible using mapped crash locations and FDOT end-treatment inventory data. Taken together, the results show that vehicle center of gravity height is more clearly associated with failure mode than guardrail height alone, while also suggesting that the 31-inch standard performs at least comparably to, and directionally better than, the older 27¾-inch standard for reducing Over failures.

At the system level, confirmed failures with known guardrail height were distributed across the 27¾-inch and 31-inch standards in proportions that closely matched the statewide inventory. This indicates that neither height standard was overrepresented in the confirmed failure dataset overall. In other words, the available data do not support the conclusion that the 31-inch standard is experiencing a disproportionate share of failures relative to its prevalence in the field. This is an important finding, because it suggests that the transition to the 31-inch MGS has not introduced evidence of worse overall breach performance when viewed against statewide exposure.

When failure mode was examined descriptively, the 27¾-inch installations showed a larger share of Over failures, whereas the 31-inch installations showed a larger share of Through failures. Although these differences were not statistically significant after accounting for statewide inventory proportions, the direction of the pattern is still meaningful. Specifically, the 31-inch installations had a lower observed share of Over failures than expected under the exposure model, while the 27¾-inch installations had a correspondingly greater share. This pattern does not prove superiority of the 31-inch standard in a strict statistical sense within the available sample, but it is consistent with the engineering purpose of the higher rail height: to better engage and redirect taller vehicles and reduce override type outcomes.

The clearest statistical evidence in the study concerned vehicle center of gravity height. Vehicles involved in Over failures had significantly higher center of gravity heights than those involved in Through failures, and logistic regression showed that center of gravity height was a statistically significant positive predictor of Over failure status. The model indicates that as vehicle center of gravity increases, the likelihood that a confirmed breach occurs as an Over failure rather than a Through failure also increases. This result is both statistically significant and physically consistent with expected crash mechanics, since taller vehicles are more likely to interact with the guardrail in ways that promote override. By contrast, vehicle weight alone did not show a statistically significant difference between Over and Through failures in the available sample, suggesting that vehicle geometry may be more influential than mass alone in determining failure mode.

The estimated transition region near a center of gravity height of approximately 25.6 inches further supports this interpretation. Rather than identifying a sharp cutoff, the analysis suggests a gradual increase in Over failure likelihood as center of gravity increases. This is consistent with the idea that guardrail adequacy is not determined by one single vehicle threshold, but instead by a shifting interaction between guardrail height and increasingly tall vehicle profiles. As the fleet continues to evolve toward SUVs, pickups, and crossover vehicles with higher centers of gravity, the challenge to roadside barriers is likely to become more pronounced.

Overall, the findings support the conclusion that the 31-inch guardrail height standard remains an appropriate and defensible improvement over the older 27¾-inch standard, particularly with respect to the concern that taller modern vehicles may be more prone to override failures. The study does not provide statistically significant evidence that the 31-inch standard has eliminated Over failures or dramatically outperformed the 27¾-

inch standard in the confirmed crash data. However, it does show that the 31-inch standard is not underperforming, and the directional pattern of the data is consistent with improved protection against Over failures. At the same time, the analysis is clear that vehicle center of gravity is a key contributing factor in guardrail breach behavior, and that continued increases in vehicle height may challenge the adequacy of any fixed guardrail height standard over time.

The most defensible conclusion is that the 31-inch standard appears to be a meaningful step in the right direction and is better aligned with the modern vehicle fleet than the 27¾-inch standard. Continued monitoring of breach crash outcomes, vehicle fleet trends, and future assessment of whether additional design adaptations are warranted will remain important. The present results support both the continued use of the 31-inch standard and the need for ongoing reassessment of guardrail performance as vehicle characteristics continue to evolve.

7 AADT-Normalized Hot-Spot Analysis and Site Review

This chapter focuses on AADT-normalized hot-spot results. For this analysis, confirmed guardrail failure counts were assigned to roadway segments and normalized using AADT. This process helps account for differences in traffic exposure and allows the analysis to focus on locations where failures appear elevated relative to roadway usage.

The AADT-normalized hot-spot analysis was performed for confirmed guardrail failures and further separated by failure mode and guardrail height standard. The analysis distinguishes between Over and Through failures and evaluates patterns associated with both the 27¾-inch and 31-inch guardrail height standards where height information was available. This structure is intended to support the research objective of identifying locations where repeated failures may be associated with guardrail height, site-specific roadway conditions, traffic operations, impact conditions, or other contributing factors.

The purpose of this analysis is not to conclude that a hot-spot location is caused by guardrail height alone. Rather, the AADT-normalized hot-spot analysis is used as a proactive screening tool to identify locations or areas of concern where repeated guardrail failures may warrant additional review. At these locations, the report considers the number and type of failure events, the guardrail height standard, available vehicle characteristics, and the roadway context. The detailed site reviews are intended to identify locations where additional field review, engineering evaluation, or potential crash mitigation may be appropriate.

The remainder of this chapter is organized as follows. Section 7.1 describes the data and methodology used to develop the AADT-normalized hot-spot analysis, including the use of data assembled in prior project tasks, the incorporation of AADT data, and the classification of failures by mode and guardrail height standard. Section 7.2 presents the AADT-normalized hot-spot results for Over and Through failures, including separate analyses for 27¾-inch and 31-inch guardrail locations. Section 7.3 provides a detailed review of selected hot-spot locations identified from the normalized analysis. Section 7.4 summarizes the key findings, limitations, and recommended next steps for field inspection or further review.

7.1 Data and Methodology

This section summarizes the data sources and methodology used to conduct the AADT-normalized hot-spot analysis. The purpose of the methodology was to use the confirmed guardrail failure data developed in prior project tasks to identify locations or roadway segments where repeated failures may represent areas of concern. The analysis was not intended to replace a detailed engineering study at each location. Rather, it was designed as a screening process to identify locations where additional review, field inspection, or potential crash mitigation may be warranted.

7.1.1 Data Sources from Prior Project Tasks

The primary crash and guardrail failure dataset used in this task was developed through prior tasks of this research project. Earlier project tasks identified confirmed guardrail failure and breach crashes, reviewed crash reports, classified failure outcomes, and linked available guardrail height information to the crash locations. Those prior tasks also assembled relevant vehicle characteristics, including vehicle make, model, model year, estimated center of gravity height, and vehicle weight where available.

For Chapter 7, the prior project dataset was used as the foundation for the spatial analysis. Each confirmed failure record was represented as a point location based on the crash location information available from the police crash report and related project records. These mapped failure locations were then used to evaluate spatial patterns by failure mode and guardrail height standard.

The analysis focused on confirmed guardrail failure events classified as either Over failures or Through failures. Where guardrail height information was available, records were further classified by the applicable guardrail height standard: 27¾-inch or 31-inch. Records without confirmed guardrail height information were retained where appropriate for the broader failure-mode analysis but were not included in height-specific comparisons.

7.1.2 AADT Data and Spatial Join Process

AADT data were incorporated into the analysis to account for differences in roadway traffic exposure. Without an exposure adjustment, hot-spot maps can be dominated by major urban areas or high-volume corridors simply because more vehicles travel through those locations. For this reason, AADT was used to normalize the mapped guardrail failure data and provide a more meaningful screening measure of where failures were concentrated relative to roadway usage.

The AADT data consisted of roadway segment features with associated traffic volume attributes. These data were imported into ArcGIS Pro and used as the roadway exposure layer for the spatial analysis. Confirmed guardrail failure points were spatially joined to the nearest roadway segment so that each crash location could be associated with an AADT value. A second spatial processing step was then used to summarize the number of confirmed guardrail failures associated with each roadway segment.

This process produced a segment-level dataset containing two key values: the number of confirmed guardrail failure events associated with the segment and the AADT value assigned to that segment. These values were then used to calculate the normalized failure measure applied in the hot-spot mapping.

7.1.3 AADT-Normalized Hot-Spot Methodology

The AADT-normalized analysis was developed to identify roadway segments where confirmed guardrail failures appeared elevated relative to traffic exposure. The normalized value was calculated using the following general relationship:

$$AADT - Normalized\ Failure\ Value\ =\ Confirmed\ Failure\ Count\ /\ AADT$$

Where,

Confirmed Failure Count is the number of confirmed guardrail failure events associated with a roadway segment, and

AADT is the annual average daily traffic volume assigned to that roadway segment

The resulting value was used as a weighting factor in the hot-spot mapping. This approach shifts the analysis away from identifying only locations with the greatest number of crashes and toward identifying locations where the number of failures may be elevated relative to the amount of traffic using the roadway.

The normalized value should be interpreted as a screening measure, not as a definitive crash rate. AADT provides an estimate of daily traffic exposure, but the analysis does not account for all factors that may influence crash or failure risk, such as segment length, roadside exposure length, guardrail length, vehicle mix, speed, curvature, shoulder width, barrier offset, or detailed impact conditions. Therefore, the normalized hot-spot maps are best used to identify candidate locations for further review rather than to rank locations as having a statistically confirmed higher failure risk.

All mapping and spatial processing were conducted in ArcGIS Pro. The analysis used spatial join procedures, segment-level failure counts, AADT attributes, and weighted hot-spot mapping to identify areas where repeated guardrail failures may warrant additional evaluation.

7.1.4 Classification by Failure Mode and Guardrail Height Standard

The hot-spot analysis was performed separately by failure mode and guardrail height standard. This classification was necessary because Over and Through failures may reflect different crash dynamics and may be associated with different vehicle, roadway, or barrier conditions.

The following analysis categories were used:

- All Over failures

- Over failures at 27¾-inch guardrail locations
- Over failures at 31-inch guardrail locations
- All Through failures
- Through failures at 27¾-inch guardrail locations
- Through failures at 31-inch guardrail locations

The “all” categories include confirmed failures of the specified mode regardless of whether a guardrail height standard was available. The height-specific categories include only records where the guardrail height standard could be linked to the crash location. As a result, the height-specific maps represent the subset of confirmed failures with known guardrail height information and should not be interpreted as the full statewide population of guardrail impacts or failure events.

This structure allows the analysis to examine whether normalized hot-spot patterns differ between Over and Through failures and whether locations associated with the 27¾-inch and 31-inch standards show different spatial patterns. However, the analysis does not by itself establish that guardrail height caused the observed failures. The height-specific results are intended to support screening and site selection for further review.

7.1.5 Selection of Locations for Detailed Review

Locations selected for detailed review were identified based on the AADT-normalized hot-spot results and the presence of multiple confirmed guardrail failure events within close spatial proximity. The goal was to identify locations or corridors where repeated failures may indicate an area of concern and where additional engineering review could provide useful information for potential mitigation.

The selection process considered the following factors:

- Presence within or near an AADT-normalized hot-spot area
- Multiple confirmed guardrail failure events in close proximity
- Representation of different failure modes, including Over and Through failures
- Availability of guardrail height information where possible
- Availability of supporting crash, vehicle, mapping, or site imagery information
- Potential relevance to future field review or crash mitigation

The selected locations are not presented as the only possible locations of concern. Rather, they represent locations that emerged from the normalized screening process and had enough supporting information to allow for a more detailed review. The detailed site reviews presented in section 7.3 summarize the failure events, available vehicle characteristics, roadway context, and preliminary interpretation for each selected location.

7.1.6 Remote Site Review and Field Inspection Status

No field inspections were conducted as part of this research. The site reviews presented in this report were conducted using the AADT-normalized hot-spot results, mapped crash locations, project data, and available remote imagery. Where field review is recommended, it is presented as a follow-up action for future consideration.

7.1.7 Limitations of the Analysis

Several limitations should be considered when interpreting the AADT-normalized hot-spot results.

First, the analysis is limited to confirmed guardrail failure events included in the project dataset. It does not represent all guardrail impacts, all roadside crashes, or all locations where a vehicle contacted guardrail without a documented failure. As a result, the hot-spot maps should be interpreted as patterns within the confirmed failure dataset rather than as a complete statewide guardrail crash inventory.

Second, the accuracy of the spatial analysis depends on the quality of the crash location information available from police crash reports and related project records. Some crash locations may be approximate, particularly where reports describe locations using ramps, mileposts, landmarks, or general roadway references rather than precise coordinates.

Third, the AADT normalization accounts for traffic volume but does not account for all relevant exposure measures. A more detailed exposure model would ideally include guardrail length, roadside hazard exposure, segment length, vehicle mix, travel speed, lane configuration, shoulder width, barrier offset, curvature, and other roadway or operational characteristics. These factors were not consistently available for all locations in the project dataset.

Fourth, the height-specific analyses are limited to locations where guardrail height information could be linked to the crash location. Therefore, the 27¾-inch and 31-inch results may be influenced by the availability and completeness of guardrail inventory data. These results should be interpreted as patterns among records with known guardrail height, not as a complete comparison of all 27¾-inch and 31-inch guardrail installations statewide.

Finally, the hot-spot analysis is a screening tool. It can identify locations or areas of concern, but it cannot determine causation by itself. Additional field inspection, engineering evaluation, and review of site-specific conditions may be needed to determine whether repeated failures are related to guardrail condition, installation details, roadway geometry, traffic operations, driver behavior, impact conditions, or other contributing factors.

7.2 AADT-Normalized Hot-Spot Results

This section presents the results of the AADT-normalized hot-spot analysis for confirmed guardrail failure events. The analysis is presented by failure mode and guardrail height standard. Over failures and Through failures are evaluated separately because these outcomes may reflect different impact conditions, vehicle characteristics, and guardrail interaction mechanisms. Where guardrail height information was available, each failure mode was further separated into 27¾-inch and 31-inch guardrail height categories. This structure supports comparison of spatial patterns by both failure mode and guardrail height standard.

7.2.1 Overview of Normalized Hot-Spot Findings

The AADT-normalized hot-spot analysis identified several areas where confirmed guardrail failures were concentrated relative to traffic volume. In general, the normalized results shifted the focus away from broad urban crash concentrations and toward specific roadway segments, ramps, interchanges, and corridors where repeated failures may warrant further review.

The normalized maps also showed that Over and Through failures do not follow identical spatial patterns. Over failures tended to appear as more isolated or localized areas of concern, while Through failures were more often associated with roadway corridors or interchange areas. However, both failure types were observed across multiple parts of the state, and neither failure mode was confined to a single region or facility type.

7.2.2 AADT-Normalized Over Failure Hot-spots

Over failures occur when a vehicle overrides or passes over the guardrail system. These events are of particular interest because prior project findings identified vehicle center of gravity as an important factor associated with failure mode. The AADT-normalized Over failure maps were developed to identify locations where Over failures were concentrated relative to traffic exposure, both overall and within the known guardrail height subsets.

7.2.2.1 All Over Failures

Figure 7-1 presents the AADT-normalized hot-spot map for all confirmed Over failures. After normalization, the distribution of Over failure hot-spots becomes more focused and less dominated by major urban areas. This indicates that traffic volume alone explains some, but not all, of the spatial concentration observed in the failure dataset.

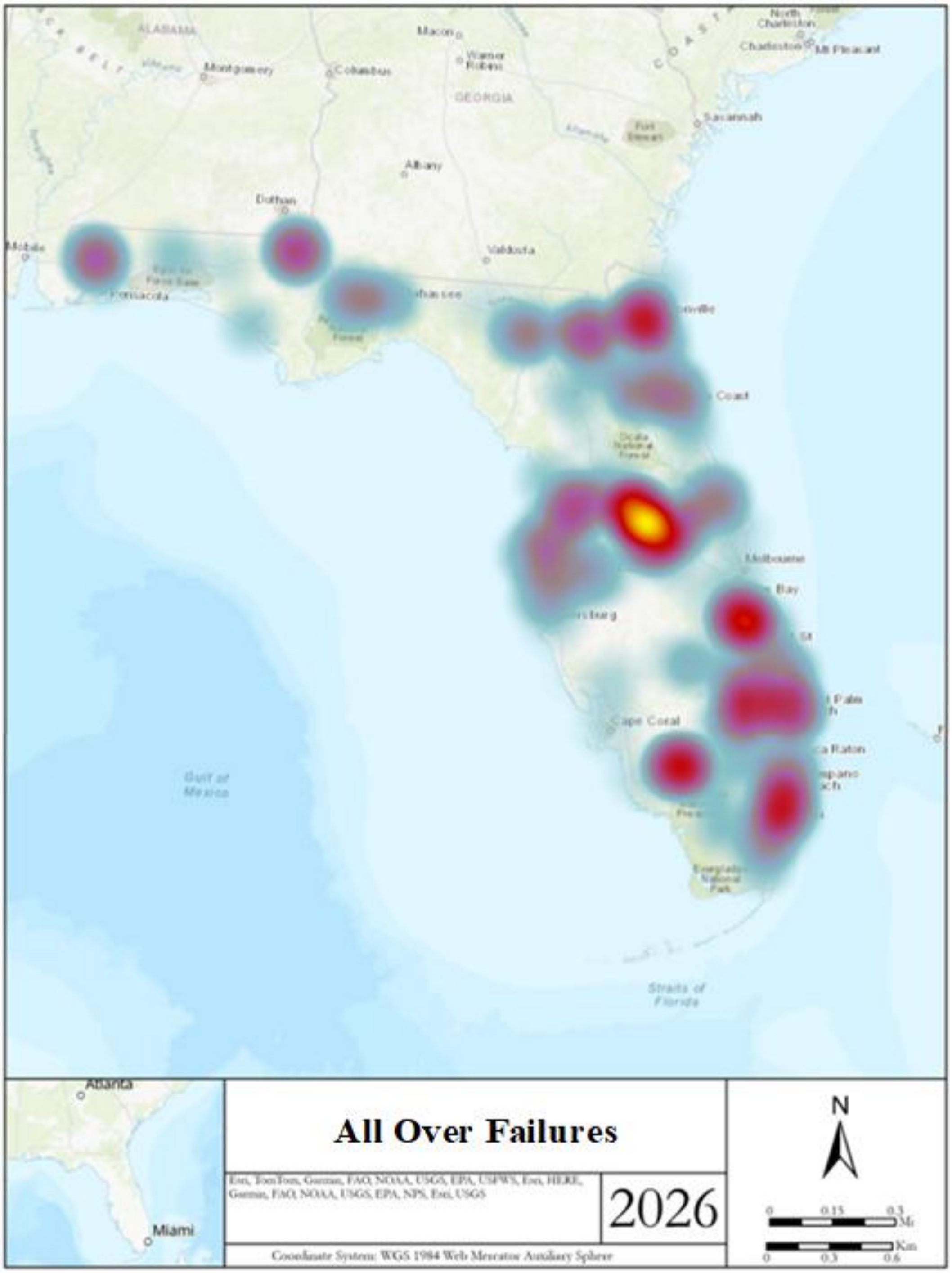

Figure 7-1: AADT-normalized all Over failures

7.2.2.2 Over Failures at 27¾-Inch Guardrail Locations

Figure 7-2 presents the AADT-normalized hot-spot map for Over failures at locations associated with the 27¾-inch guardrail height standard. The normalized results show more focused areas of concern than would be expected from a simple crash-density map. This suggests that some locations with repeated Over failures may not be explained solely by high traffic volume.

The 27¾-inch Over failure map is especially useful for identifying locations where the older guardrail height standard may warrant additional review. However, these results should not be interpreted as evidence that the 27¾-inch standard caused the failures at those locations. Instead, the map identifies locations where Over failures occurred in the known 27¾-inch subset and where further evaluation may help determine whether site-specific conditions, impact characteristics, or guardrail configuration contributed to the observed pattern.

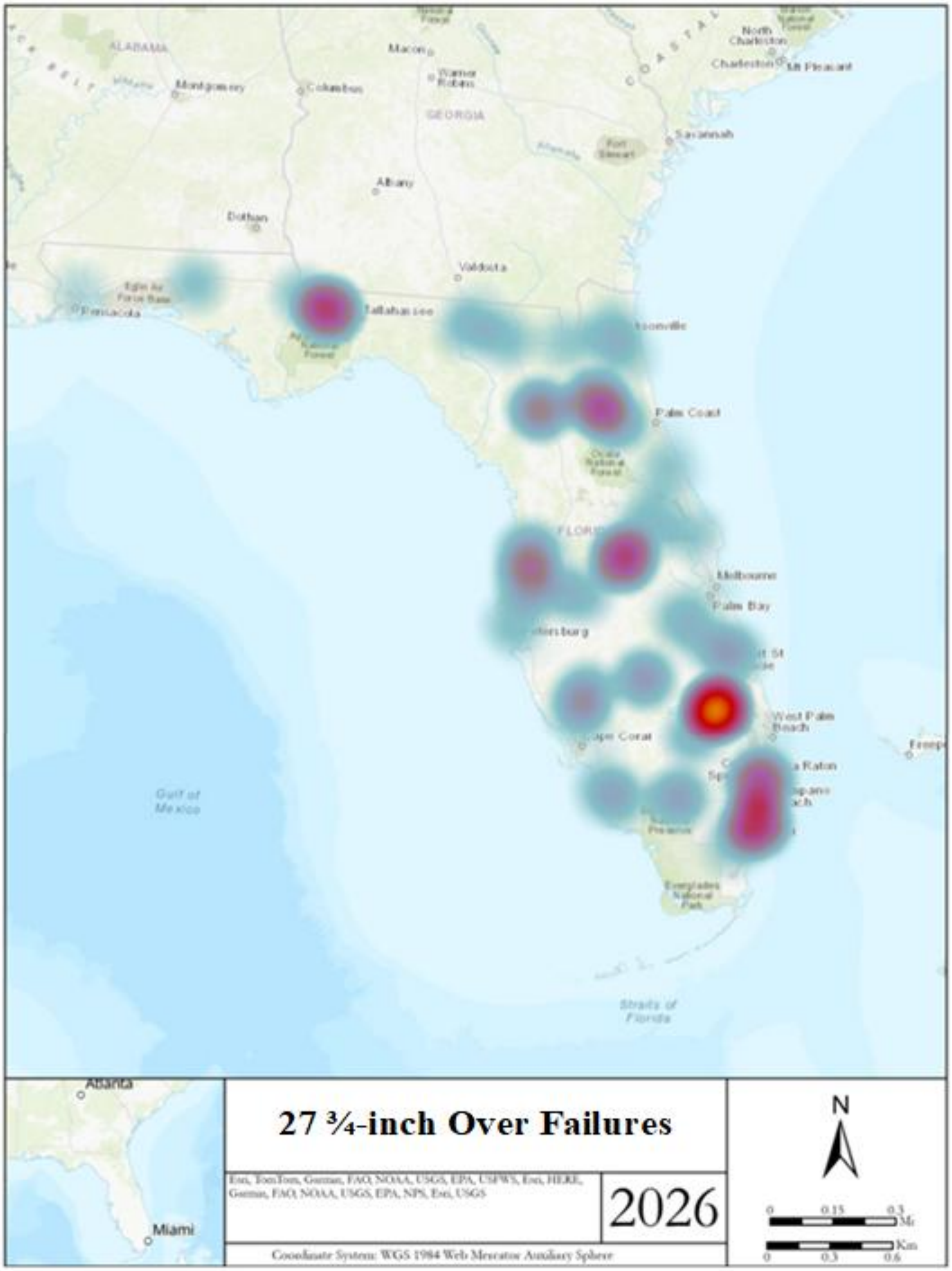

Figure 7-2: AADT-normalized Over failures at 27¾-inch guardrail locations

7.2.2.3 Over Failures at 31-Inch Guardrail Locations

Figure 7-3 presents the AADT-normalized hot-spot map for Over failures at locations associated with the 31-inch guardrail height standard. The smaller number of Over failures at 31-inch locations should be interpreted in the context of the statewide guardrail inventory. In the known end-treatment inventory used for this study, 31-inch installations represent approximately 23 percent of installations, compared with approximately 77 percent for 27¾-inch installations. Therefore, fewer Over failures would be expected at 31-inch locations even if failures were occurring in proportion to inventory exposure. The broader Task 4 analysis found that the observed share of Over failures at 31-inch locations was slightly lower than the inventory-proportional expectation, but that difference was not statistically significant. As a result, the reduced number of 31-inch Over failure locations should not be interpreted as conclusive evidence that the 31-inch standard reduces Over failures. Instead, the map is most useful for identifying specific 31-inch locations where repeated or exposure-normalized Over failures may warrant further review.

The presence of normalized Over failure hot-spots at 31-inch locations remains important. The 31-inch MGS was adopted to better accommodate changes in the vehicle fleet, but repeated Over failures at specific 31-inch locations may still indicate the need for closer review. These locations may involve high-center-of-gravity vehicles, high-speed impact conditions, roadway curvature, ramp geometry, roadside slope, barrier placement, or other site-specific factors that cannot be fully evaluated from the hot-spot map alone.

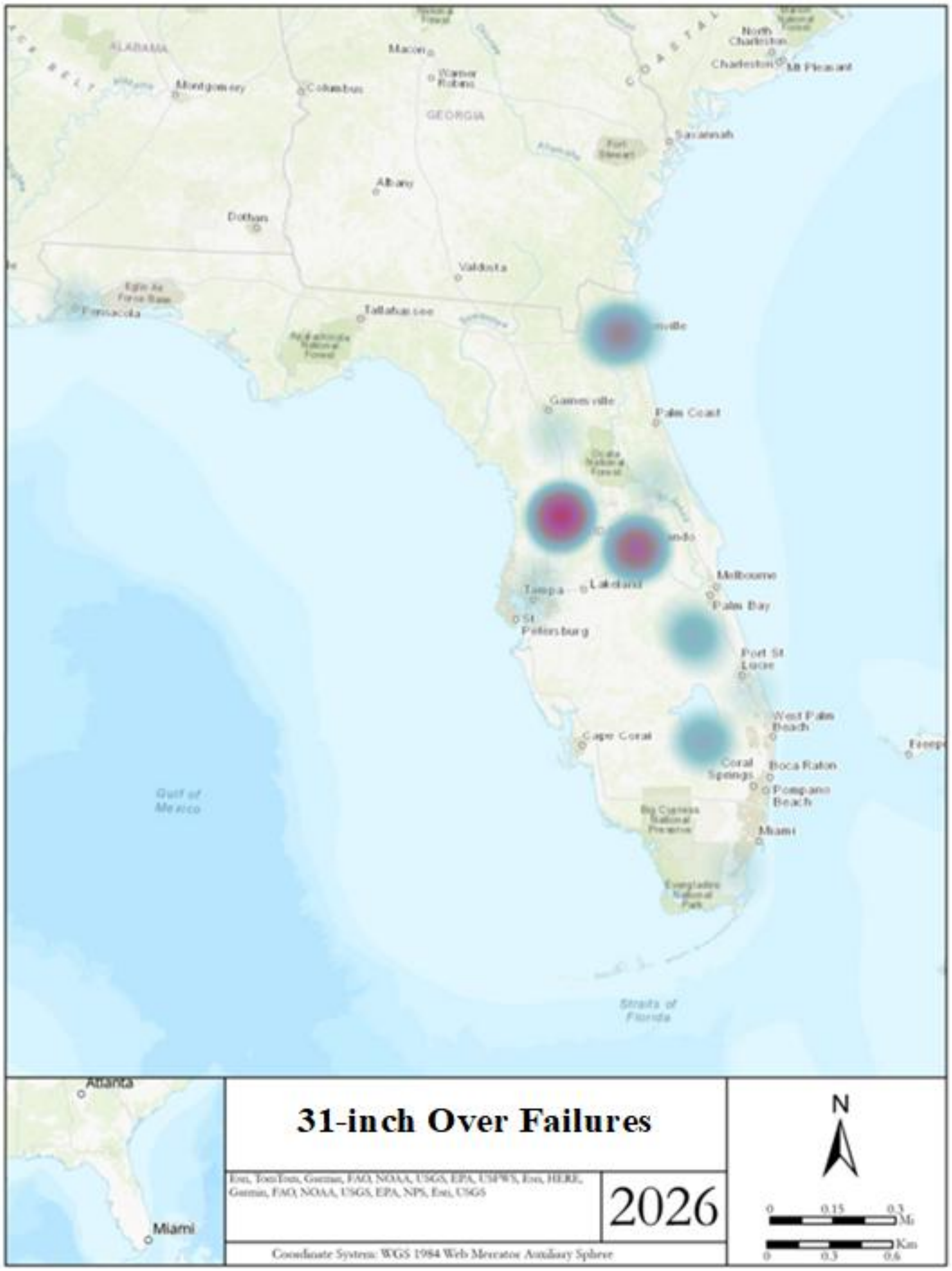

Figure 7-3: AADT-normalized Over failures at 31-inch guardrail locations

7.2.3 AADT-Normalized Through Failure Hot-spots

Through failures occur when a vehicle penetrates or passes through the guardrail system. These failures may be influenced by impact angle, vehicle mass, speed, guardrail condition, installation details, post performance, roadside grading, or other local factors. The AADT-normalized Through failure maps were developed to identify locations where Through failures were concentrated relative to traffic exposure.

7.2.3.1 All Through Failures

Figure 7-4 presents the AADT-normalized hot-spot map for all confirmed Through failures. The normalized results show that Through failures are often associated with specific roadway corridors or localized roadway segments rather than broad regional concentrations. This pattern suggests that Through failures may be influenced by site-specific or corridor-specific conditions in addition to traffic exposure.

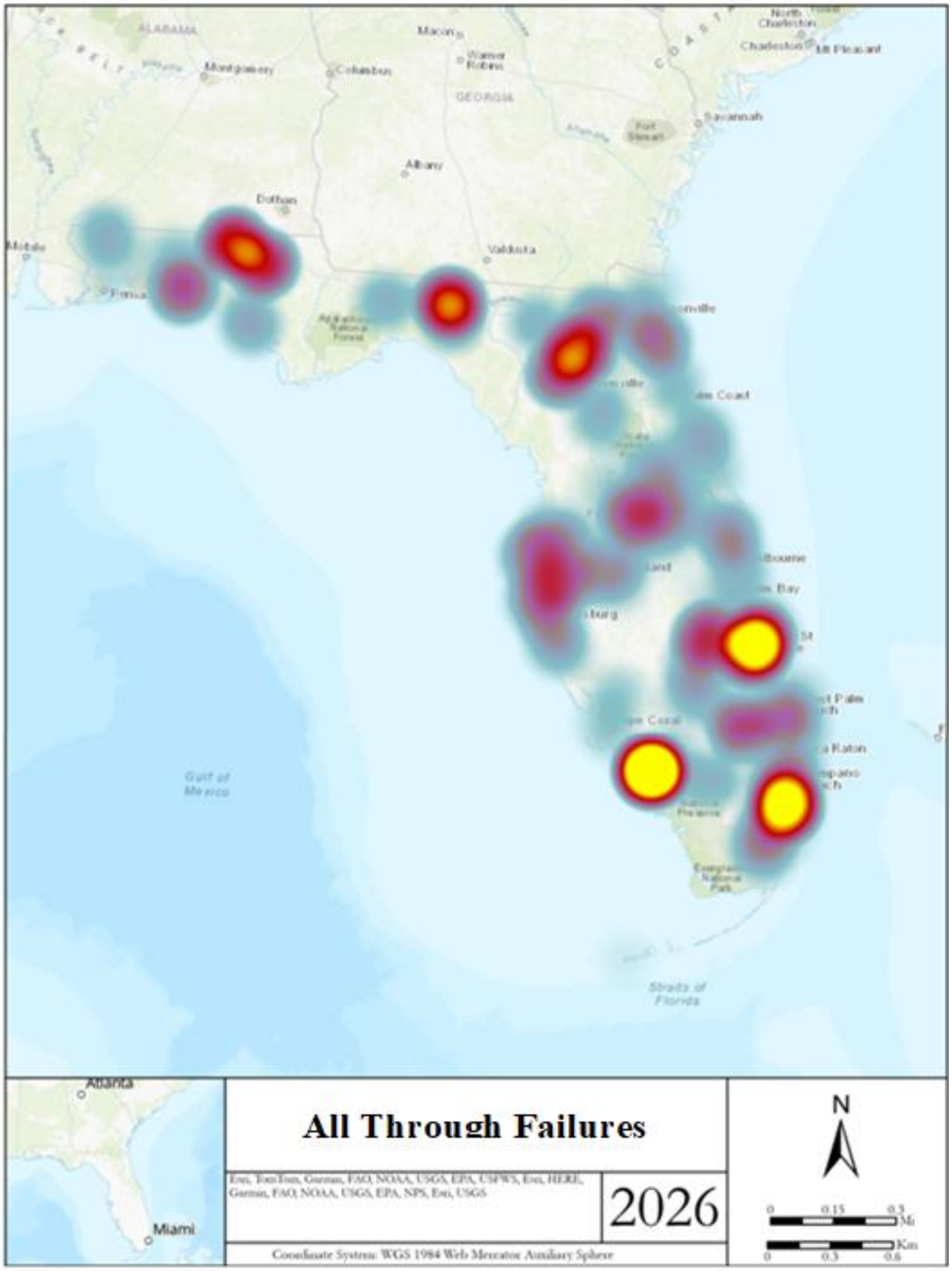

Figure 7-4: AADT-normalized all Through failures

7.2.3.2 Through Failures at 27¾-Inch Guardrail Locations

Figure 7-5 presents the AADT-normalized hot-spot map for Through failures at locations associated with the 27¾-inch guardrail height standard. The map identifies locations where Through failures occurred in the known 27¾-inch subset at levels elevated relative to traffic exposure.

Several of the normalized hot-spots in this category appear to follow roadway segments or corridors rather than isolated point locations. This may indicate that some Through failure patterns are associated with recurring roadway or roadside conditions, such as alignment, speed environment, traffic operations, or guardrail placement. However, the map alone cannot determine whether guardrail height, installation condition, or other site-specific factors contributed to the failures.

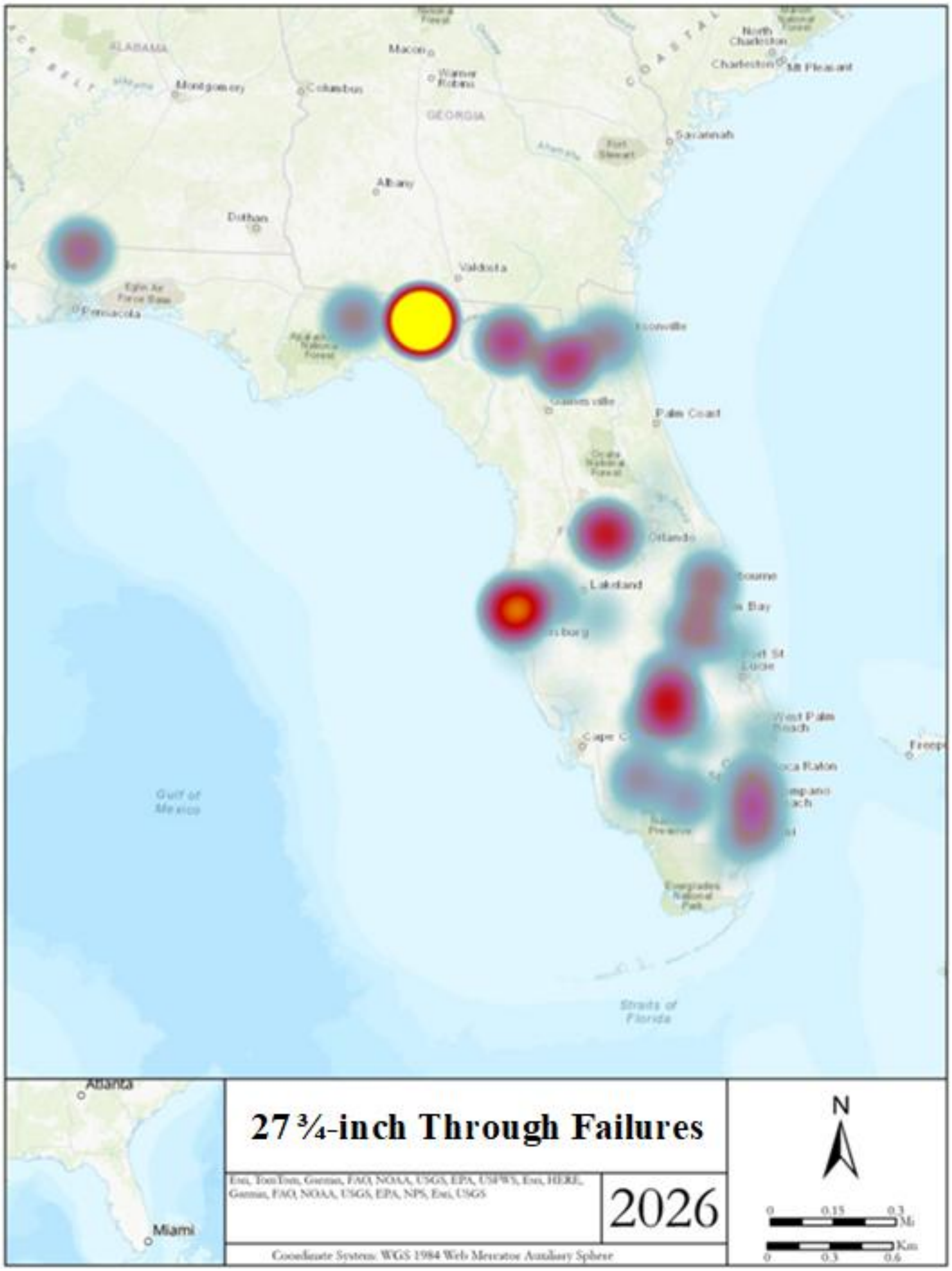

Figure 7-5: AADT-normalized Through failures at 27¾-inch guardrail locations

7.2.3.3 Through Failures at 31-Inch Guardrail Locations

Figure 7-6 presents the AADT-normalized hot-spot map for Through failures at locations associated with the 31-inch guardrail height standard. Consistent with the inventory context discussed above, the smaller number of 31-inch hot-spots should be interpreted cautiously because 31-inch installations represent a smaller share of the known guardrail inventory. Therefore, fewer 31-inch failure locations are expected even before considering potential differences in performance.

The remaining Through-failure hot-spots at 31-inch locations are still important for screening purposes. These locations may identify areas where additional review is warranted to better understand whether repeated failures are associated with impact conditions, roadway geometry, installation characteristics, barrier condition, or other site-specific factors. As with the other height-specific maps, the results should be interpreted as a tool for identifying locations or areas of concern, not as a definitive measure of comparative guardrail performance.

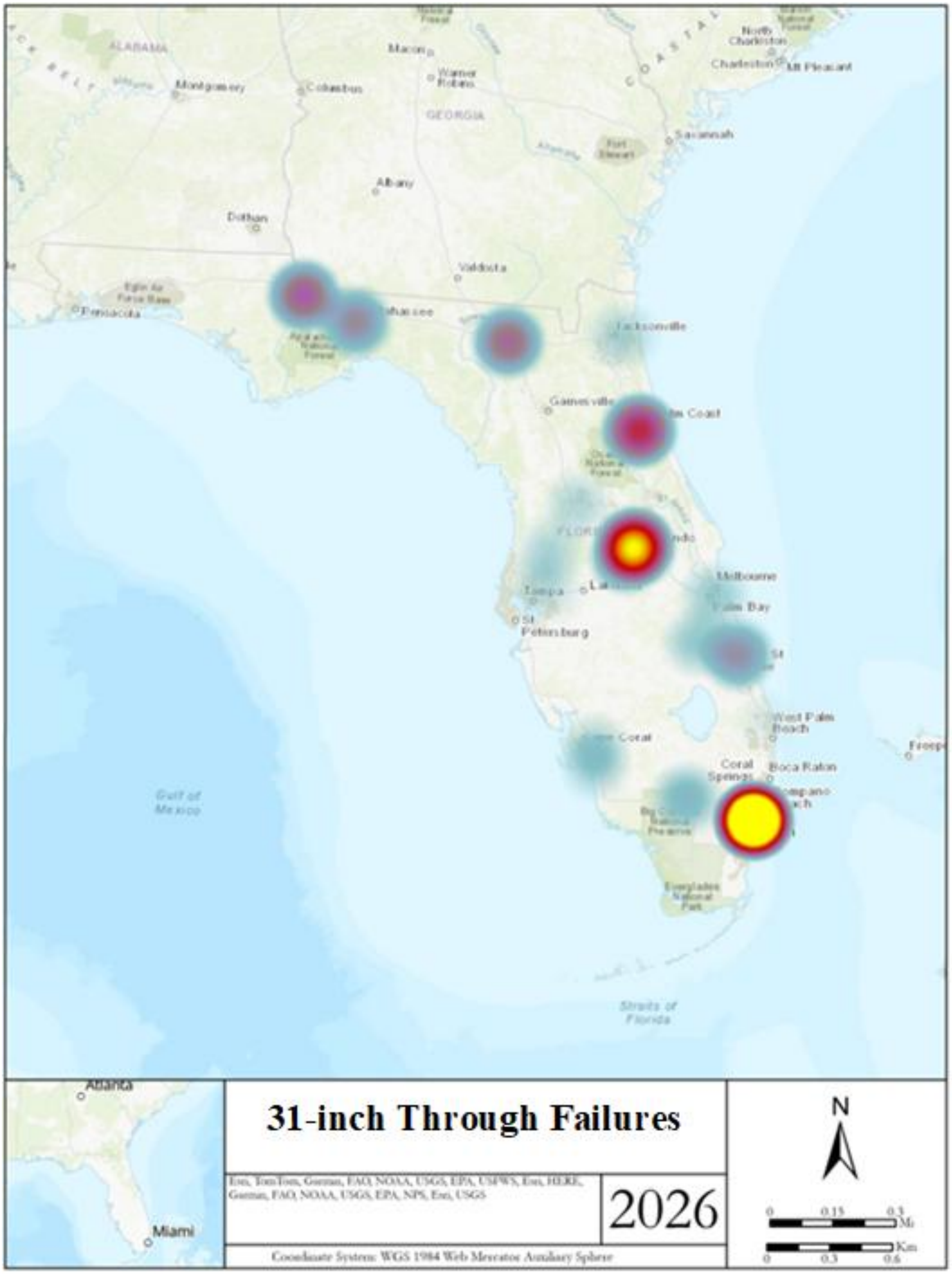

Figure 7-6: AADT-normalized Through failures at 31-inch guardrail locations

7.2.4 Comparison of Normalized Hot-Spot Patterns by Failure Mode and Guardrail Height

The AADT-normalized results show that several guardrail failure concentrations remain visible after accounting for traffic volume. This indicates that the observed patterns are not simply a reflection of high-volume urban areas or heavily traveled corridors. Instead, the normalized maps help identify specific locations, ramps, interchanges, and roadway segments where repeated failures appear elevated relative to traffic exposure. This supports the use of AADT-normalized hot-spot analysis as a proactive screening method for identifying areas of concern and prioritizing locations for further review.

The comparison by failure mode indicates that Over and Through failures may reflect different spatial patterns. Over failure hot-spots appear more localized in several areas, while Through failure hot-spots more often align with roadway segments, ramps, or interchange areas. This distinction is important because Over and Through failures may involve different crash dynamics, vehicle characteristics, impact conditions, and barrier interaction mechanisms. For this reason, the two failure modes should continue to be evaluated separately during site-level review. Combining the failure modes could obscure meaningful differences in the types of locations where failures are occurring and the types of mitigation strategies that may be appropriate.

The comparison by guardrail height standard should be interpreted in the context of the known guardrail inventory. The 31-inch subsets generally include fewer observations and produce fewer, more isolated hot-spots than the 27¾-inch subsets. However, this is expected in part because 31-inch installations represent a smaller share of the known end-treatment inventory, approximately 23 percent compared with approximately 77 percent for 27¾-inch installations. Therefore, fewer failures at 31-inch locations would be expected even if failures were occurring in proportion to inventory exposure. Prior analysis found that Over failures were slightly less common at 31-inch installations than would be expected based on their inventory share, but that difference was not statistically significant. As a result, the hot-spot maps should not be used to draw broad conclusions about comparative performance between the two height standards.

Overall, the normalized results are most useful as a location-screening tool rather than as a basis for statewide performance conclusions. The value of the analysis is in identifying specific locations, corridors, or interchange areas where repeated failures appear elevated relative to exposure and where additional engineering review may support future crash mitigation decisions. In some cases, a hot-spot area may include multiple nearby guardrail sections with different height standards, as well as different failure modes. Therefore, the maps should be used to guide site selection and follow-up review, while site-level interpretation should consider the specific guardrail section, failure mode, vehicle characteristics, and roadway context associated with each crash.

7.2.5 Locations Selected for Detailed Site Review

Based on the AADT-normalized hot-spot results and review of confirmed failure locations, four locations were selected for more detailed site-level discussion in section 7.3. These locations were selected because they exhibited repeated guardrail failure events in close spatial proximity and had sufficient supporting information to allow additional review of failure mode, guardrail height standard, vehicle characteristics, and roadway context.

The selected locations are:

1. **Miramar — Florida's Turnpike westbound exit ramp to NW 27th Avenue**
   This location includes multiple Through failures at a 31-inch guardrail location and was selected because of the repeated occurrence of failures at the same ramp area.

2. **Jacksonville — Northbound I-95**
   This location includes repeated Over failures at a 31-inch guardrail location and was selected because of the consistency of failure mode and the involvement of vehicles with relatively high center of gravity values.

3. **Lake City — I-75 and I-10 interchange area**
   This location includes multiple failure events within a complex interchange environment, including both Over and Through failures and more than one guardrail height standard.

4. **I-75 Alligator Alley near the Broward-Collier County line**
   This location includes several failure events along a rural freeway corridor with multiple guardrail sections. Some sections are associated with the 27¾-inch guardrail height standard, while others are associated with the 31-inch standard. Both Through and Over failures occurred within the corridor, including Through failures at both height standards and Over failures at 31-inch sections. This location was selected because the concentration of failures suggests a corridor-level area of concern rather than a single isolated guardrail location.

These locations are not presented as the only possible areas of concern in the statewide dataset. Rather, they represent locations identified through the normalized screening process where repeated failures and available supporting information justify further review. Section 7.3 provides a more detailed discussion of each location and identifies where additional field inspection or engineering evaluation may be appropriate.

7.3 Detailed Review of Selected Hot-Spot Locations

This section provides a detailed review of selected locations identified through the AADT-normalized hot-spot analysis. The locations discussed in this section were selected because they exhibited multiple confirmed guardrail failure events in close spatial proximity and had sufficient supporting information to allow additional review of failure mode, guardrail height standard, vehicle characteristics, and roadway context. The analysis presented here provides a screening-level interpretation and identifies locations where field inspection or further engineering evaluation may be appropriate. No field inspections were conducted. Where field review is recommended, it is presented as a follow-up action for future consideration.

7.3.1 Site Review Approach

The site review process used the AADT-normalized hot-spot results, mapped crash locations, confirmed failure classifications, available guardrail height information, vehicle characteristics, and aerial or street-level imagery. For each selected location, the review summarizes the number and type of failure events, the guardrail height standard where available, vehicle center of gravity and weight information, and the general roadway context.

Because this review was conducted using available project data and remote imagery, it should not be treated as a substitute for a field inspection. Guardrail height, post condition, rail alignment, hardware condition, grading, deflection space, terminal condition, and installation details may not be fully visible or verifiable from available imagery. Where repeated failures are identified, field review may be needed to confirm existing conditions and determine whether site-specific mitigation is warranted.

The site-level reviews are organized around four selected locations:

1. Miramar — Florida's Turnpike westbound exit ramp to NW 27th Avenue
2. Jacksonville — Northbound I-95
3. Lake City — I-75 and I-10 interchange area
4. I-75 Alligator Alley near the Broward-Collier County line

7.3.2 Hot-Spot Location 1: Miramar —Turnpike Westbound Exit Ramp, NW 27th Ave.

7.3.2.1 Location and Site Context

The first selected hot-spot location is in Miramar, Florida, at the westbound exit ramp from Florida's Turnpike to NW 27th Avenue. This location includes three confirmed guardrail failure events occurring in close spatial proximity. All three failures were classified as Through failures and were associated with the 31-inch guardrail height standard.

Figure 7-7 shows the mapped location of the three confirmed Through failures at the westbound exit ramp from Florida's Turnpike to NW 27th Avenue. The figure illustrates the close spatial proximity of the failure events and provides the basis for identifying this ramp as a selected hot-spot location for detailed review.

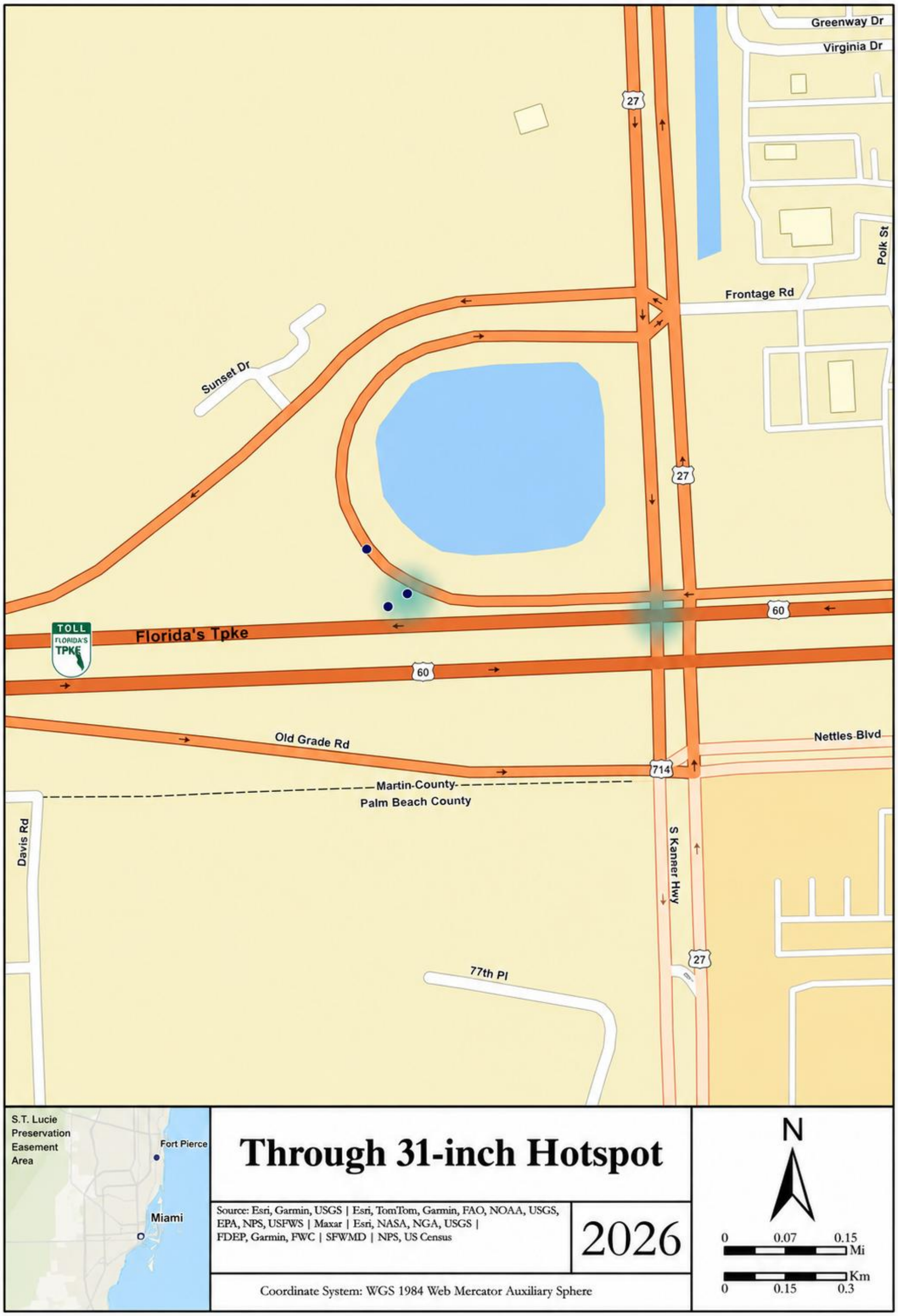

Figure 7-7: Hot-spot location 1 — Miramar, Florida

The repeated occurrence of Through failures at this ramp location suggests that the site may represent an area of concern. Based on available imagery provided in Figure 7-8, the ramp includes a curved alignment, and the failure events appear to be concentrated within the ramp environment. This type of location may involve interactions between approach speed, ramp curvature, driver path, impact angle, and roadside barrier placement. Figure 7-8 provides a site-level image of the ramp area to support the preliminary review of roadway context.

Figure 7-8: Hot-spot location 1 site image

Figure 7-8 shows the exit ramp from Florida's Turnpike to NW 27th Avenue. The image shows a ramp advisory speed of 30 mph and visible evidence of a recent guardrail Through failure at the time the image was captured. The apparent failure location is on the outside of the ramp curve, where vehicles departing the roadway would be expected to strike the guardrail face.

The combination of the 30 mph advisory speed, the relative sharpness of the ramp curve, and the location of the guardrail failure on the outside of the curve suggests that the repeated Through failures may be associated with vehicles entering or approaching the curve at speeds above the advisory speed. Under this scenario, a vehicle may lose lateral control, depart the travel lane, and strike the guardrail at a high impact angle. A high-angle impact into the face of the guardrail may cause the post-and-rail system to fail to redirect the vehicle, resulting in a Through failure.

This observation suggests that the repeated failures at this location may be driven more by ramp geometry, operating speed, and impact angle than by guardrail height or guardrail design alone.

7.3.2.2 Summary of Failure Events and Vehicle Characteristics

Table 7-1 summarizes the three confirmed failures identified at this location. The involved vehicles include a passenger car, a sport utility/pickup-style vehicle, and a sedan. Vehicle center of gravity values ranged from 20.64 inches to 28.52 inches. Vehicle weight was available for two of the three events.

Table 7-1: Hot-spot location 1 failure summary

Crash Number	Failure Mode	Guardrail Height (in.)	Vehicle	Crash Date	Vehicle CG Height (in.)	Vehicle Weight (lbs.)
89719353	Through	31	2024 Honda Civic	12/2024	20.64	N/A
26456702	Through	31	2005 Chevrolet Avalanche	07/2024	28.52	2,657.10
88570548	Through	31	2018 Infiniti Q50	01/2022	20.87	1,813.00

Note: N/A = data not available

The range of vehicle center of gravity values suggests that the repeated Through failure pattern at this location is not limited to high-center-of-gravity vehicles. Two of the three vehicles had relatively low center of gravity values, while one vehicle had a substantially higher center of gravity. This variation indicates that vehicle characteristics alone may not explain the repeated failure pattern at this site.

7.3.2.3 Preliminary Interpretation and Inspection Recommendation

The repeated occurrence of Through failures at this 31-inch guardrail location identifies the ramp as an area of concern. However, the available site imagery suggests that the observed failures are more likely related to geometric and speed-related conditions than to a deficiency in the 31-inch guardrail height standard. The failure location is on the outside of a relatively sharp exit ramp curve with a posted advisory speed of 30 mph. This context suggests that some vehicles may be entering or approaching the curve at speeds above the advisory speed, losing control, and striking the guardrail at a high impact angle.

In this type of impact scenario, the guardrail may be subjected to conditions that exceed its ability to safely redirect the vehicle. The resulting Through failure appears to be less a direct indication of inadequate guardrail height or installation and more an indication that the ramp geometry, speed environment, and impact conditions may be producing repeated high-angle guardrail strikes.

Potential mitigation options should therefore focus first on reducing the likelihood or severity of roadway departure at the curve. The most direct geometric improvement would be to increase the curve radius and reduce the sharpness of the ramp alignment. However, this option may not be practical because of right-of-way constraints and the existing ramp configuration. Other geometric options could include introducing or improving a spiral transition, increasing superelevation where feasible, or otherwise modifying the ramp geometry to better accommodate vehicle path and speed through the curve.

Another potential mitigation approach would be to evaluate whether the roadside condition behind the guardrail can be modified. If the guardrail is protecting a critical slope, additional fill or slope flattening could potentially transition the roadside to a non-recoverable or recoverable slope condition. This could reduce or eliminate the need for guardrail at the specific location, increase the effective clear zone, and reduce the likelihood of a severe rollover outcome if a vehicle leaves the roadway.

A less desirable but potentially feasible option would be to replace the existing system with a more rigid barrier treatment, such as a concrete barrier or retaining-wall-type system, if roadside conditions require positive containment. This option may improve the likelihood of redirecting errant vehicles and reduce the probability of a vehicle penetrating the barrier and traversing the critical slope. However, it may also increase the severity of the barrier impact compared with a more forgiving roadside or flexible barrier system. This tradeoff would need to be evaluated carefully.

Overall, this location does not appear to indicate a deficiency in the current 31-inch guardrail height standard. Instead, the repeated Through failures appear more likely to reflect a geometric and speed-related issue that is producing high-angle guardrail impacts on the outside of the ramp curve. A field inspection is not recommended as the primary next step unless FDOT wishes to confirm existing conditions. The more appropriate next step would be a targeted engineering review of ramp geometry, operating speeds, advisory speed compliance, roadside slope conditions, and feasible mitigation alternatives.

7.3.3 Hot-Spot Location 2: Jacksonville — Northbound I-95

7.3.3.1 Location and Site Context

The second selected hot-spot location is in Jacksonville, Florida, along northbound I-95. This location includes two confirmed guardrail failure events occurring in close proximity.

Both failures were classified as Over failures and were associated with the 31-inch guardrail height standard.

Figure 7-9 shows the mapped location of the two confirmed Over failures along northbound I-95 in Jacksonville. Both failures occurred in close proximity and were associated with the 31-inch guardrail height standard, supporting the selection of this site for detailed review.

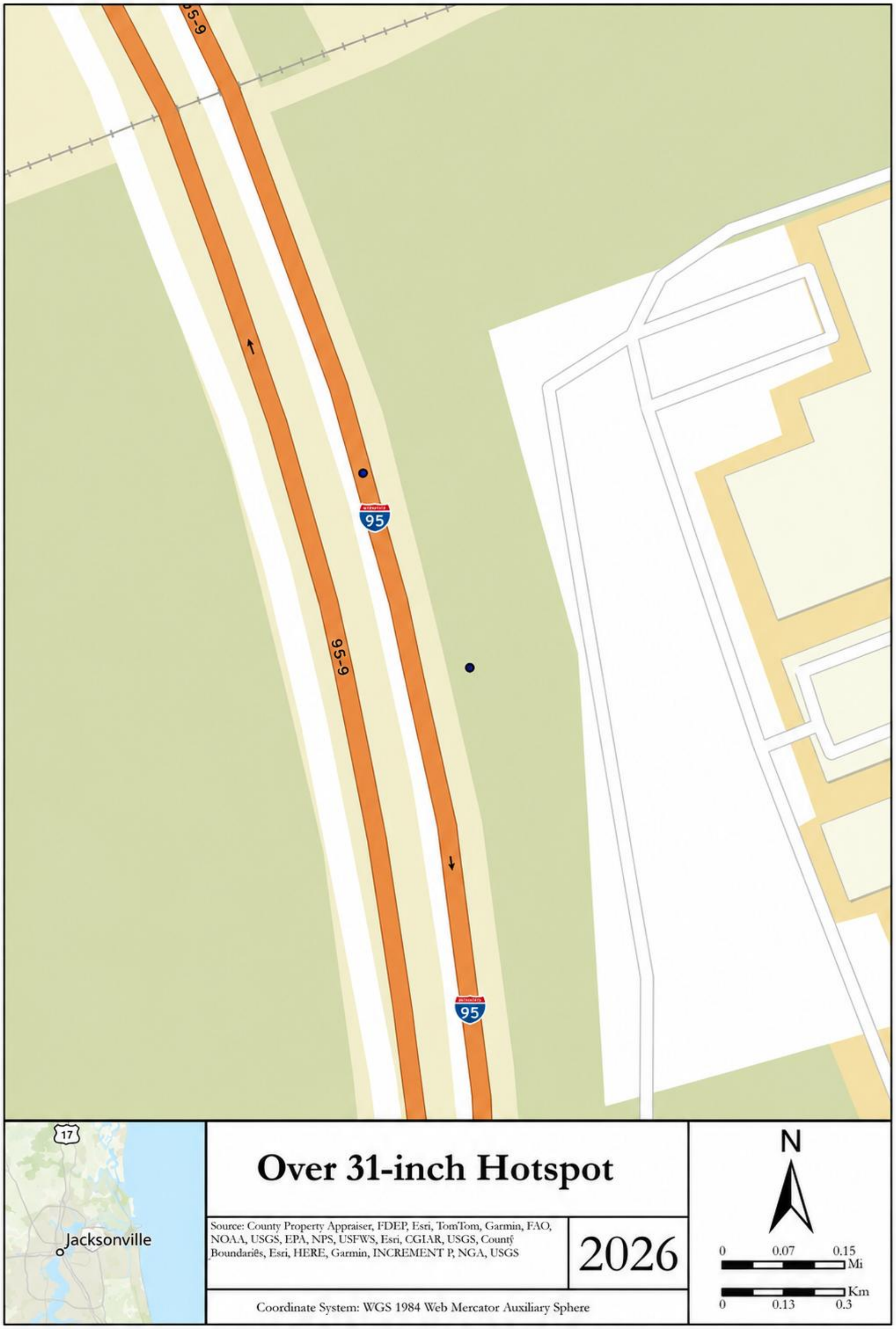

Figure 7-9: Hot-spot location 2 — Jacksonville, Florida

The repeated occurrence of Over failures at a 31-inch guardrail location is notable because the 31-inch standard was adopted to better address the modern vehicle fleet. The roadway context includes a freeway environment where operating speeds and vehicle departure path may be important factors in understanding the observed failures. Figure 7-10 shows the northbound I-95 roadway segment associated with Hot-Spot Location 2. The roadway includes a gradual horizontal curve to the left. As shown in Figure 7-9, the documented Over failures occurred on the outside of this curve, along the right side of the roadway.

Figure 7-10: Hot-spot location 2 site image

The image suggests that the three travel lanes are superelevated through the curve, while the outside shoulder appears to transition to a negative cross slope. The guardrail is located beyond this outside shoulder. This configuration may be important because vehicles departing from the positively superelevated travel lanes at high speed may continue across the negatively sloped shoulder before contacting the guardrail. Under this condition, the vehicle trajectory and the relative elevation difference between the travel lane and the guardrail base may effectively reduce the functional height of the guardrail at impact.

In other words, although the guardrail may meet the 31-inch height standard when measured at the rail location, the vehicle may approach the barrier from a higher roadway plane and contact the rail higher than expected. This condition could increase the likelihood of an Over failure, particularly for vehicles with higher centers of gravity or vehicles departing the roadway at higher speeds.

7.3.3.2 Summary of Failure Events and Vehicle Characteristics

Table 7-2 summarizes the two confirmed failures identified at this location. Both involved pickup trucks with relatively high center of gravity values.

Table 7-2: Hot-spot location 2 failure summary

Crash Number	Failure Mode	Guardrail Height (in.)	Vehicle	Crash Date	Vehicle CG Height (in.)	Vehicle Weight (lbs.)
24916183	Over	31	2005 GMC Sierra	05/2022	28.71	N/A
24998817	Over	31	2007 Chevrolet Silverado	09/2022	28.18	2,557.60

Both failures involved vehicles with center of gravity heights greater than 28 inches. This is consistent with the broader project finding that higher vehicle center of gravity is associated with Over failure outcomes. However, the site-specific sample includes only two events, and vehicle weight information was unavailable for one of them. Therefore, the repeated Over failure pattern should not be attributed solely to vehicle characteristics without additional review.

7.3.3.3 Preliminary Interpretation and Inspection Recommendation

This location is a strong candidate for additional review because both documented failures were Over failures at a 31-inch guardrail location and both involved pickup trucks with relatively high center of gravity values. The consistency of the failure mode and vehicle type suggests that impact dynamics are important at this site. However, the site imagery also suggests that the roadway cross-section and barrier placement may have contributed to the observed failure pattern.

The roadway appears to include a gradual horizontal curve with superelevated travel lanes. The documented Over failures occurred on the outside of the curve, where vehicles leaving the roadway would travel across the outside shoulder toward the guardrail. Based on the available image, the outside shoulder appears to have a slight negative cross slope, with the guardrail located near the outside edge of that shoulder. This configuration may effectively reduce the guardrail height relative to the vehicle’s departure path. A vehicle leaving the positively superelevated travel lanes at high speed may carry its momentum across the negative shoulder and contact the guardrail from a higher approach plane than would be expected if the roadway and barrier were on the same cross-slope plane.

This does not necessarily indicate a deficiency in the 31-inch guardrail height standard itself. Instead, the location may reflect a combination of high-center-of-gravity vehicles, high-speed roadway departure, curve geometry, shoulder cross slope, and guardrail placement. These factors could increase the likelihood that a vehicle contacts the guardrail higher on the rail face and overrides the system.

A field inspection or targeted engineering review is recommended for this location. The review should verify the actual cross slopes of the travel lanes and shoulder, the installed guardrail height, the relative elevation between the travel lane edge and the guardrail base, barrier offset, shoulder width, roadside grading, and evidence of prior impacts. Particular attention should be given to whether the guardrail height is being measured from a local ground line that is lower than the vehicle departure path from the adjacent travel lanes. If confirmed, potential mitigation may include adjusting shoulder grading, modifying the barrier offset or height, improving the roadside cross-section, or evaluating whether a different barrier treatment is appropriate for the departure conditions at this location.

7.3.4 Hot-Spot Location 3: Lake City — I-75 and I-10 Interchange Area

7.3.4.1 Location and Site Context

The third selected hot-spot location is in Lake City, Florida, within the I-75 and I-10 interchange area. This location includes five confirmed guardrail failure events within the interchange system. Unlike the first two locations, this site includes both Through and Over failures, multiple ramp movements, and more than one guardrail height standard.

Figure 7-11 shows the mapped location of the confirmed guardrail failures within the I-75 and I-10 interchange area near Lake City. The figure illustrates that the failures are not concentrated at a single guardrail segment, but instead occur across multiple ramp movements within the interchange. This spatial pattern supports treating the location as an interchange-level area of concern rather than an isolated point location.

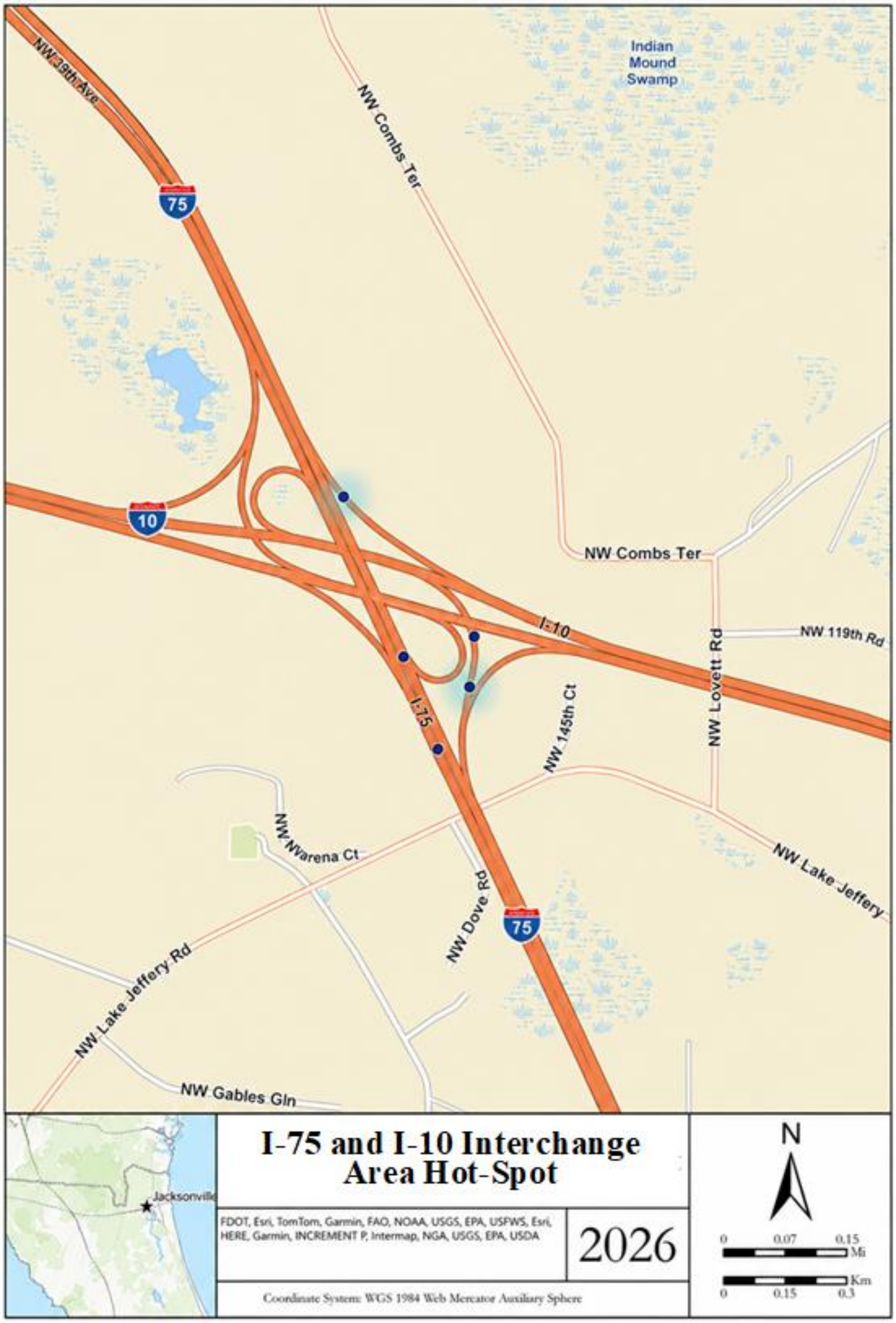

Figure 7-11: Hot-spot location 3 — Lake City, Florida

The interchange appears to be an older Interstate-era facility. Although the exact construction date and subsequent reconstruction history were not confirmed as part of this task, older interchange designs may have been developed under design assumptions that differ from current conditions, including vehicle fleet characteristics, operating speeds, traffic volumes, and driver expectations. If some ramp curves or roadside conditions no longer align well with current operating conditions, the interchange may experience a greater potential for run-off-road events. An increase in roadway departure events would also increase the opportunity for guardrail impacts and, in some cases, guardrail failures. This interpretation suggests that the observed hot-spot may reflect an interchange-level roadway departure issue rather than a localized guardrail design, installation, or maintenance deficiency.

7.3.4.2 Summary of Failure Events and Vehicle Characteristics

Table 7-3 summarizes the five confirmed failures identified in the I-75 and I-10 interchange area. The events include three Through failures, one Over failure at a known 27¾-inch location, and one Over failure where guardrail height information was unavailable.

Table 7-3: Hot-spot location 3 failure summary

Crash Number	Failure Mode	Guardrail Height (in.)	Vehicle	Crash Date	Vehicle CG Height (in.)	Vehicle Weight (lbs.)
89618131	Through	31	2010 Jeep Wrangler	07/2023	28.39	N/A
89761720	Through	27¾	2018 Toyota Highlander	04/2024	26.04	2,080.00
24926354	Through	27¾	2016 Nissan Altima	07/2022	21.60	1,534.00
89702837	Over	27¾	2003 Dodge Ram 1500	11/2023	27.38	N/A
88578464	Over	N/A	2000 Jeep Grand Cherokee	12/2021	26.95	N/A

Vehicle center of gravity values ranged from 21.60 inches to 28.39 inches. Several of the involved vehicles had moderate to high center of gravity values, but the failure outcomes were mixed. Through failures occurred at both 27¾-inch and 31-inch locations, while Over failures occurred at a 27¾-inch location and at one location where guardrail height was unavailable.

This mixture of failure modes, vehicle types, and guardrail height standards suggests that no single factor explains the repeated failure pattern. Instead, the interchange context may be an important consideration in understanding why multiple failures occurred within the same broader area.

7.3.4.3 Preliminary Interpretation and Inspection Recommendation

The Lake City interchange is a candidate for interchange-level review because it includes multiple failure events across different ramp movements and more than one failure mode. The available data do not suggest that a single guardrail section is consistently failing. Instead, the pattern suggests that the interchange geometry and operating environment may be contributing to repeated roadway departure events that result in guardrail impacts.

Because the interchange appears to be an older Interstate-era facility, it may have been designed under assumptions that differ from current traffic conditions, vehicle fleet characteristics, and operating speeds. The exact construction date, reconstruction history, and current design-standard compliance of the ramp curves were not verified as part of this task. Therefore, it would not be appropriate to conclude that the ramp geometry is deficient. However, the presence of multiple failures across different ramp movements suggests that some elements of the interchange may warrant review from a roadway departure and roadside safety perspective.

In this context, the repeated failures are not necessarily evidence of a guardrail height, installation, or maintenance problem. Rather, the hot-spot may indicate that the interchange has locations where vehicles are more likely to leave the roadway and strike roadside barriers. If roadway departure events are occurring more frequently because of ramp curvature, speed selection, merging and diverging conditions, or driver path through the interchange, then guardrail failures may be a consequence of the broader interchange operating environment.

A field inspection focused only on guardrail condition is not recommended as the primary next step. The more appropriate next step would be a targeted engineering review of the interchange, including ramp geometry, curve advisory speeds, operating speeds, superelevation, delineation, signing, roadside slopes, barrier placement, and roadway departure history. This review would help determine whether the observed failures are associated with specific ramp movements or whether the interchange as a whole may benefit from roadway departure countermeasures.

7.3.5 Hot-Spot Location 4: I-75 Alligator Alley near the Broward-Collier County line

7.3.5.1 Location and Site Context

The fourth selected hot-spot location is along I-75 Alligator Alley near the Broward-Collier County line. A total of six confirmed guardrail failure events were identified within a roughly 8-mile section of highway. This location differs from the other selected sites because it is a rural freeway corridor rather than an urban ramp or complex interchange.

Figure 7-12 shows the mapped location of the confirmed guardrail failures along I-75 Alligator Alley near the Broward-Collier County line. The figure illustrates that the failures occurred within the same general rural freeway corridor, but not necessarily at a single guardrail installation. This spatial pattern supports treating the location as a corridor-level area of concern, particularly because the segment includes multiple guardrail sections, more than one guardrail height standard, and both Over and Through failure modes.

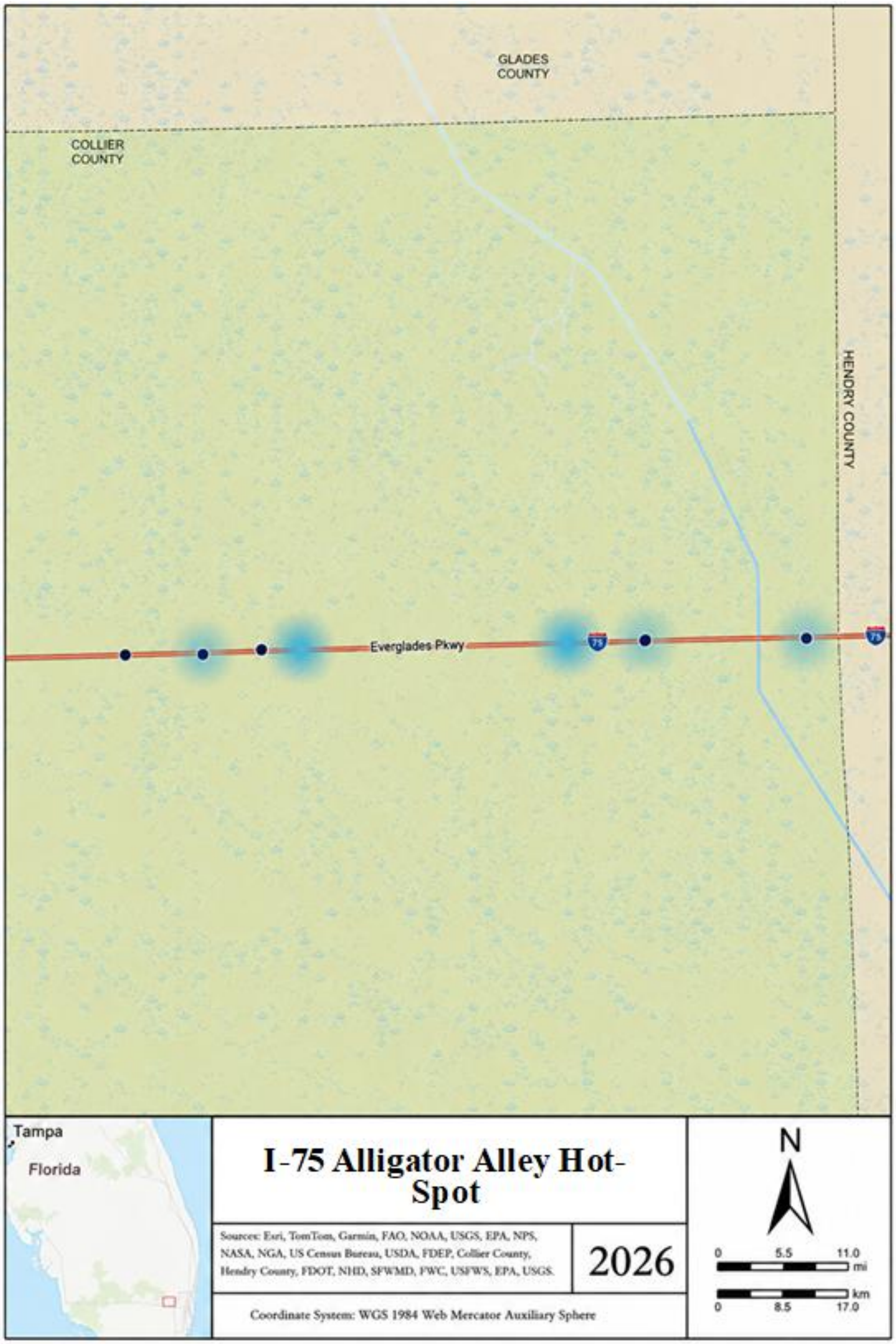

Figure 7-12: Hot-spot location 4 — I-75 Alligator Alley near the Broward-Collier County line

Because the failures are distributed along a rural freeway corridor rather than at a ramp or interchange, the repeated failures may be associated with broader corridor conditions rather than a single isolated guardrail location. Potential contributing factors may include high operating speeds, long-distance rural driving conditions, driver fatigue, distraction, overcorrection, roadside slope conditions, guardrail section transitions, or other impact-related factors.

7.3.5.2 Summary of Failure Events and Vehicle Characteristics

Table 7-4 summarizes the six confirmed failures identified along the I-75 Alligator Alley segment. The events include four Through failures and two Over failures. The Through failures occurred at both 27¾-inch and 31-inch guardrail sections, while the two documented Over failures occurred at 31-inch guardrail sections.

Table 7-4: Hot-spot location 4 failure summary

Crash Number	Failure Mode	Guardrail Height (in.)	Vehicle	Crash Date	Vehicle CG Height (in.)	Vehicle Weight (lbs.)
24933549	Through	27¾	2005 Dodge Caravan	10/2022	26.57	1,875.10
26284532	Through	27¾	2020 Nissan Altima	04/2025	21.05	1,633.00
26293619	Through	27¾	2012 Dodge Durango	02/2024	27.01	2,555.00
89699544	Through	31	2017 Toyota Corolla	02/2024	21.78	1,400.00
88285326	Over	31	2020 Hyundai Sonata	03/2021	21.91	1,498.00
25042089	Over	31	2004 Toyota 4Runner	11/2022	29.27	N/A

Vehicle center of gravity values ranged from 21.05 inches to 29.27 inches. The Through failures occurred across both lower and higher center of gravity vehicles and across both guardrail height standards. The two Over failures occurred at 31-inch guardrail sections, but the vehicle characteristics varied substantially, with one involving a lower-center-of-gravity passenger car and the other involving a higher-center-of-gravity SUV. This variation suggests that vehicle characteristics alone are insufficient to explain the concentration of failures along this corridor.

7.3.5.3 Preliminary Interpretation and Inspection Recommendation

The I-75 Alligator Alley location is a candidate for corridor-level review because the failures are distributed across a rural freeway segment with multiple guardrail sections rather than concentrated at a single ramp, interchange, or isolated barrier location. The presence of both Over and Through failures, and the involvement of both 27¾-inch and 31-inch guardrail sections, suggests that the corridor should be reviewed as a system rather than as one individual guardrail installation.

A field review is recommended for this location. Unlike the ramp and interchange hot-spots discussed previously, the available information does not indicate an obvious geometric feature, such as a sharp curve or complex ramp movement, that would readily explain the concentration of guardrail failures. As a result, a field review may provide useful insight into both why vehicles are leaving the roadway along this section of interstate and why those roadway departure events are resulting in guardrail failure outcomes.

The field review should document the location, height, and condition of each guardrail section within the corridor where failures occurred. Particular attention should be given to transitions between guardrail sections, rail alignment, shoulder width, roadside slope, barrier offset, terminal locations, evidence of recurring impacts or repairs, and whether the failures are associated with particular roadway or roadside features.

Because this location is a rural freeway corridor, the review should also consider operational and behavioral factors such as high operating speeds, long-distance driving conditions, driver fatigue, distraction, and overcorrection. Overall, this location may be useful for evaluating whether repeated guardrail failures can occur across multiple guardrail sections within the same corridor and whether corridor-level roadside safety improvements or more detailed engineering review may be appropriate.

7.4 Hot-Spot Summary, Findings, and Recommendations

The AADT-normalized hot-spot analysis provided a useful basis for identifying potential areas of concern by accounting for differences in traffic exposure. By accounting for traffic exposure, the normalized results reduced the influence of high-volume urban areas and helped identify locations where repeated guardrail failures appeared elevated relative to roadway usage.

The normalized maps showed that guardrail failure patterns were not explained by traffic volume alone. Several locations remained prominent after AADT normalization, suggesting that repeated failures at these locations may reflect site-specific conditions, roadway departure patterns, impact characteristics, or other factors that warrant closer review. These findings support the use of exposure-normalized hot-spot analysis as a proactive screening method for identifying candidate locations for crash mitigation.

The analysis also showed that Over and Through failures should be evaluated separately. Over failures and Through failures appeared to follow somewhat different spatial patterns and may reflect different combinations of vehicle characteristics, impact conditions, roadway geometry, and barrier interaction. Combining the two failure modes could obscure meaningful differences in how and where guardrail failures are occurring.

7.4.1 Findings by Failure Mode and Guardrail Height Standard

The AADT-normalized Over failure maps identified locations where vehicles passed over the guardrail system relative to traffic exposure. Some Over failure locations involved vehicles with higher centers of gravity, which is consistent with prior project findings indicating that vehicle center of gravity is an important factor in Over failure outcomes. However, the selected hot-spot locations also showed that vehicle characteristics alone do not fully explain the occurrence of Over failures. Roadway geometry, departure path, impact speed, shoulder cross slope, and the effective height of the guardrail relative to the vehicle approach path may also be important.

The AADT-normalized Through failure maps identified locations where vehicles penetrated or passed through the guardrail system. Several Through failure locations appeared to be associated with ramp, interchange, or corridor conditions where vehicles may be striking the guardrail at high impact angles or under conditions that reduce the likelihood of successful redirection. These patterns suggest that Through failures may often require evaluation of roadway departure conditions in addition to guardrail condition or height.

The height-specific results should be interpreted in the context of the known guardrail inventory. The 31-inch guardrail sections represent a smaller share of the known end-treatment inventory than 27¾-inch sections, so fewer failure events at 31-inch locations are expected even before considering potential differences in performance. Prior analysis found that the observed share of Over failures at 31-inch locations was slightly lower than expected based on inventory proportion, but that difference was not statistically significant. Therefore, the hot-spot maps should not be used to draw broad statewide conclusions about the comparative performance of the 27¾-inch and 31-inch standards. Their primary value is in identifying specific locations or corridors where repeated failures may warrant further review.

7.4.2 Role of Site-Specific Conditions

The detailed site reviews suggest that repeated guardrail failures are not necessarily evidence of a guardrail height deficiency, installation deficiency, or maintenance problem. In several cases, the observed failures appear more likely to be associated with site-specific roadway or operational conditions that increase the likelihood of roadway departure or produce severe impact conditions.

At the Miramar location, repeated Through failures occurred at a 31-inch guardrail section on the outside of a relatively sharp exit ramp curve with a 30 mph advisory speed. The available site image suggests that vehicles may be entering or approaching the curve at speeds above the advisory speed, losing control, and striking the guardrail at a high impact angle. This location appears to reflect a ramp geometry and speed-related issue more than a guardrail height issue.

At the Jacksonville location, repeated Over failures occurred at a 31-inch guardrail section on the outside of a gradual horizontal curve. The roadway appears to include superelevated travel lanes with an outside shoulder that may transition to a slight negative cross slope. This configuration may effectively reduce the functional guardrail height relative to the vehicle departure path, particularly for high-speed departures from the travel lanes. This site may therefore involve a combination of high-center-of-gravity vehicles, curve geometry, shoulder cross slope, and barrier placement.

At the Lake City location, failures occurred across multiple ramp movements within the I-75 and I-10 interchange and included more than one failure mode and guardrail height standard. This pattern does not suggest that one specific guardrail section is repeatedly failing. Instead, the hot-spot may reflect an interchange-level roadway departure issue associated with ramp geometry, operating speeds, merging and diverging areas, or driver path through the interchange.

At the I-75 Alligator Alley location near the Broward-Collier County line, failures were distributed across a rural freeway corridor with multiple guardrail sections. Both Over and Through failures occurred, and both 27¾-inch and 31-inch guardrail sections were involved. Unlike the ramp and interchange locations, this corridor does not present an obvious geometric explanation based on the available information. This makes the location a strong candidate for field review to better understand why vehicles are leaving the roadway and why those events are resulting in guardrail failures.

Table 7-5 summarizes the recommended next step for each selected hot-spot location.

Table 7-5: Recommended follow-up review by hot-spot location

Hot-Spot Location	Primary Concern	Recommended Next Step
Miramar — Florida's Turnpike westbound exit ramp to NW 27th Avenue	Repeated Through failures on the outside of a sharp ramp curve with a 30 mph advisory speed	Targeted engineering review of ramp geometry, advisory speed compliance, operating speeds, impact angle, roadside slope, and feasible mitigation options. A field inspection focused only on guardrail condition is not recommended as the primary next step.
Jacksonville — Northbound I-95	Repeated Over failures at a 31-inch guardrail location involving high-center-of-gravity vehicles and possible effective guardrail height reduction due to cross-slope conditions	Field inspection or targeted engineering review to verify travel lane and shoulder cross slopes, relative elevation between travel lane and guardrail base, installed guardrail height, barrier offset, and roadside grading.
Lake City — I-75 and I-10 interchange area	Multiple failure events across several ramp movements, with both Over and Through failures	Targeted interchange-level engineering review of ramp geometry, curve advisory speeds, operating speeds, superelevation, signing, delineation, roadside slopes, barrier placement, and roadway departure history. A guardrail-condition-only inspection is not recommended as the primary next step.
I-75 Alligator Alley near the Broward-Collier County line	Multiple failures across a rural freeway corridor with no obvious ramp or interchange-related explanation	Field review recommended to evaluate why vehicles are leaving the roadway and why those roadway departure events are resulting in guardrail failure outcomes. Review should document guardrail sections, height, condition, transitions, shoulder width, roadside slope, barrier offset, terminal locations, and evidence of recurring impacts or repairs.

7.4.3 Hot-Spot Analysis Limitations and Data Needs

Several limitations should be considered when interpreting the findings from this task. First, the analysis is limited to confirmed guardrail failure events included in the project dataset. It does not represent all guardrail impacts, all roadside crashes, or all roadway departure events. As a result, the hot-spot results reflect patterns within the confirmed failure dataset rather than a complete statewide inventory of guardrail performance.

Second, the AADT-normalized analysis accounts for traffic volume but does not account for all relevant exposure variables. A more complete exposure model would include guardrail length, roadside hazard exposure, segment length, vehicle mix, operating speed, curvature, shoulder width, barrier offset, roadside slope, and other roadway characteristics. These variables were not consistently available statewide for this task.

Third, the accuracy of the hot-spot analysis depends on the accuracy of the crash location information. Some crash locations may be approximate, especially where the source records describe the crash location using ramps, mileposts, landmarks, or general roadway references.

Fourth, guardrail height information was not available for every failure event. The height-specific maps and site reviews therefore reflect the subset of records where guardrail height could be linked to the crash location. These results should not be interpreted as a complete statewide comparison of all 27¾-inch and 31-inch guardrail installations.

Finally, the site reviews were based on available project data and remote imagery. Field conditions such as exact rail height, post condition, rail alignment, grading, deflection space, terminal condition, and recent repairs cannot always be verified from remote review. Where field review is recommended, it should be used to confirm existing conditions and determine whether mitigation is warranted.

7.4.4 Guardrail Hot-Spot Analysis Conclusions

The AADT-normalized hot-spot analysis provided a useful basis for identifying potential areas of concern by accounting for differences in traffic exposure. The normalized results helped identify locations where repeated guardrail failures appeared elevated relative to roadway usage.

The detailed site reviews indicate that repeated guardrail failures may be influenced by a combination of factors, including roadway geometry, operating speeds, impact angle, shoulder cross slope, barrier placement, roadside conditions, and vehicle characteristics. In several cases, the observed hot-spots do not appear to indicate a deficiency in the guardrail height standard itself. Instead, they suggest locations where roadway departure patterns or site-specific impact conditions may be increasing the likelihood of guardrail failure.

Overall, the findings support the continued use of exposure-normalized screening methods to identify locations where guardrail failures may warrant further review. The most productive next step is not a broad conclusion that one height standard is performing better or worse based on map patterns alone, but rather targeted follow-up at locations where repeated failures suggest potential opportunities for roadway departure mitigation, roadside safety improvements, or site-specific engineering review.

8 Conclusion

This study evaluated whether current guardrail height standards used by the FDOT remain appropriate in relation to modern vehicle characteristics and observed guardrail breach crash outcomes. The research was motivated by the continued evolution of the vehicle fleet, particularly the increasing prevalence of SUVs, pickup trucks, and other vehicles with higher centers of gravity, as well as the broader shift toward heavier and taller vehicles than those that influenced earlier guardrail design standards. While controlled crash testing has guided the development of the 31-inch MGS, this research sought to examine how guardrail performance is reflected in real-world Florida crash history and whether vehicle characteristics help explain breach failure outcomes.

The literature review showed that guardrail height standards have evolved in response to changes in crash testing protocols and vehicle design. National guidance and prior research consistently support the use of taller guardrail systems to improve interaction with modern vehicles, particularly those with higher centers of gravity that may be more susceptible to override. Florida's use of the 31-inch system reflects this broader shift away from the older 27¾-inch standard. At the same time, the literature also made clear that there remains an important gap between controlled crash testing and field performance, reinforcing the need to evaluate actual crash outcomes and not rely exclusively on laboratory or test-track results.

The results of the crash-data analysis indicate that vehicle center of gravity height is more strongly associated with guardrail breach failure mode than guardrail height alone. Vehicles involved in Over failures generally had higher centers of gravity than those involved in Through failures, and the statistical analyses supported that relationship. Logistic regression further showed that center of gravity height was a statistically significant positive predictor of Over failure status, indicating that the likelihood of an Over failure increased as vehicle center of gravity increased. By contrast, vehicle weight did not show the same clear or statistically significant relationship with failure mode in the available sample. These findings suggest that vertical vehicle geometry may be more influential than mass alone in determining how a vehicle interacts with a guardrail during a breach event.

With respect to guardrail height standard, the findings did not show that the 31-inch system was overrepresented in the confirmed failure dataset relative to its presence in the statewide inventory. This suggests that the 31-inch standard is not underperforming when compared to the older 27¾-inch standard. When failures were examined by mode, the 27¾-inch installations showed a greater share of Over failures, while the 31-inch installations showed a greater share of Through failures. Although these differences were not statistically significant enough to claim a definitive performance advantage in all respects, the directional pattern is consistent with the engineering purpose of the 31-inch system: to improve engagement with taller vehicles and reduce override-related outcomes. Taken together, the results support the conclusion that the 31-inch standard represents a meaningful and defensible improvement over the older 27¾-inch standard.

The hot-spot analysis provided an additional practical contribution by identifying areas where confirmed guardrail failures cluster spatially and where future field investigation may be most beneficial. These mapped patterns help move the research beyond statewide summary statistics by pointing to specific locations and corridors that may warrant closer inspection, context review, or design evaluation. In this way, the spatial analysis supports a more targeted approach to roadway safety assessment and provides a framework for prioritizing future investigation of high-frequency breach locations.

Overall, the findings of this report support the continued use of the 31-inch guardrail standard in Florida while also showing that guardrail adequacy cannot be viewed as a fixed issue solved permanently by one design change. The modern vehicle fleet continues to evolve, and the increasing prevalence of taller vehicles with higher centers of gravity may continue to challenge roadside safety hardware over time. The present study does not show that the 31-inch standard has eliminated breach failures, nor does it establish a strict cutoff beyond which current systems become inadequate. Instead, it shows that the 31-inch standard is better aligned with the modern fleet than the 27¾-inch standard, while also emphasizing that vehicle center of gravity remains a key factor influencing failure mode.

Accordingly, the most defensible conclusion is that Florida's current 31-inch guardrail height standard remains appropriate based on the available evidence, but continued monitoring is necessary. The findings also suggest that the 31-inch standard should be viewed as an appropriate current standard rather than a permanent endpoint for guardrail height evaluation. The 31-inch standard did not appear to underperform relative to the older 27¾-inch standard in the available confirmed-failure dataset, and the observed pattern of Over failures was directionally consistent with the intended benefit of the higher rail height. However, confirmed failures continued to occur at 31-inch installations, and vehicle center of gravity remained an important factor in Over failure outcomes. Prior research indicates that higher top-rail heights may be feasible under certain crash-test conditions, including 34-inch and 36-inch MGS configurations; however, additional testing and evaluation would be needed before such heights could be considered for broader application (Stolle et al., 2012; Asadollahi Pajouh et al., 2018). As the vehicle fleet continues to shift toward taller vehicles with higher centers of gravity, continued monitoring and future evaluation of potential design adaptations may be warranted. By combining literature, crash history, vehicle characteristics, and spatial analysis, this research contributes to a more complete understanding of guardrail performance in Florida and provides support for ongoing data-driven evaluation of roadside safety standards.

8.1 Research Limitations

Several limitations should be considered when interpreting the findings of this study. First, the analysis was based on a dataset of confirmed guardrail face failures rather than the full population of guardrail strikes. As a result, the study identifies patterns within documented breach outcomes, but it does not estimate the overall probability of failure for each guardrail height standard. Accordingly, the findings should not be interpreted as direct failure rates or as definitive comparative risk measures per impact.

Second, guardrail height could only be assigned for crashes that were successfully matched to the FDOT eMaintenance end-treatment inventory. Because comprehensive statewide guardrail segment height data were not available, end-treatment height was used as a proxy for the connected guardrail segment height. Although this is a practical and reasonable approach given the available data, some misclassification is possible if the terminal height did not fully represent the specific section of guardrail involved in the crash.

Third, not all confirmed failures could be linked to both usable vehicle information and guardrail height data. The analytic sample was therefore reduced for several comparisons, particularly those requiring both vehicle characteristics and assigned guardrail height. This limitation affected subgroup sample sizes and may have reduced the statistical power of the study to detect meaningful differences, especially for the 31-inch guardrail subgroup and for analyses involving vehicle weight.

Fourth, vehicle specification data were compiled from external sources using crash report make, model, and year information. In some cases, direct center of gravity values were not available and had to be estimated using static stability factor and vehicle dimensions. When an exact model year was unavailable, the closest year within the same vehicle generation and body style was selected. While this approach provided a reasonable basis for approximating vehicle characteristics, it introduces some uncertainty into the center of gravity and weight variables used in the analysis.

Fifth, the study focused on guardrail height, vehicle center of gravity height, and vehicle weight, but other potentially important contributors to guardrail performance were not explicitly modeled. These may include impact speed, impact angle, roadway geometry, slope conditions, barrier condition, installation details, maintenance history, and other crash-specific factors. Because these variables were not consistently available across the confirmed failure dataset, the analysis should be interpreted as identifying associations rather than establishing fully causal relationships.

Sixth, the exposure model used to compare failures across guardrail heights assumed that guardrail strike exposure is proportional to statewide end-treatment prevalence. This assumption provides a practical benchmark for comparing observed and expected counts, but it is still a simplification of real-world exposure. Actual opportunity for guardrail impact likely varies by roadway type, traffic volume, speed environment, and site conditions. Therefore, the expected counts derived from statewide inventory proportions should be interpreted as an approximation rather than as a fully exposure-adjusted measure.

Taken together, these limitations do not invalidate the findings of the study, but they do indicate that the results should be interpreted as evidence of patterns within the available confirmed failure dataset, rather than as definitive estimates of comparative guardrail performance under all crash conditions.

8.2 Issues Potentially of Interest to FDOT

One notable finding is the apparent slow transition within the eMaintenance end-treatment inventory used in this study from the older 27¾-inch guardrail standard to the 31-inch standard. At the time of the eMaintenance inventory extract used in this study, approximately 23 percent of recorded end treatments were associated with 31-inch systems, while approximately 77 percent remained associated with 27¾-inch systems. Because FDOT adopted the 31-inch MGS standard in 2016, this suggests that, roughly a decade after the change in standard, a substantial portion of the statewide inventory still reflects the older height.

This should not necessarily be interpreted as a deficiency, since guardrail replacement occurs gradually through construction, resurfacing, rehabilitation, damage repair, and other asset-management cycles. However, from a programmatic standpoint, the finding suggests that statewide implementation of the newer standard may be proceeding more slowly than some might expect, particularly if the policy objective of the 2016 change was to better align roadside hardware with the modern vehicle fleet. For FDOT, this may warrant additional review of how quickly legacy systems are being replaced, where older-height systems remain concentrated, and whether there are corridors or facility types where accelerated transition would be beneficial.

Another important issue is that vehicle center of gravity height emerged as a stronger indicator of failure mode than guardrail height alone. Over failures were associated with significantly higher vehicle center of gravity heights than Through failures, and the logistic regression showed that increasing center of gravity height significantly increased the odds of an Over failure. This finding is important because it suggests that the safety challenge is not limited to legacy 27¾-inch systems. Rather, it reflects a broader and continuing mismatch between evolving vehicle geometry and fixed roadside hardware. For FDOT, this means that the 31-inch standard may be an improvement over the older standard, but it should not necessarily be assumed to be the final long-term answer as the vehicle fleet continues shifting toward taller SUVs, pickups, and crossovers.

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