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EVALUATION OF INTEGRATED OVERWEIGHT ENFORCEMENT SYSTEM USING HIGH ACCURACY WIM SYSTEM AND NON-PROPRIETARY ALPR SYSTEM

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16. Abstract

The team developed a calibration procedure by comparing four (4) standards, including two U.S. Standards (NIST HB44 and ASTM E1318-09), one European Standard (COST323), and one International Standard (OIML R134-1). This calibration process encompassed testing three prevalent truck types on the BQE at two GVWs (full and empty) and three speeds (post-speed, crawling speed to simulate congestion scenarios, and an average of two) to prove consistent accuracy across different trucks and traffic conditions. Following the sensor installation, the calibration procedure was executed, and the results indicated that the system met the accuracy requirements of ASTM E1318-09 Type III and COST 323 B(10), which mandated 95% compliance. However, it fell short of achieving the target accuracy for B+(7), primarily due to errors in single-axle weight, which were identified in three out of 353 runs. Furthermore, it was not feasible to meet the specified target accuracy in OIML R134-1 F(10) Verification.

The team evaluated the accuracy of the WIM system under congested conditions, with a specific focus on stop-and-go scenarios commonly encountered in urban traffic. Initially, they defined congestion using WIM data. Based on the WIM data, it was found that the maximum flow of the BQE corridor was 3138 vehicles, and the average speed corresponding to the maximum flow was approximately 17 mph, establishing that congestion typically initiates when the average speed falls below this speed. Subsequently, the team designed a range of stop-and-go traffic scenarios to assess the system's accuracy during congested conditions. The results consistently indicated an underestimation of GVW measurements, with several cases showing less than a 5% overestimation.

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Evaluation of Integrated Overweight Enforcement System using High Accuracy WIM System and Non-Proprietary ALPR System

Hani Nassif, PE, PhD
Principal Investigator
Rutgers University, New Jersey
0000-0002-3441-3589

Kaan Ozbay, PhD
Co-PI
New York University, New York
0000-0001-7909-6532

Chaekuk Na, PhD
Research Associate
Rutgers University, New Jersey
0000-0001-5887-2483

Patrick Lou, PhD
Research Associate
Rutgers University, New Jersey
0000-0001-7951-1337

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Executive Summary

The team established a new testbed on the Brooklyn-Queens Expressway (BQE) for overweight enforcement. Initially, the team conducted a thorough evaluation of the BQE roadway profile, utilizing data from NYCDOT and Google Maps to identify the most appropriate segments that aligned with the ASEM E1318-09 standards. After considering various segments, the team chose a location between the Brooklyn Bridge and Manhattan Bridge due to the presence of an existing gantry and traffic patterns. To meet the legal requirement for a notice of liability (NOL), the team proposed two arrays of a double-staggered layout, ensuring uniformity in weighments by sharing the same pavement, traffic pattern, and other conditions. This layout was developed through a collaborative effort between Rutgers/C2SMART, NYCDOT, and Kistler Instrument Corp.

The team developed a calibration procedure by comparing four (4) standards, including two U.S. Standards (NIST HB44 and ASTM E1318-09), one European Standard (COST323), and one International Standard (OIML R134-1). This calibration process encompassed testing three prevalent truck types on the BQE at two GVWs (full and empty) and three speeds (post-speed, crawling speed to simulate congestion scenarios, and an average of two) to prove consistent accuracy across different trucks and traffic conditions. Following the sensor installation, the calibration procedure was executed, and the results indicated that the system met the accuracy requirements of ASTM E1318-09 Type III and COST 323 B(10), which mandated 95% compliance. However, it fell short of achieving the target accuracy for B+(7), primarily due to errors in single-axle weight, which were identified in three out of 353 runs. Furthermore, it was not feasible to meet the specified target accuracy in OIML R134-1 F(10) Verification.

The team evaluated the accuracy of the WIM system under congested conditions, with a specific focus on stop-and-go scenarios commonly encountered in urban traffic. Initially, they defined congestion using WIM data. Based on the WIM data, it was found that the maximum flow of the BQE corridor was 3138 vehicles, and the average speed corresponding to the maximum flow was approximately 17 mph, establishing that congestion typically initiates when the average speed falls below this speed. Subsequently, the team designed a range of stop-and-go traffic scenarios to assess the system's accuracy during congested conditions. The results consistently indicated an underestimation of GVW measurements, with several cases showing less than a 5% overestimation.

The team collaborated with the NYPD Highway Patrol to validate the WIM accuracy. The team provided records of overweight trucks, including GVW, license plates, truck images, and more, while the NYPD verified the gross and axle weights of the violated trucks against legal limits. Based on these tests, the system demonstrated the capability to provide weight data with less than a 10% error in 93.1% of cases.

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Section 1 – Introduction

Highway transportation stands as the predominant mode of goods and services movement in the United States, providing rapid delivery for shipments traveling shorter distances compared to alternative transportation methods. The Federal Highway Administration (FHWA) regulates truck weights on the National Highway System (NHS), setting maximum gross weight limits at 80,000 lbs., axle weights at 20,000 lbs. for single axles and 34,000 lbs. for tandem axles, and implementing the Federal Bridge Formula (FBF) regulation to restrict the weight of specific axle configurations. In contrast, New York State and City maintain stricter standards, with single and tandem axle weight limits set at 22,400 lbs. and 36,000 lbs., respectively, in accordance with NYS Law §385.8 and §385.9. However, trucks often exceed these legal limits to optimize their operations, such as reducing the number of trips. Weigh-in-motion (WIM) stations in New York City reveal that the daily average of overweight (OW) trucks and the magnitude of OW tonnage far exceed those in other regions. This substantial number of daily OW trucks poses a significant threat to the structural integrity of many bridges (Nassif, et al., 2016).

One particular concern revolves around the triple cantilever section of the Brooklyn-Queens Expressway (BQE), which has experienced substantial deterioration due to environmental conditions and the presence of numerous OW trucks. Constructed in the 1940s and 1950s under multiple contracts, this 1.5-mile section of the BQE (triple cantilever) has seen minimal rehabilitation efforts. Consequently, the New York City Department of Transportation (NYCDOT) has outlined plans for its rehabilitation in the next decades. One key element to maintain a safe and efficient regional corridor until the rehabilitation project starts is to reduce the OW trucks effectively by enforcing them.

To address this concern, the team has collaborated with NYCDOT to establish a testbed along the BQE corridor. In this endeavor, the team established a testbed in the northern portion of the triple cantilever, spanning from the Brooklyn Bridge to the Manhattan Bridge. This testbed includes a high-accuracy WIM system designed to analyze site-specific characteristics of overweight trucks (e.g., origin, truck type, OW tonnage) and an automated license plate recognition (ALPR) system to identify these overweight trucks. Based on the initial results from this testbed, the New York State Senate passed legislation in December 2021 to enforce weight restrictions on trucks (NYS Senate, 2021). This enforcement legislation and associated efforts will enhance the resilience of the city's 800 bridges and 18,000 lane-miles of pavement.

The first testbed operated in one lane, limiting its capacity to capture all the overweight trucks crossing the BQE corridor. Therefore, the establishment of a network of WIM stations throughout New York City is imperative to monitor the movement of overweight trucks within the city. In this proposed research, the team will collaborate with NYCDOT to create another testbed equipped with WIM and ALPR systems for all three lanes.

Section 2 – New Smart Roadway Testbed

As part of the BQE testbed project undertaken by C2SMART, the team engaged in a UTC-agency-industry collaborative effort between Rutgers/C2SMART, NYCDOT, and Kistler Instrument Corporation (KIC) to establish an innovative smart roadway testbed in the northern part of the BQE corridor. This state-of-the-art testbed will incorporate eight (8) Quartz sensors and two loops per lane within the Queens-bound roadway of the BQE corridor.

2.1. Criteria for Site Selection

The American Society for Testing and Materials (ASTM) Standards E1318-09 emphasizes the critical importance of WIM station conditions regarding WIM system performance, testing, and evaluation. It is crucial to take precautions to ensure providing and maintaining an excellent operating environment for the WIM sensors and system. System performance can deteriorate over time, particularly when the operating environment deviates from established standards.

According to ASTM E1318-09, several WIM site requirements are specified, encompassing an area within 200 ft in advance of and 100 ft beyond the WIM sensors. These requirements are as follows:

1) **Horizontal Alignment:** It is advisable to design a straight roadway with a radius of greater than 5700 ft. This configuration prevents vehicles from running into the middle of the lane when the road curves.
2) **Longitudinal Alignment (Profile):** It is recommended to avoid steep inclines as vehicles tend to alter their speed when traversing WIM sensors. A recommended profile would feature a gradient of 1% or less.
3) **Cross Slope:** It is suggested a cross slope of less than 3% should be avoided as it can lead to an imbalance between the left and right wheels of vehicles.
4) **Lane Width and Markings:** To ensure that drivers stay within their lane when traversing WIM sensors, it is crucial to maintain wider lanes (12 ft or wider) with clear lane markings. Lane shifting or overlap can create errors in WIM data.
5) **Surface Smoothness:** It is advisable to comply with the International Roughness Index (IRI) and roadway rutting (Rut) requirement as factors that can impact the dynamic interaction between vehicle suspensions and the pavement
6) **Other Requirements:** When selecting WIM stations, it is recommended to account for the availability of adequate electrical power and a reliable data communication link. These components are crucial for the station's effective operation.

2.2. Selection of the New WIM Site Location

The team conducted a thorough evaluation of the BQE roadway profile, referencing data from NYCDOT and utilizing Google Maps to identify the most appropriate segments complying with the ASEM E1318-09 at large. While it's worth noting that all segments might not fully align with the requirement per ASTM E1318-09, the team diligently strived to identify the most appropriate segments for overweight enforcement practice within the BQE corridor. Figure 1 provides an overview of the BQE corridor under consideration for site selection. In Figure 1, Segment 1 corresponds to the triple cantilever bridge sections, which necessitates exclusion because of the higher vehicle dynamic on the bridge. Segment 2, characterized by significant curves and elevation changes, also does not comply with the profile requirement and should consequently be excluded. Segment 3, residing on the retaining wall and exhibiting less curved roadway compared to two other segments, warranted a more detailed review.

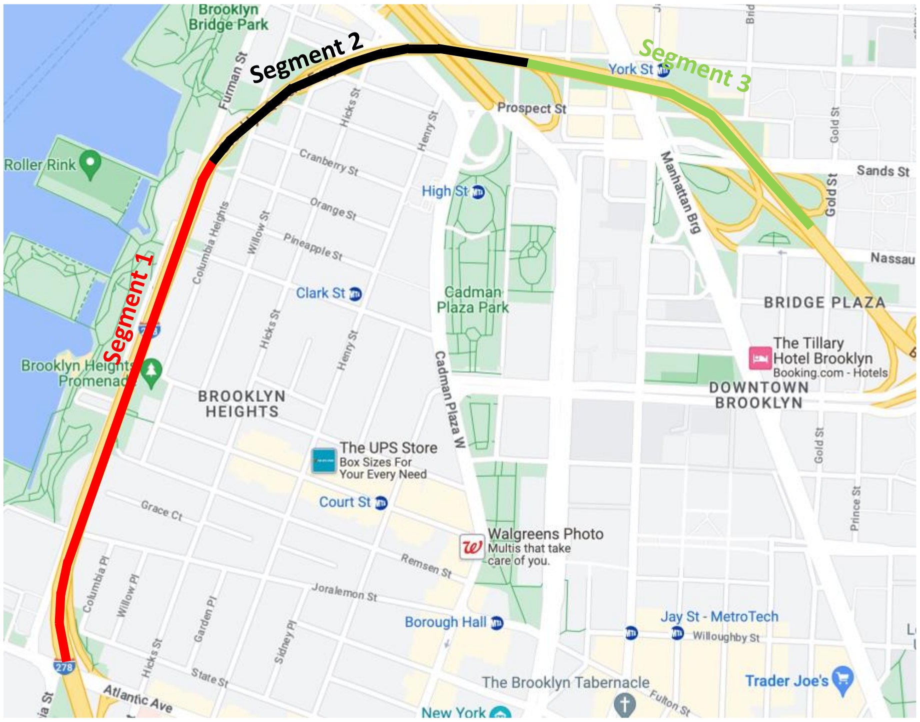


Figure 1: BQE Corridor Segments

Four subsegments within Segment 3 of the Queens Bound direction were selected. Figure 2 shows the four segments from QB1 to QB4 that were carefully chosen for the new testbed. These subsegments were delineated between local roads, and the geometries were determined through analysis of Google Earth profile data. Table 1 provides a summary of the advantages and disadvantages associated with each candidate.

QB1: Adams St. ~ Pearl St.

This subsegment features a slope ranging from -2% to +2% and exhibits a concave profile, featuring a straight length of 200 feet. Notably, it aligns with the existing testbed which has previously demonstrated its capability to yield relatively robust WIM data about vehicle weights and traffic patterns.

QB2: Pearl St. ~ Jay St.

In this subsegment, an uphill profile with a +2% slope is present, along with a straight stretch spanning 200 feet.

QB3: Jay St. ~ Prospect St.

This subsegment introduces a curved roadway extending over 250 ft with a slope ranging from +2% to 0%. Its profile is convex in nature.

QB4: Prospect St. ~ Sands St.

QB4 represents a downhill subsegment with a -2% slope, encompassing both partially curved and straight roadway.

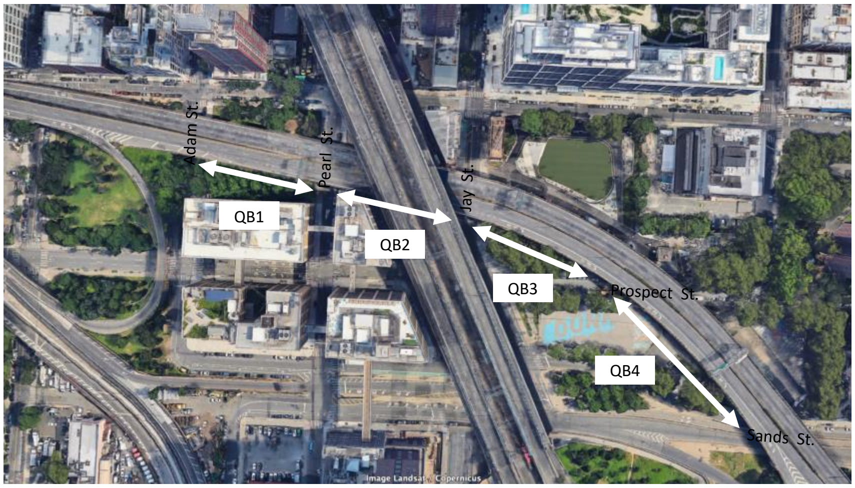


Figure 2: Subsegments and Geometries within Segment 3

Table 1. Features and Pros/Cons of the Candidates in Queens Bound

Sub-segment	QB1	QB2	QB3	QB4
Existing Infrastructure?	Existing gantry	Manhattan bridge but vibration/fatigue issue	N/A.	Existing gantry
Permanent Power?	Available	N/A. Extra work required.	N/A. Extra work required.	N/A. Extra work required.
Space behind guiderail?	Yes	No	No	No
Traffic?	Two lanes with shoulder	Two lanes with shoulder. Should becoming traffic lane	Two thru lanes and one exit lane	Two thru lanes and one exit lane

After the assessment of the subsegments, QB1 would be the most appropriate location for several compelling reasons.

- **Utilization of Existing Gantry**: The presence of the overhead gantry could be leveraged for the installation of ALPR systems and power supply lines.
- **Space for Equipment and Maintenance**: The availability of space behind the guiderail could present a practical area for the setup of various sensors or systems while allowing for ease of maintenance.
- **Traffic**: QB1 encompasses two lanes to all traffic.

2.3. Designing the Sensor and System Layout

WIM sensors offer various layout options ranging from configurations with 4, 6, to 8 sensors depending on the target accuracy. Table 2 shows the typical layout of Quartz WIM sensors. The "2-row" is commonly employed when traffic congestion is not anticipated. The "double staggered" is recommended for use in scenarios where congestion is expected. The "3-row" is suggested for enforcement purposes as it provides a higher level of accuracy compared to the 4-sensor layouts. The "3-row tilt" is a specialized layout to employ layout when the identification of single or dual tires of the vehicle is necessary

While the addition of extra sensors can enhance accuracy, it is important to consider that it may also entail increased costs. Therefore, it is essential to determine an optimized layout by balancing between accuracy and overall cost without compromising either aspect.

Table 2. WIM Sensor Typical Layout

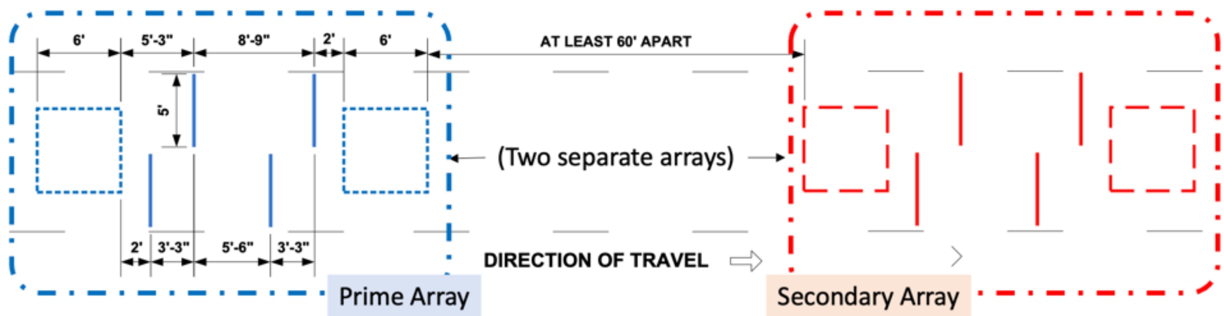
Category	2-row	Double staggered	3-row	3-row tilt
Layout				
Number of Quartz	4	4	6	6
Target Accuracy	5%	5%	3.5%	4%
Stop & Go	No	Yes	Yes	Yes
Single/Dual Tire Detection	No	No	No	Yes
Additional Est. Cost	-	+10%	+20%	+30%

In general, legal proceedings typically two independent measurements to validate any violation. Similarly, the overweight enforcement legislation mandates two weighments to issue a notice of liability (NOL) to the truck owner. Accordingly, the team proposed two viable options to fulfill this requirement as summarized in Figure 3.

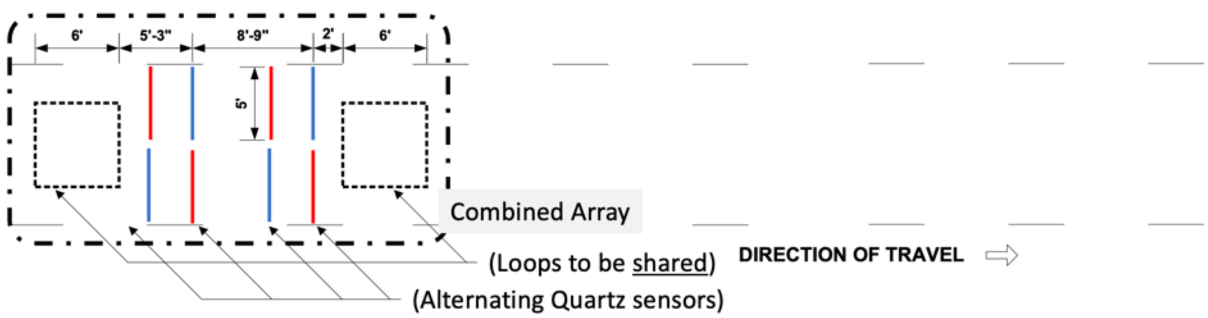
Option 1 involves the installation of two separate arrays, represented by the "blue" and "red" colors in Figure 3(a), at a minimum distance of 60 feet apart. The 60-foot distance ensures the decoupling of any vehicle dynamic effects between the two arrays. One key advantage of Option 1 is the easy maintenance – each sensor can be repaired or replaced without impacting the functionality of others. However, It is worth noting that Option 1 may result in varying accuracy levels between arrays due to disparities in pavement conditions, traffic patterns, and other constraints.

Option 2 entails the installation of two independent arrays at the same location. This creates a similar configuration similar to the 4-row array but with a dual-double-array layout. The advantage of Option 2 lies in the uniformity of the two weighments since they share the same conditions – pavement, traffic pattern, and other constraints. However, It is worth noting that in the event of sensor failure, Option 2 requires the replacement of two sensors as they are embedded within the same slot.

Based on the collaborative partnership between Rutgers/C2SMART, NYCDOT, and KIC, Option 2 was deemed most appropriate for this testbed. Consequently, the final layout for the new testbed has been developed, as illustrated in Figure 4.



(a)



(b)

Figure 3: Proposed Layout for Two Independent Weighment; (a) Option 1; and (b) Option 2

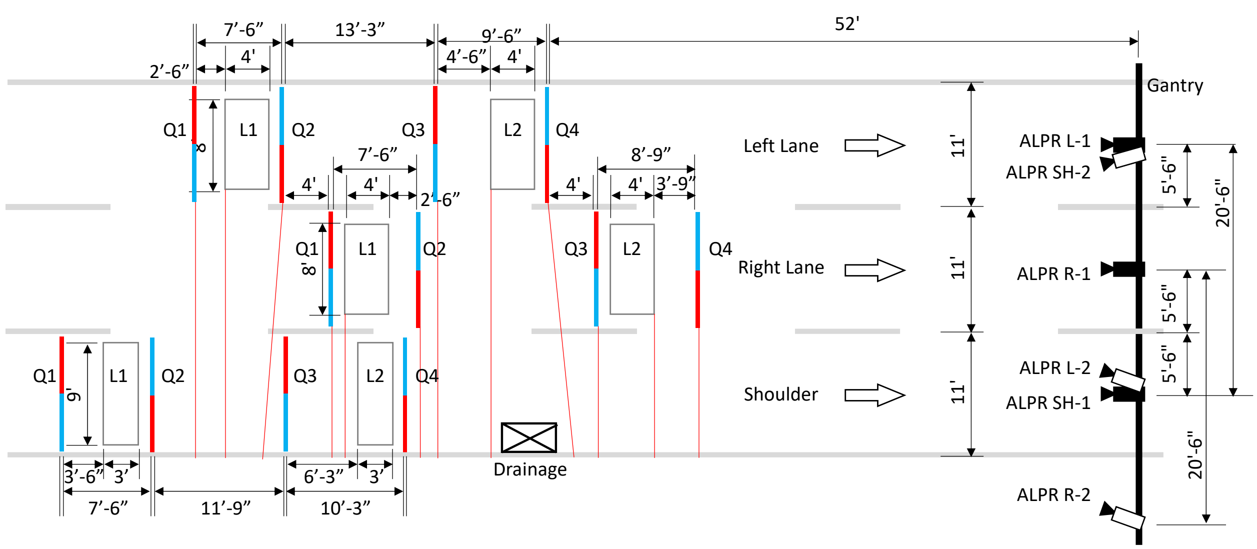


Figure 4: Final Layout for Two Independent Weighment; (a) Option 1; and (b) Option 2

2.4. Installation of WIM Sensors

The WIM sensor installation was executed in three distinct stages: (1) the preparation of a new pavement, (2) marking and cutting the sensor layout, and (3) the actual sensor installation.

In the first stage, a new Portland Cement Concrete (PCC) was poured, followed by the micro-milling of the new PCC using a Diamond grinder to ensure compliance with the profile requirement outlined in ASTM E1318-09. Following the micro-milling process on the new PCC (Figure 5(a)), a 16-ft straight edge was employed to assess the smoothness aligning with the criteria specified in Section 6.1.5. in ASTM E1318-09 (Figure 5(b)).

Figure 5: Diamond Grinding of the New PCC Validation of Smoothness Using a 16-ft Straight Edge

The second stage covers the delineation of sensor locations and the pavement-cutting process. During this phase, the contractor marked the sensor locations and then used a spray to draw the necessary lines for the guidance provided in Figure 4. Once the drawing process was concluded, the contractor employed two wet concrete saws for the subsequent step – one concrete saw equipped with a 1/8" blade for crafting Quartz sensor slots, and another with a 3/8" blade for cutting cable slots as shown in Figure 6. The Quartz sensor slots were approximately 3 inches wide and 2.25 inches deep, while the cable slots measured 3/8 inches in width and 2 inches in depth.

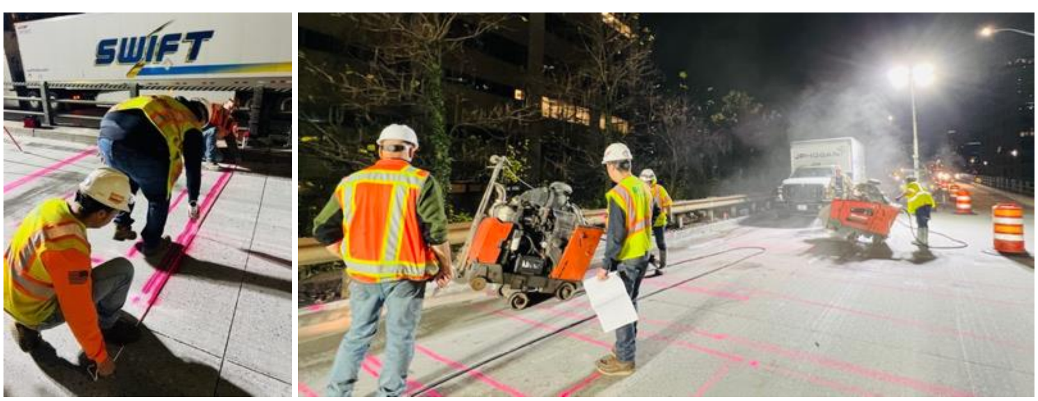


Figure 6: Marking sensor location and Sawcutting for Quartz sensor and loop

The final phase comprises an epoxy application, sensor installation, epoxy curing, and final treatment. Once the slot was cleaned and dried, epoxy was carefully mixed and poured into the slot. Subsequently, the Quartz sensors were carefully positioned within the epoxy to ensure the sensors did not come into direct contact with the slot surface. Then, 100 lbs of weight was evenly distributed along the sensor to fix the sensor location until the epoxy was fully cured. Any surplus epoxy was then ground off to create a uniform and smooth profile. Figure 7 summarizes the overview of the installation procedure

Figure 7: Sensor installation – Epoxying, Installing, Curing, and Grinding.

Section 3 – Calibration of WIM System

3.1. Comparison between Standards

Among various international standards and specifications, four (4) standards and specifications, National Institute of Standards and Technology (NIST) Handbook (HB) 44 Section 2.25, ASTM E1318-09, COST 323, and International Organization of Legal Metrology (OIML) R134-1 have been widely used in the U.S., Europe, and other countries to evaluate WIM system performance. Each standard has its advantages and disadvantages, catering to various applications and operational conditions for WIM systems used in the automated enforcement of overweight (OW) trucks on regular highways. Consequently, individual jurisdictions must develop their standards, specifications, and test procedures to comply with their respective regulations and legislation. It is therefore crucial to understand the different requirements among these standards when considering their utilization in the US for automated OW enforcement to minimize unnecessary additional work between different jurisdictions in the country.

NIST HB44 Section 2.25, originally developed based on the Scale Specification (Section 2 dedicated to Scale), lacks sufficient detail for WIM enforcement. ASTM E1318-09 serves as a good starting point for developing the specification in the U.S., as it covers a majority of aspects of WIM enforcement, although it is not as comprehensive as COST 323 and OIML R134-1. COST 323 provides a viable example for adoption, but it entails a significant number of calibration runs and may require modifications to suit the US context, considering its original design for Europe. On the other hand, OIML R134-1 is excessively stringent, imposing a 100% compliance requirement with very low error.

NIST HB44 Section 2.25 is specifically designed for Class A, which is equivalent to ASTM Type I (GVW 10% and Axle 20%), and it is not intended for enforcement purposes. ASTM E1318-09 Type III is designed for enforcement with 6% GVW error and 95% compliance; however, it is not yet approved in the US for enforcement. As for COST 323, classes ranging between A(5) (GVW 5%, Axle 8%, and Tandem 7%), B+(7) (GVW 7%, Axle 11%, and Tandem 10%), and B(10) (GVW 10%, Axle 15%, and Tandem 13%) are nearly identical to ASTM Type III. In the case of OIML R134-1, Class F10 closely approximates the target accuracy of ASTM E1318-09 Type III. Class F10 entails a 5% and 10% error of GVW in verification and service, respectively, as well as an 8% and 16% error of axle weight in verification and service, respectively. Although OIML R134-1 and COST 323 offer higher accuracy, their implementation is challenging due to their excessively strict accuracy requirements. ASTM, NIST, and COST standards necessitate 95% compliance, while OIML R134-1 mandates 100% compliance.

FHWA Class 9 or equivalent covers all standards. In general, each standard seeks for prevailing trucks. ASTM E1318 requires two Class 9 trucks with 90+% of GVWR - one typical 3S2 Class 9 truck, and one Class 9 with a split tandem. NIST requires one Class 9 with up to 80 kips of GVW and one Class 5 with up to 10 kips of GVW. OIML R134-1 requires a 2-axle FHWA Class 5 equivalent truck and a minimum of 2 additional trucks among Class 5/6 with a drawbar trailer, Class 6~7, or Class 8 ~10 with fully loaded and unloaded cases. COST 323 requires a minimum of 3-4 trucks according to European Classifications, which are similar to Class 3, Class 5/6/7 (with and without a trailer), and Class 8/9/10.

FHWA Class 9 or its equivalent encompasses all the standards. Generally, each standard focuses on representative truck configurations. ASTM E1318-09 necessitates the use of two Class 9 trucks, both with 90% or more of their GVWR. One of the Class 9 trucks is a typical 3S2 Class 9 truck, while the other is a Class 9 with a split tandem. NIST requires the use of one Class 9 truck with a maximum GVW of 80 kips, along with one Class 5 truck with a maximum GVW of 10 kips. COST 323 mandates a minimum of 3-4 trucks, adhering to European classifications. These classifications are similar to Class 3, Class 5-7 (with and without a trailer), and Class 8-10. OIML R134-1 requires the use of a 2-axle truck equivalent to FHWA Class 5, as well as a minimum of two additional trucks selected from the following categories: Class 5/6 with a drawbar trailer, Class 6/7, or Class 8-10. These trucks must be tested in both fully loaded and unloaded conditions.

All standards require the calibration trucks to be tested at various speeds, encompassing a wide range of speeds. ASTM E1318-09 mandates the use of three (3) speeds for calibration and two (2) speeds for verification. The three calibration speeds consist of a speed of 5 mph lower than the maximum speed, a speed of 5 mph higher than the minimum speed, and the average of these two speeds. The difference between the two aforementioned speeds must be at least 20 mph. The two verification speeds exclude the average speed. NIST HB44 Section 2.25 specifies that the calibration should be conducted at the posted speed or a speed 20% below the posted speed. COST 323 specifies testing at three (3) speeds: the mean operating speed (Vm), 0.8 Vm, and 1.2 Vm. Similarly, OIML R134-1 requires testing at three

(3) speeds: one near the maximum operating speed, one near the minimum operating speed, and one at the center of the range of operating speeds.

All standards require a certain number of test runs to ensure the repeatability of the WIM system. ASTM E1318-09 necessitates 6 runs for calibration and 10 runs for verification per truck and speed. For calibration, 2 runs are performed at each speed (3 speeds) in the middle of each lane. For verification, a minimum of 3 runs are conducted in the middle of each lane at two speeds, while one run is carried out near the left and right lane edges, also at two speeds. NIST HB44 Section 2.25 mandates a minimum of 20 runs per truck and 40 runs in total. This comprises 5 runs near each left and right lane edge, as well as 10 or more runs in the middle of the lane. COST 323 calls for a minimum of 110 runs in total according to Test Plan No2.2. This encompasses 2-3 speed levels and both fully-loaded and half-loaded conditions. OIML R134-1 requires a minimum of 30 runs per truck and 90 runs in total. This entails 5 runs at 3 speeds with both fully loaded and unloaded conditions.

Based on the comparison between four (4) standards, the following calibration procedures were proposed for this project. Table 3 summarizes the number of runs proposed.

- **Trucks**: three (3) trucks of FHWA Class 9, Class 6, and Class 5.
    - Class 9 and Class 5 meet all four (4) standards and specifications.
    - Class 6 meets only two (2) standards and specifications of OIML R134-1 and COST 323. This was selected to cover different types of heavy trucks.
- **Gross Weights**: two (2) weights of full and empty
- **Speeds**: three (3) speeds of low, high, and average.
- **Number of Runs**: A minimum of 45 runs per truck
    - Full load for 30 runs
    - Empty load for 15 runs

Table 3. Number of Tests per Test Vehicle

Category	Speed
Full Load (30 runs)	High Speed (10 runs)
	Low Speed (10 runs)
	Operation Speed (10 runs)
Empty Load (15 runs)	High Speed (5 runs)
	Low Speed (5 runs)
	Operation Speed (5 runs)
Total (45 runs)	15 runs x 3 speeds

3.2. WIM Calibration and Demonstration

3.2.1. Calibration and Results

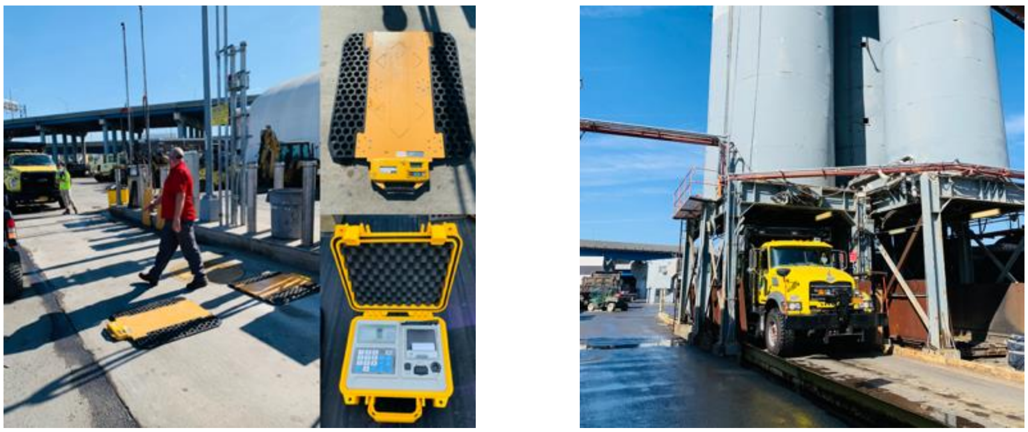
The WIM system was calibrated using the proposed calibration procedure in Section 4.1. To comply with the calibration test, three (3) trucks were selected from the NYCDOT fleet as shown in Figure 8. Before the calibration test, all axle spacings and weights were measured.

All the wheel weights and GVW were measured using four portable scales, as shown in Figure 9(a). Additionally, the GVW was measured using a static scale, as depicted in Figure 9(b). In some instances, the GVW measured by the static scale differed from that measured by the portable scales. Consequently, the wheel weights and axle weights were adjusted proportionally based on the GVW obtained from the static scale. Table 4 provides an overview of the GVW for all calibration trucks.

The distance between the center of the two axles, known as the axle spacing, was measured using a steel measuring tape. Additionally, the track width between the center of the two wheels was measured. Figure 10 provides visual examples of these measurements. It is worth noting that Class 9 and Class 6 trucks were equipped with multi-leaf suspension. On the other hand, the Class 5 truck was equipped with spring suspension.

(a) (b) (c)

Figure 8: Calibration Trucks; (a) R1-Class 9 (886T), (b) R2-Class 6 (243FF), and (c) R3-Class 5 (106E)



(a) (b)

Figure 9: Weight Measurement using Portable Scale and Static Scale; (a) portable, and (b) static

(a) (b)

Figure 10: Axle Spacing Measurements; (a) wheel width, and (b) axle spacing

Table 4. Summary of Calibration Trucks

Truck & FHWA Classification	Weight	GVW	Steering Axle	Drive Tandem	Trailer Tandem
R1 – Class 9 (886T)	Full	80,380 lb.	11,096 lb.	37,526 lb.	31,758 lb.
	Empty	47,860 lb.	12,114 lb.	20,926 lb.	14,820 lb.
R2 – Class 6 (243FF)	Full	72,800 lb.	21,884 lb.	50,916 lb.	-
	Empty	39,600 lb.	17,408 lb.	22,192 lb.	-
R3 – Class 5 (106E)	Full	33,900 lb.	10,635 lb.	23,265 lb.	-
	Empty	24,040 lb.	10,550 lb.	23,080 lb.	-

The calibration test was conducted over a span of two days, covering different scenarios throughout the day. On the first day, the WIM system was calibrated using full-load trucks for a total of 26 runs. The second day involved empty trucks running the WIM site, completing 22 runs. To ensure accuracy, two different loads were employed to demonstrate that the system's performance is independent of the weight being carried. During the calibration process, three trucks ran in a series, maintaining a minimum spacing of 100 ft between each truck to minimize any potential interactions. All trucks were instructed to drive in the center of the lane at a consistent speed without any acceleration or deceleration unless safety concerns necessitated a deviation between a 200 ft distance upstream and a 100 ft distance downstream. Three different speeds were tested, 45 mph, 30 mph, and 10 mph, to account for various traffic conditions that may arise.

Throughout the calibration test, the WIM system was designed to detect any abnormal behavior exhibited by the trucks, such as acceleration, braking, running along the edge of the lane, high dynamic effects, imbalance, and more. Figure 11 illustrates an error case where a truck steered towards the edge of the lane, causing the left wheel to fall outside the sensor load-receiving element, resulting in errors in axle weight and gross weight measurements. Acceleration and braking actions also introduced high dynamic effects, leading to increased axle measurement errors. During data analysis, such erroneous data points were excluded to accurately evaluate compliance with different standards and specifications.

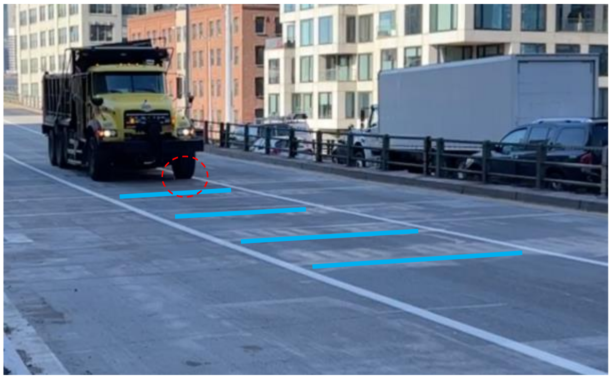
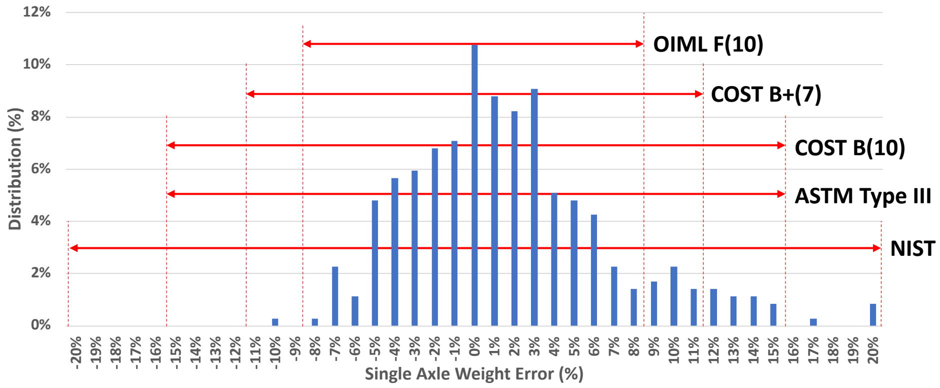


Figure 11: Error Case – Running on the Lane Edge

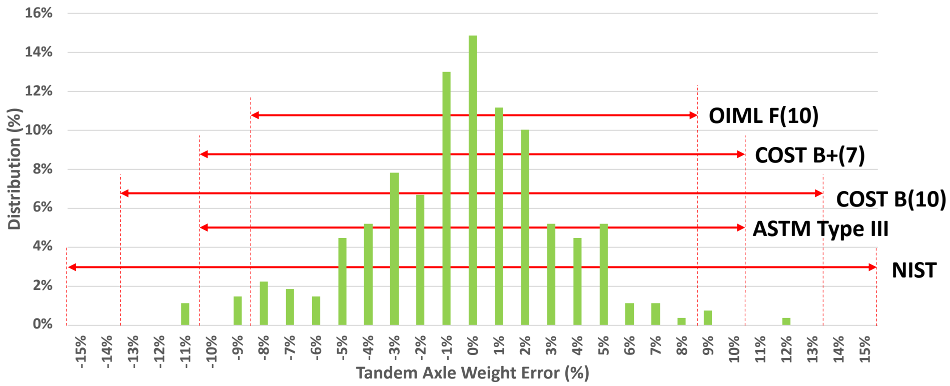
Table 5 provides a summary of compliance with the target accuracy for single, tandem, and gross weights, while Figure 12 illustrates the distribution of weight errors for each of these categories. All single axle weights, tandem axle weights, and gross vehicle weights achieved the desired target accuracy levels of 20%, 15%, and 10%, respectively, with a compliance rate of 100%. Similarly, this WIM system successfully met the ASTM E1318-09 Type III accuracy targets of 15%, 10%, and 6%, respectively, with a compliance rate of 95%. The system demonstrated accurate measurements for COST 323 B(10) accuracy requirements. However, it fell short of meeting the target accuracy for B+(7), primarily due to errors in single axle weight, which were missed in three out of 353 runs. On the other hand, the system did not comply with the target accuracy specified in OIML R134-1 F(10) In Verification.

Considering these results, it can be concluded that the target accuracy outlined in the proposed procedure is attainable. Figure 12 visually indicates the error distribution and the axle weights might be overestimated, while the tandem axle weight and gross vehicle weight, which involve combinations of multiple axle weights, could be slightly underestimated.

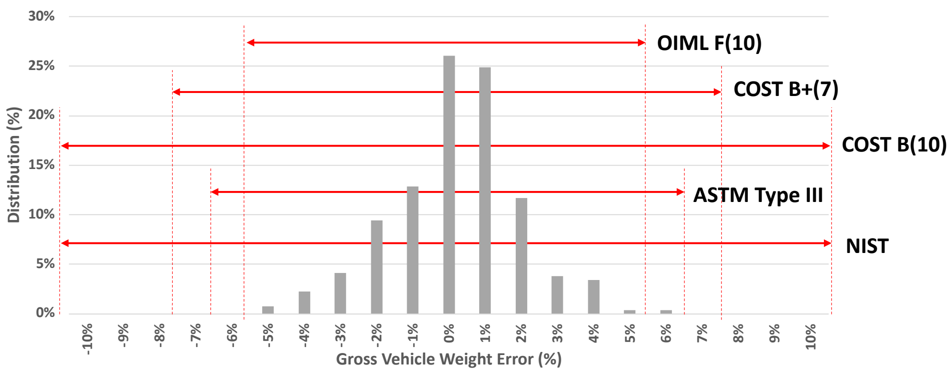


(a)

Figure 12: Calibration Test Run Error Distribution per Standard; (a) Single Axle Weight, (b) Tandem Axle Weight, and (c) Gross Vehicle Weight



(b)



(c)

Figure 12: Calibration Test Run Error Distribution per Standard; (a) Single Axle Weight, (b) Tandem Axle Weight, and (c) Gross Vehicle Weight (continued)

Table 5. Calibration Results

Standard/ Specification	Target Accuracy (Single/Tandem/Gross)	Compliance	Single	Tandem	Gross
NIST HB44 2.25	Class E: 20%/15%/10%	100%	100%	100%	100%
ASTM E1318-09	Type III: 15%/10%/6%	95%	98.9%	98.5%	100%
COST 323	B(10): 15%/13%/10%	95%	98.9%	100%	100%
	B+(7): 11%/10%/7%	95%	94.3%	98.5%	100%
OIML R134-1	F(10): 8%/8%/5%	100%	88.4%	94.1%	98.9%

Section 4 – Evaluation of WIM Accuracy during Congestion

The objective of this test was to assess the accuracy of the WIM system in congested conditions, specifically focusing on the stop-and-go scenarios commonly encountered in urban traffic.

4.1. Congestion Condition

The team processed and analyzed WIM data for several months before altering the lane configuration from 3 to 2 lanes. This analysis aimed to identify the average hourly speed of the BQE corridor. Figure 13 shows the average hourly speed for different time periods, including weekdays (Monday to Friday, inclusive of holidays), weekends (Saturday and Sunday), and the entire week (Monday to Sunday). Before altering the land configuration, weekday afternoons exhibited lower average speeds (< 20 mph) compared to mornings and evenings (> 20 mph). Particularly during the peak congestion hours between 4 pm and 7 pm, speeds dropped below 10 mph. Figure 13 also shows recent speed data collected by the NYCDOT after altering the lane configuration to 2 lanes. Following the lane reduction to two lanes, average speeds decreased further.

When the speeds before and after altering the lane configuration, the speed during the most congested time (3 pm – 7 pm) remained similar (9.4 mph → 7.8 mph, -17%), and the speed overnight (6 pm – 6 am the next day) also remained similar (25.1 mph → 28.1 mph, +12%). However, significant reductions in average speeds were observed during all other hours. Between 10 am and 3 pm, speeds dropped from 18.8 mph to 9.3 mph (-50%). Between 6 am and 10 am, speeds decreased from 24.2 mph to 13.2 mph (-45%).

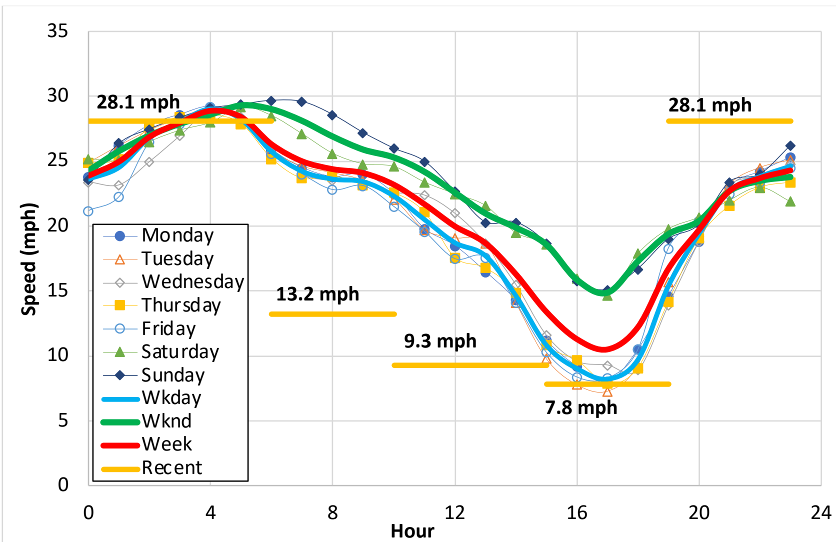


Figure 13. Average Speed per Hour

4.1.1. Traffic Model – Greenshield's Model

Greenshield's model was to develop an uninterrupted and continuous traffic flow model capable of predicting and explaining trends observed in real traffic flows. While it's important to note that Greenshield's model is not flawless, it offers a reasonably accurate and relatively straightforward representation. The fundamental assumption is that speed and density (number of vehicles per mile) are linearly related under uninterrupted traffic flow. Based on this assumption, the relationship between flow (the number of vehicles per hour) and speed yields a parabolic trend, as shown in Figure 14. This graph clarifies that as flow increases, speed initially rises until it reaches the maximum capacity of the corridor. Once this maximum capacity is reached, congestion ensues, leading to a subsequent decrease in speed.

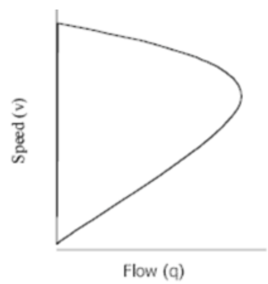


Figure 14. Relationship between Speed and Flow per Greenshield's Model

The team utilized Greenshield's model to analyze the maximum flow (number of vehicles per hour) of the BQE corridor. Figure 15 shows the relationship between average hourly speed and the hourly number of vehicles. It becomes evident that the average speed begins to decline once the flow surpasses roughly 3,000 vehicles per hour. At the point of maximum flow, the average speed is about 17 mph, suggesting that congestion is likely to start when the average speed drops below 17 mph.

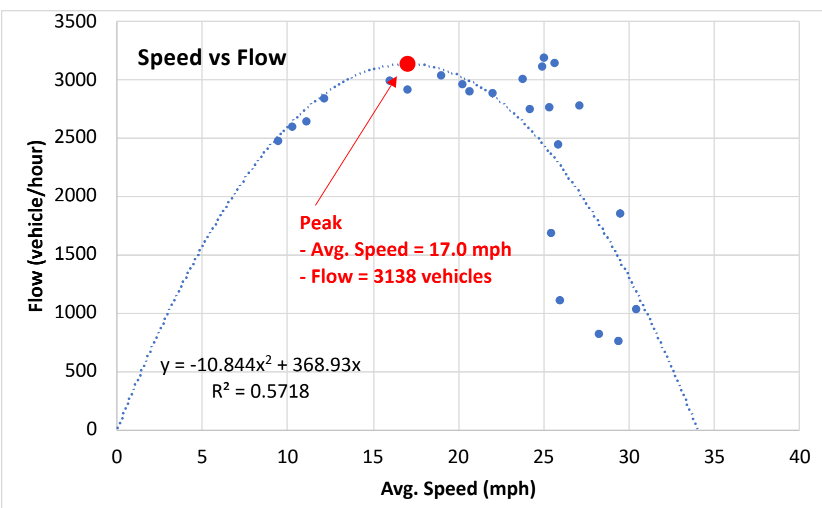
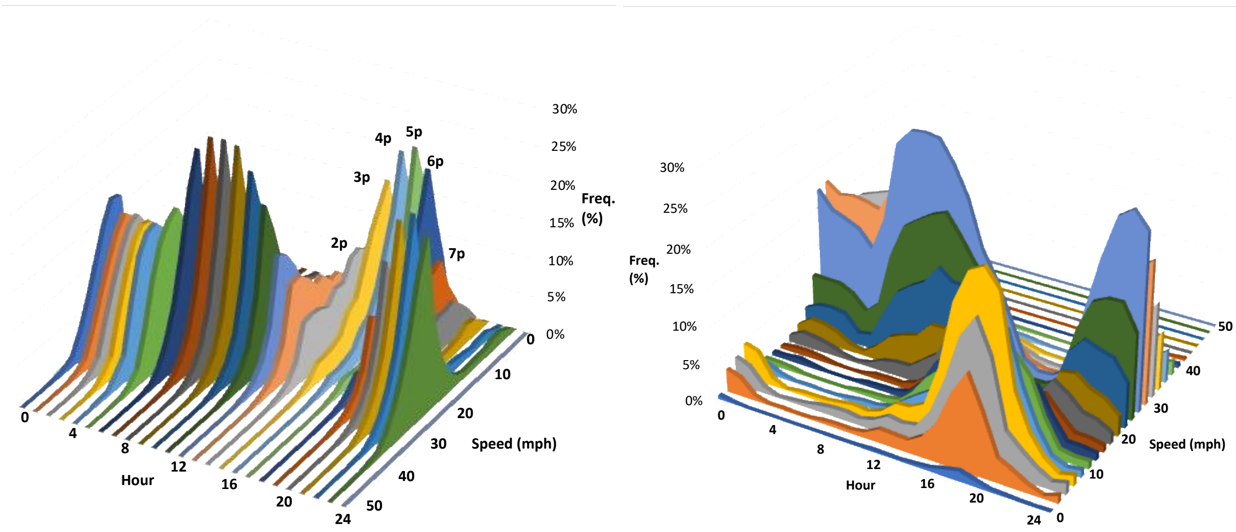


Figure 15. Relationship between Speed and Flow under 2-Lane Configuration

4.1.2. Analysis of Vehicle Frequency per Hour and Speed

Figure 16(a) shows a 3D histogram depicting the average vehicle speed per hour, while Figure 16(b) displays a 3D histogram representing the hours per speed bin. Table 6 provides a summary of congestion frequency and flow for all vehicles and trucks. In this context, congestion refers to situations where the percentage of vehicles traveling at or below the critical speed of 17 mph is significant. It shows that the peak speeds at each hour remained above 17 mph until 1 pm. Subsequently, after 1 pm, peak speed decreased to 17 mph or less. The peak speeds resumed to levels exceeding 17 mph after 8 pm. Furthermore, Table 6 demonstrates that once the flow exceeded approximately 3000 vehicles at 1 pm, more than half of the vehicles (> 50%) were traveling at speeds below 17 mph between 2 pm and 7 pm.



(a) **(b)**

Figure 16. Vehicle Speed Frequency; (a) per Hour and (b) per Average Speed

The findings indicate that congestion occurred between 2 pm and 7 pm. Although the average speed during congestion remained below 17 mph, determining the precise number of vehicles experiencing stop-and-go conditions is challenging. Figure 17 shows a speed histogram and cumulative frequency distribution for all trucks during congestion. It shows that the predominant dominant speed was 6 mph, suggesting that trucks traveling below 4 mph (below this critical speed) likely encountered stop-and-go conditions. Table 7 summarizes two different scenarios. If a speed threshold of 4 mph is considered for identifying stop-and-go conditions**,** the estimated percentage of trucks undergoing the stop-and-go condition (speed < 17 mph) would be 17%. Alternatively, if the cut-off speed is lowered to 2 mph, the estimated percentage of trucks facing stop-and-go conditions would be reduced to 3%.

Table 6. Congestion Frequency and Flow for All Vehicles and Trucks

Hour	Frequency		Flow (Veh/Hour)	
	< 17 mph	> 17 mph	All Vehicles	Trucks
0	15.0%	85.0%	1642	106
1	12.8%	87.2%	1085	118
2	4.9%	95.1%	809	128
3	1.6%	98.4%	743	150
4	1.5%	98.5%	1013	184
5	1.3%	98.7%	1832	252
6	1.9%	98.1%	2765	319
7	4.1%	95.9%	3121	308
8	5.0%	95.0%	3174	303
9	4.5%	95.5%	3093	331
10	8.0%	92.0%	2985	352
11	18.4%	81.6%	2852	329
12	28.7%	71.3%	2926	324
13	36.9%	63.1%	3016	295
14	57.3%	42.7%	2986	239
15	80.9%	19.1%	2832	185
16	88.8%	11.2%	2599	159
17	91.0%	9.0%	2469	145
18	84.7%	15.3%	2628	120
19	50.3%	49.7%	2913	109
20	27.6%	72.4%	2901	112
21	10.9%	89.1%	2713	108
22	6.5%	93.5%	2729	123
23	8.0%	92.0%	2417	121

Table 7. Estimated Truck Percentage per Speed

	Speed considered as stop-and-go	% of trucks during congestion (2p-7p)
Scenario 1	< 4 mph	17%
Scenario 2	< 2 mph	3%

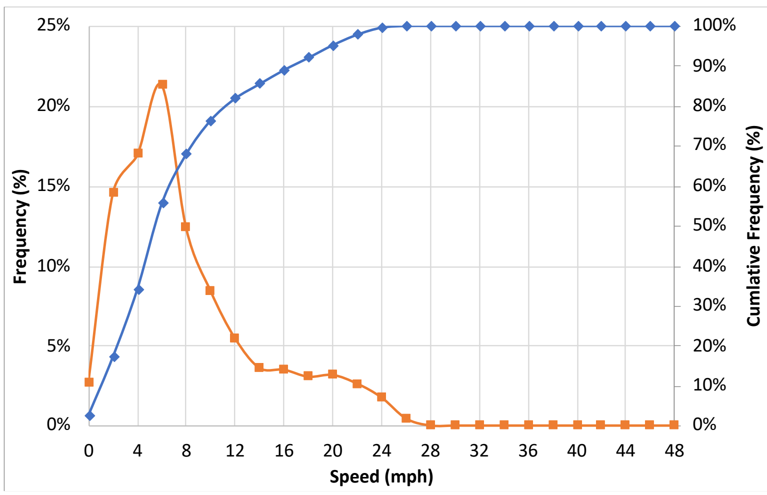


Figure 17. Frequency and Cumulative Frequency per each Speed Bin

4.1.3. Hourly Distribution of Truck Traffic

Table 8 and Figure 18 summarize an overview of the vehicle count per hour, while Table 9 and Figure 19 detail the truck count per hour. Additionally, Table 10 and Figure 20 present the number of OW trucks per hour. The data indicates a consistent number of vehicles, exceeding 2500 vehicles per hour, throughout the daytime hours (from 7 am to 9 pm). In Table 8 and Figure 18, a slight reduction is evident between 4 pm and 6 pm, possibly attributed to congestion. In Table 9 and Figure 19, the number of trucks remained relatively steady between 6 am and 1 pm. However, the number of OW trucks exhibited a different pattern compared to the overall truck count. While most OW trucks were observed during typical daytime hours (between 4 am and 12 pm), there was a notable increase in OW trucks between 8 pm and 10 pm.

Table 8. ADT per Hour

Hr	Mon	Tues	Wed	Thu	Fri	Sat	Sun	Wkdy	Wknd	Week
0	1548	1513	1720	1771	1658	2154	2529	1642	2342	1842
1	949	950	1188	1146	1191	1596	1999	1085	1798	1288
2	723	729	879	815	897	1285	1414	809	1350	963
3	663	667	815	754	817	1095	1228	743	1162	863
4	959	951	1060	1034	1060	1159	1170	1013	1165	1056
5	1798	1798	1883	1864	1818	1238	1029	1832	1134	1633
6	2781	2718	2792	2789	2743	1774	1226	2765	1500	2403
7	3229	3134	3088	3029	3127	2361	1618	3121	1990	2798
8	3321	3199	3105	3147	3096	2823	2124	3174	2474	2974
9	3191	3087	3080	3063	3045	3177	2568	3093	2873	3030
10	3072	2862	2987	3049	2957	3341	3017	2985	3179	3041
11	2868	2655	2864	2887	2987	3503	3267	2852	3385	3004
12	2833	2792	3028	2848	3129	3592	3362	2926	3477	3083
13	3002	2857	3084	2977	3161	3605	3440	3016	3523	3161
14	2956	2813	2992	3058	3113	3593	3479	2986	3536	3143
15	2846	2659	2704	2963	2988	3572	3453	2832	3513	3026
16	2644	2434	2472	2731	2713	3462	3297	2599	3380	2822
17	2511	2363	2407	2561	2504	3301	3189	2469	3245	2691
18	2616	2554	2499	2650	2820	3330	3152	2628	3241	2803
19	2784	2850	2768	2959	3203	3371	3166	2913	3269	3014
20	2677	2926	2819	2945	3137	3322	3091	2901	3207	2988
21	2458	2786	2669	2660	2990	3335	2965	2713	3150	2838
22	2477	2793	2655	2773	2949	3252	2876	2729	3064	2825
23	2172	2478	2316	2419	2700	3147	2389	2417	2768	2517

Table 9. ADTT per Hour

Hr	Mon	Tues	Wed	Thu	Fri	Sat	Sun	Wkdy	Wknd	Week
0	77	111	111	115	116	95	49	106	72	96
1	89	121	123	125	131	111	48	118	80	107
2	99	133	135	138	134	105	42	128	74	112
3	123	155	151	161	158	98	35	150	67	126
4	155	189	192	189	193	103	31	184	67	150
5	231	264	253	253	260	114	32	252	73	201
6	314	318	319	323	322	150	44	319	97	256
7	300	313	301	301	324	161	54	308	108	251
8	306	309	292	296	313	164	62	303	113	249
9	337	333	322	320	343	158	54	331	106	267
10	355	349	347	353	357	135	53	352	94	278
11	329	316	324	323	351	114	46	329	80	258
12	314	316	329	313	349	113	47	324	80	254
13	301	280	289	305	302	103	45	295	74	232
14	239	236	229	244	246	89	40	239	65	189
15	189	184	164	188	198	79	43	185	61	149
16	162	158	148	155	173	74	49	159	62	131
17	147	143	134	139	163	68	47	145	58	120
18	117	116	119	119	131	60	53	120	57	102
19	114	102	109	112	109	56	56	109	56	94
20	120	108	107	112	113	57	64	112	61	97
21	113	107	103	114	104	51	58	108	55	93
22	127	123	118	133	112	46	62	123	54	103
23	123	122	115	132	113	49	68	121	59	103

Table 10. OW ADTT per Hour

Hr	Mon	Tues	Wed	Thu	Fri	Sat	Sun	Wkdy	Wknd	Week
0	3.4	5	2.9	2.1	4.7	5.5	1.6	3.6	3.6	3.6
1	2.1	3.2	3.4	1.7	4.6	4.1	1.7	3	2.9	3
2	3.5	3.8	4	4.2	4.8	5	1.5	4.1	3.3	3.8
3	5.4	5.3	6	5.3	5.7	4.7	0.7	5.5	2.7	4.7
4	7.8	10.2	9.7	10.5	10.1	5.1	0.6	9.7	2.9	7.7
5	15.1	12	10.8	12.7	13	6.9	0.5	12.7	3.7	10.1
6	11.5	10.4	9.6	9.5	11.2	6.3	1.7	10.4	4	8.6
7	10.6	9.7	8.1	9.5	9	3.4	2.3	9.4	2.9	7.5
8	8.9	6.7	7.9	7.7	8	4.2	1.7	7.8	3	6.4
9	9.8	8.3	8.3	8.3	8.9	5	2.5	8.7	3.8	7.3
10	9.5	9	9.9	8.5	8.5	4.4	1.7	9.1	3.1	7.4
11	9.6	8	9.7	8	15.3	3.3	1.9	10.1	2.6	8
12	8.8	7.9	8	5.6	10.8	3.2	1.5	8.2	2.4	6.5
13	5.6	5.6	5.2	5.1	8.2	2.2	0.6	5.9	1.4	4.6
14	4.6	3.2	3	3.5	4.6	1.1	0.6	3.8	0.9	2.9
15	3	1.9	2.1	1.4	3.5	1.1	0.7	2.4	0.9	2
16	4.8	3.5	2.9	3	3.7	0.9	0.6	3.6	0.8	2.8
17	5.1	4.2	3.3	2.9	5.3	0.8	0.4	4.2	0.6	3.1
18	3.6	2.8	2.6	3	5	1.7	0.3	3.4	1	2.7
19	7.1	7.3	5	4	9	1.7	1	6.5	1.4	5
20	12.4	11.9	8.1	12.1	12.3	2.3	1.5	11.4	1.9	8.7
21	18	15.9	13	12.4	11.7	1.7	3.1	14.2	2.4	10.8
22	16.4	11.2	9.2	13	8.1	1.7	3.9	11.6	2.8	9.1
23	9.5	5.5	4	7.6	5.1	1.8	3.1	6.3	2.5	5.2

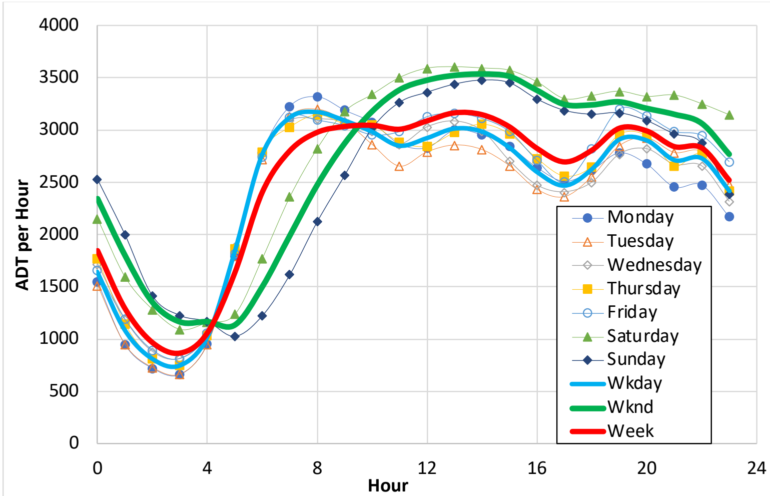


Figure 18. ADT per Hour

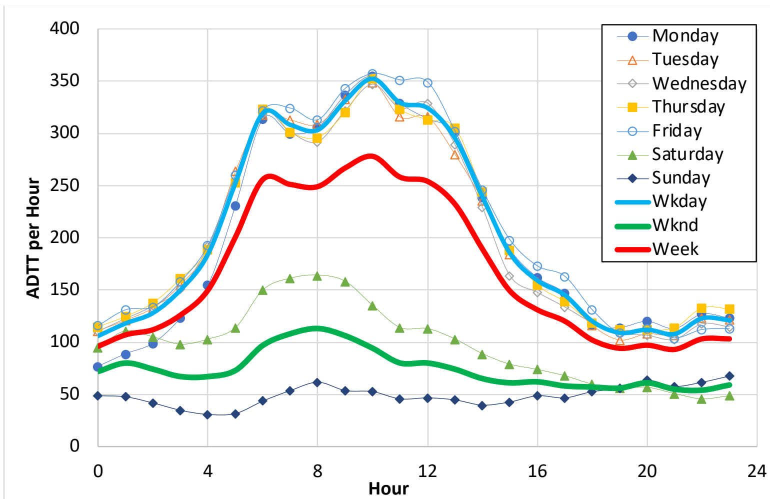


Figure 19. ADTT per Hour

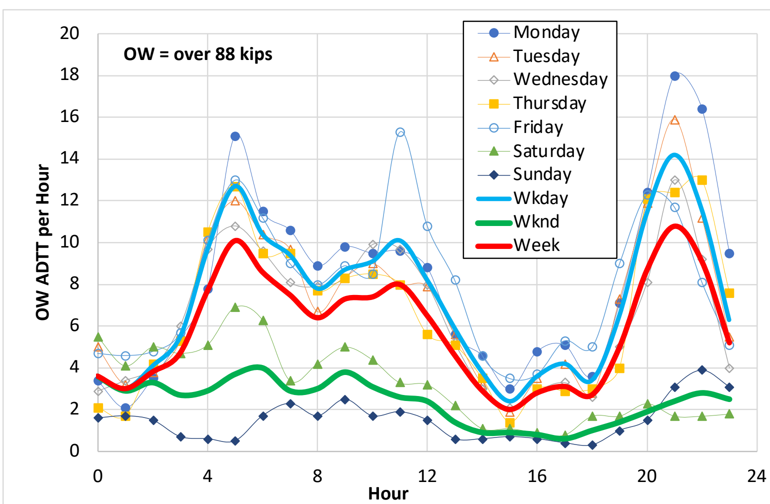


Figure 20. OW ADTT per Hour

4.1.4. Estimation of the Number of OW Trucks in Stop-and-Go Conditions

Table 11 provides a summary of the average count of OW trucks per hour, along with associated speed data. Here, "OW" is defined as having GVW exceeding 88 kips (+10% of the legal weight). On weekdays, the average number of OW trucks experiencing congestion (speed < 17 mph) would be 93.5 trucks per day.

Table 11. Average Speed and Number of OW Trucks per Hour Segment

Hour	Number of OW Trucks (GVW > 88 kips)		
	Weekday (%)	Weekend (%)	Week (%)
6a-10a	36.3 (21%)	13.7 (24%)	29.8 (21%)
10a-3p	37.1 (21%)	10.4 (18%)	29.4 (21%)
3p-7p	20.1 (11%)	4.7 (8%)	15.6 (11%)
Overnight	82.1 (47%)	28.7 (50%)	66.7 (47%)
Total	175.6 (100%)	57.5 (100%)	141.5 (100%)

Table 12 summarizes the estimated number of trucks for each scenario outlined in Table 7. When considering a speed threshold of less than 4 mph, it is projected that 15.9 trucks, constituting 9.1% of the total OW trucks per day, would experience stop-and-go conditions. Approximately 11.9 trucks or 6.8% of the total OW trucks per day might be underestimated in this scenario, while 4.0 trucks, equivalent to 2.3% of the total OW trucks per day, could be overestimated. It's worth noting that Quartz sensors may tend to underestimate axle and gross weights when trucks engage in stop-and-go movements between the sensors. However, their weight measurements are more accurate when trucks are moving at very slow speeds.

Table 12. Estimated Number of Trucks under Stop-and-Go Condition

Scenario	Speed considered as stop-and-go	trucks % during congestion (2p-7p)	Total stop-and-go	Overestimated Trucks (25%)	Underestimated Trucks (75%)
#1	< 4 mph	17%	15.9 (9.1%)	4.0 (2.3%)	11.9 (6.8%)
#2	< 2 mph	3%	2.8 (1.6%)	0.7 (0.4%)	2.1 (1.2%)

4.2. Congestion Testing Plan

The team designed a range of stop-and-go traffic scenarios to evaluate the system's accuracy during congested conditions. Two trucks were employed for the congesting testing: a Class 9 semi-trailer truck and a Class 6 single-unit truck. Table 13 summarizes axle configurations, including their weights and spacing, for both of these vehicles.

Table 13. Features and Pros/Cons of the Candidates in Queens Bound

Truck	Class 6	Class 9
GVW	70,900 lbs	80,420 lbs
No. of Axle	3	5
Wheelbase	22'-0"	43'-1.5"
Configuration		

The Class 6 truck has three axles, consisting of single and tandem axles. It has a GVW of 70,900 lbs, loaded with recycled asphalt, and a wheelbase of 22'. This truck underwent a comprehensive testing regimen, covering all possible combinations of stop-and-go conditions for each axle group. Table 14 presents a detailed breakdown of these scenarios, ensuring a thorough evaluation of the Class 6 truck's performance under varying conditions.

The Class 9 truck or Standard 3S2 configuration includes a tractor and a dump trailer. It has a GVW of 80,420 lbs, carrying recycled asphalt, and the total from the steering wheel to the trailer tandem is 43'. This truck has five axles with three distinct axle groups - the front axle (FA), the driver tandem (DrTan), and the trailer tandem (TrTan). The Class 9 truck also underwent a similar rigorous testing procedure. The team explored all potential combinations of stop-and-go conditions for each of these axle groups. Table 15 provides a comprehensive overview of these scenarios, allowing for a comprehensive assessment of the Class 9 truck's performance.

For a more in-depth understanding of the testing procedure, Table 14 and Table 15 show a visual representation of the scenarios executing the testing protocol for both truck classes.

Table 14. Class 6 Stop-and-Go Scenarios

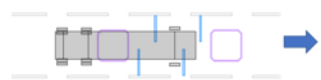
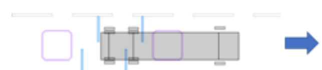
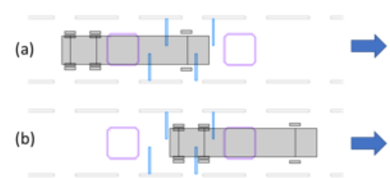
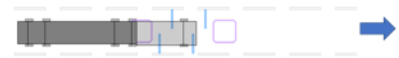
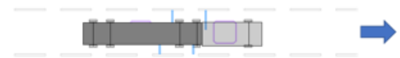
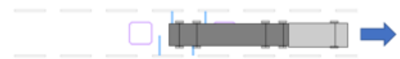
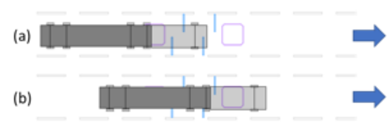
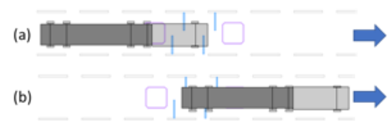
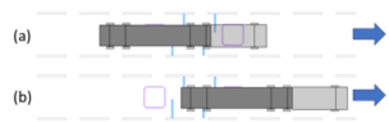
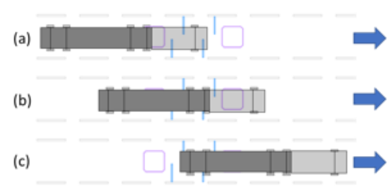
Scenario Code		**FA**	**DrTan**	**Vehicle Position**
Single Axle Group	**A-1**	Stop	-	
	A-2	-	Stop	
Two Axle Group	**B-1**	Stop	Stop	

Table 15. Class 9 Stop-and-Go Scenarios

Scenario Code		FA	DrTan	TrTan	Vehicle Position
Single Axle Group	C-1	Stop	-	-	
	C-2	-	Stop	-	
	C-3	-	-	Stop	
Two Axle Group	D-1	Stop	Stop	-	
	D-2	Stop	-	Stop	
	D-3	-	Stop	Stop	
All Axle Groups	E-1	Stop	Stop	Stop	

During the testing process, if a sequence of two or more steps was required, the subsequent step was executed immediately upon the completion of the preceding step. Moreover, the team ensured that the truck's wheels did not sit over the sensors during the weighing process, ensuring the accuracy and reliability of the data collected. Figure 21 illustrates Scenario A-2 during the stop-and-go congestion testing.

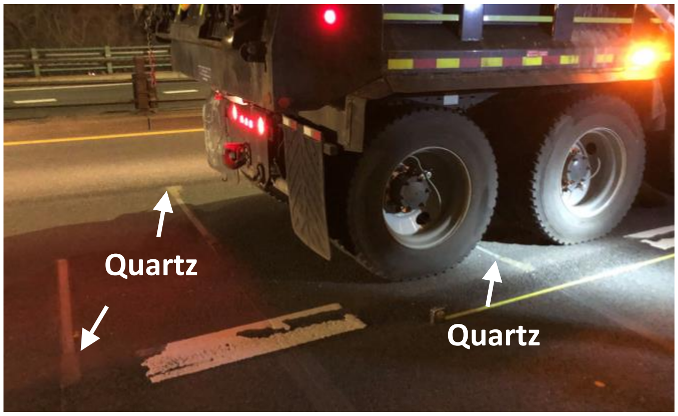


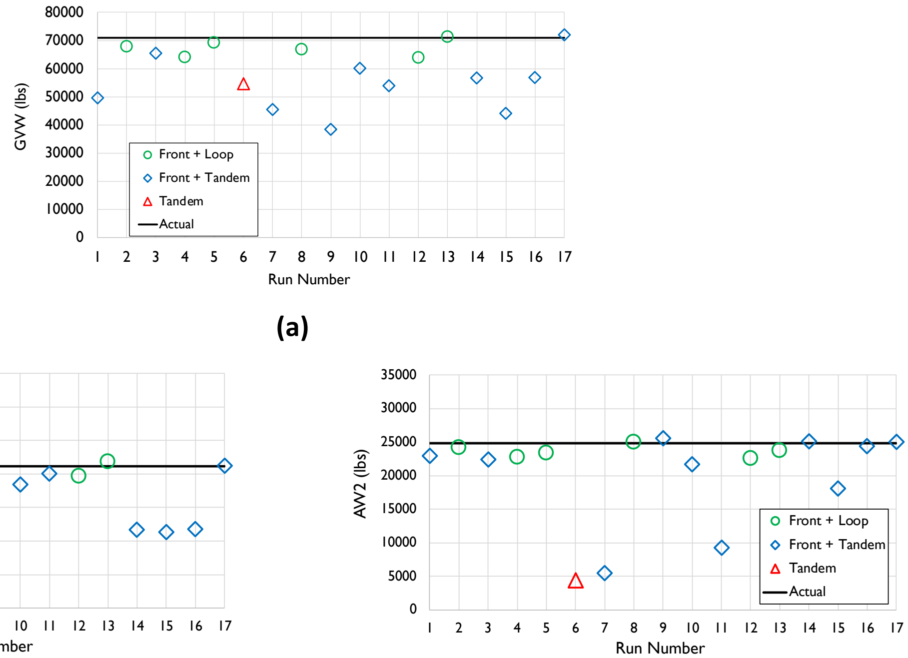
Figure 21: Scenario A-2

4.3. Congestion Testing Results

4.3.1. GVW, Axle Weight, and Tandem Weight

Figure 22 illustrates a visual representation of the weight accuracy of a Class 6 truck, with a total of 17 runs conducted for different scenarios. In this context, "FA + Loop" denotes the A-1 scenario, "DrTan" represents the A-2 scenario, and "FA + DrTan" corresponds to the B-1 scenario. Table 16 compiles the minimum, maximum, and average error percentages for GVW in each scenario. The results show that the A-1 scenario yielded the most precise GVW measurements, with an overall mean absolute error for GVW of 17%. For the axle weight accuracy, the A-1 scenario demonstrated the least deviation among runs, while the B-1 scenario exhibited the highest variability among runs. The maximum error for axle weight was 8% while the minimum error for axle weight was -82%.

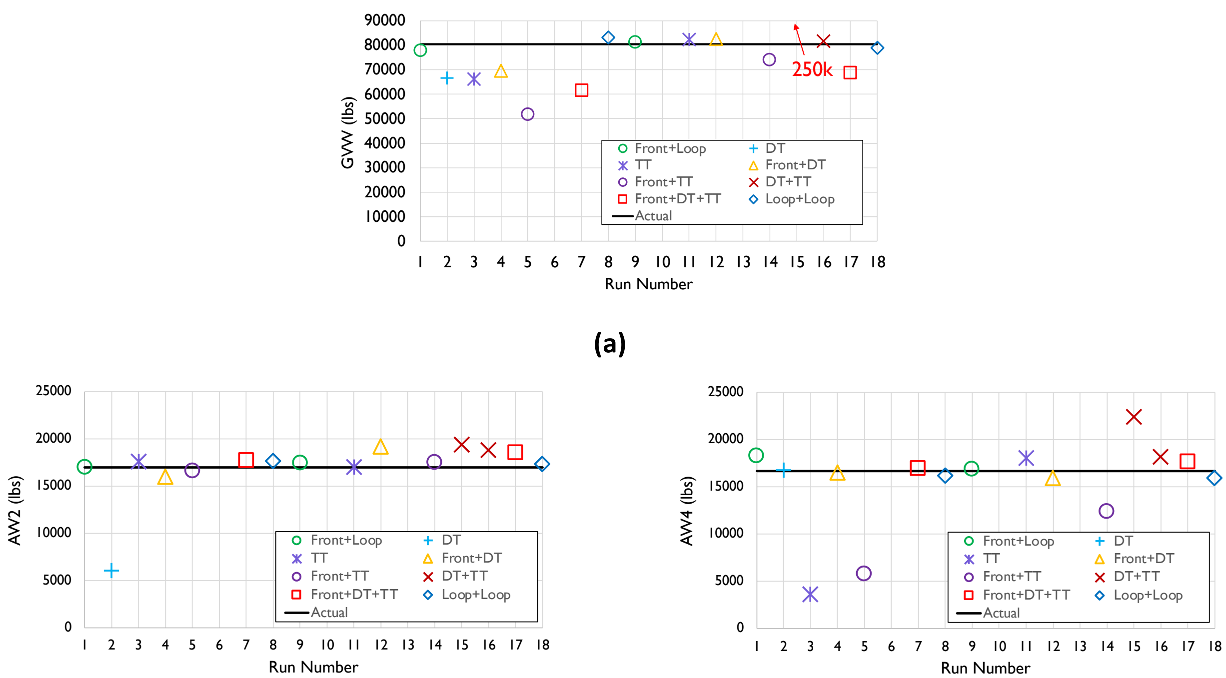
Figure 23 represents a visual representation of the weight accuracy of the Class 9 truck based on 18 runs executed for various scenarios. Three runs (runs #6, #10, and #13) were excluded from the analysis as the axle(s) were resting on the sensors. Each case represents a distinct scenario: C-1 = FA + Loop, C-2 = DrTan, C-3 = TrTan, D-1 = FA + DrTan, D-2 = FA + TrTan, D-3 = DrTan + TrTan, E-1 = FA + DrTan + TrTan. Table 17 summarizes the minimum, maximum, and average error percentages for GVW in each scenario. The findings indicate that the C-1 scenario produced the most accurate GVW measurements, with an error within 5%. There was one extreme case (run #15) that recorded a GVW of 250,000 lbs. Considering this run as an outlier, the maximum error remained within +3%, while the errors for all other scenarios were scattered, resulting in an overall mean absolute error of 24%.



(a)

(b) (c)

Figure 22: Class 6 Weight Accuracy; (a) GVW, (b) AW1, and (c) AW2



(a)

(b) (c)

Figure 23: Class 9 Weight Accuracy; (a) GVW, (b) AW2, and (c) AW4

Table 16. GVW Error of Different Scenarios for Class 6 (* Mean of absolute errors)

Scenarios	Min Error	Max Error	Mean Error*
A-1 (Front + Loop)	-10%	+1%	6%
A-2 (Tandem)	-23%	-23%	23%
B-1 (Front + Tandem)	-46%	2%	24%

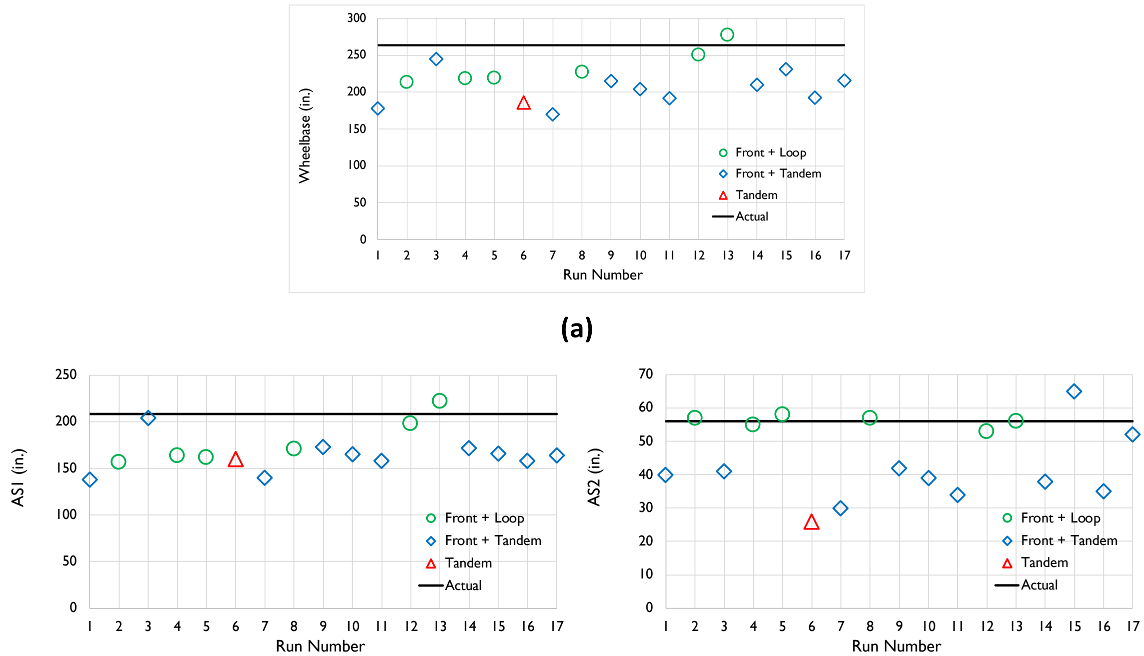
Table 17. GVW Error of Different Scenarios for Class 9 (* Mean of absolute errors; # Only one case. Extreme case.)

Scenarios	Min Error	Max Error	Mean Error*
Front + Loop	-3%	1%	2%
DT	-17%	-17%	17%
TT	-18%	2%	10%
Front + DT	-14%	3%	8%
Front + TT	-36%	-8%	22%
DT + TT	1%	211%#	106%
Front + DT + TT	-24%	-15%	19%
Loop + Loop	-2%	3%	3%

Based on the results, it would appear that stop-and-go congestion tends to result in weight underestimation. This is significant information for overweight enforcement, as it implies that vehicles would not be overestimated even under congested conditions.

4.3.2. Axle Spacing

Figure 24 illustrates the axle spacing accuracy of the Class 6 truck, while Table 18 summarizes the minimum, maximum, and average error percentages for wheelbase in each scenario. It is worth noting that the A-1 scenario produced the most accurate GVW measurements; however, wheelbase and axle spacing measurements were not as consistent across scenarios as the GVW, and axle weights were. Nonetheless, similar to axle weight, the maximum error for wheelbase was 5% and stop-and-go congestion did not result in an overestimation of wheelbase and axle spacing.



(a)

(b)

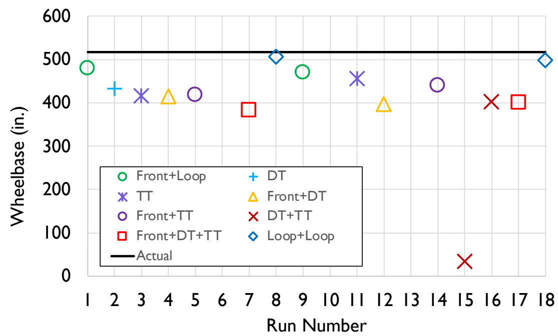
(c)

Figure 24: Class 6 Axle Spacing Accuracy; (a) Wheelbase, (b) AS1, and (c) AS2

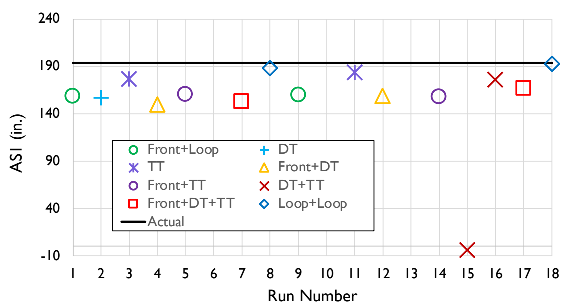
Table 18. Wheelbase Error of Different Scenarios for Class 6 (* Mean of absolute errors)

Scenarios	Min Error	Max Error	Mean Error*
A-1 (Front + Loop)	-19%	+5%	10%
A-2 (Tandem)	-30%	-30%	-30%
B-1 (Front + Tandem)	-36%	-7%	20%

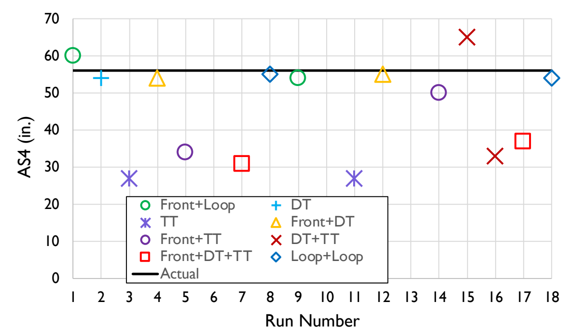
Figure 25 shows the axle spacing accuracy for Class 9 truck, while Table 19 provides a summary of the minimum, maximum, and average error in axle spacing for each scenario. The results show that in all scenarios, the wheelbases were consistently underestimated. The maximum error in axle spacing was -2% and the minimum was -23% except for run #15 which represents an extreme case in GVW measurement.



(a)



(b)



(c)

Figure 25: Class 9 Axle Spacing Accuracy; (a) Wheelbase, (b) AS1, and (c) AS4

Table 19. Wheelbase Error of Different Scenarios for Class 9 (* Mean of absolute errors)

Scenarios	Min Error	Max Error	Mean Error*
Front + Loop	-9%	-7%	8%
DT	-16%	-16%	16%
TT	-19%	-12%	16%
Front + DT	-23%	-20%	21%
Front + TT	-19%	-15%	17%
DT + TT	-93%	-22%	58%
Front + DT + TT	-26%	-22%	24%
Loop + Loop	-4%	-2%	3%

4.4. Discussion on Congestion Testing

The evaluation of WIM sensor measurements under congested traffic conditions has revealed significant discrepancies in accuracy. In most instances, the GVW measurements were consistently underestimated, with only one extreme case standing out as an exception. Similarly, measurements related to the vehicle's length, such as wheelbase and axle spacings, were found to be underestimated.

The team observed 8 runs of “overestimations (25%)” and 24 runs of “underestimations (75%). Figure 26 shows one extreme overestimation of more than > 210%, while the remaining overestimation is less than 5%. The majority of stop-and-go runs (75%) fell into the underestimated category. Therefore, we could assume that 75% of OW trucks under the stop-and-go conditions would be underestimated, and consequently, not subject to citation.

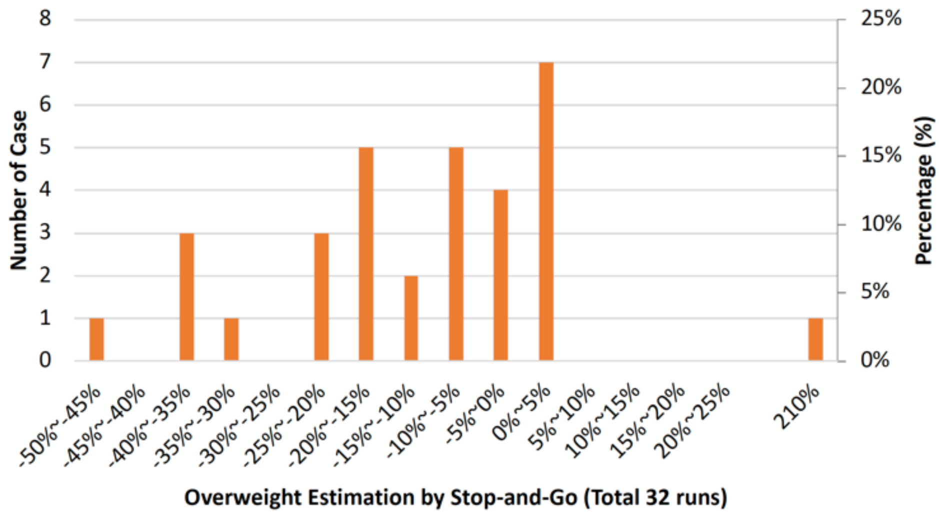


Figure 26: GVW Estimation Frequency during Stop-and-Go Calibration Test

Among the various testing scenarios conducted, it was observed that the "FA" cases (A-1 and C-1) yielded measurements that were closest to the actual values. However, the scenarios involving "Tan" cases exhibited significant variability and scatter in the results, indicating a challenge in accurately capturing data in these situations.

Several data records in the WIM dataset were found to be missing, primarily due to timeouts caused by wheels sitting on the sensors. This issue is exacerbated by the staggered placement of Quartz sensors in the pavement, resulting in not all wheels being in contact with the sensors simultaneously. This misalignment likely contributed to the inaccuracies observed in the measurements.

Section 5 – Validation of the WIM System

The New York Police Department (NYPD) Highway Patrol has occasionally pulled over suspicious trucks to verify their gross and axle weights against the legal limits. However, the NYPD selected random trucks, and many of them were found to be within legal limits. To improve their practice and validate the accuracy and repeatability of the WIM system, real-time WIM data for overweight (OW) trucks was gathered to produce violation records and delivered to the NYPD for targeted enforcement.

When the OW WIM record is gathered, the WIM report is sent in real-time to designated recipients in various formats, including PDF, PNG, and via email or SFTP transfer. The challenge was to synchronize the timestamp of the WIM data, deliver the record within a short turnaround period, and pull over the OW trucks at a safe area off the BQE.

On March 9, 2023, a significant milestone was achieved with the first proof test of the real-time WIM violation detection system. This demonstration aimed to validate the system's real-time reporting capabilities and its effectiveness in assisting law enforcement. The demonstration was conducted in collaboration with the NYPD Highway Patrol on the Queens-bound direction of the BQE, between the Tillary Street exit and entrance ramps, located approximately 0.5 miles from the WIM site. Figure 27 presents the real-time PD report protocol. To allow sufficient time for the record to be delivered to the NYPD, enforcement officers waited for the real-time report just after exiting onto the local street, as it took 36 to 45 seconds (at speeds of 40 to 50 mph) to travel the distance from the WIM site to the NYPD standby position. The protocol was planned in such a way that the real-time report could be delivered several seconds before the OW truck reached the standby position. Subsequently, the NYPD tagged the OW truck and directed it to exit onto the local road approximately 2 miles downstream (as shown in the pulled-over location in Figure 27).

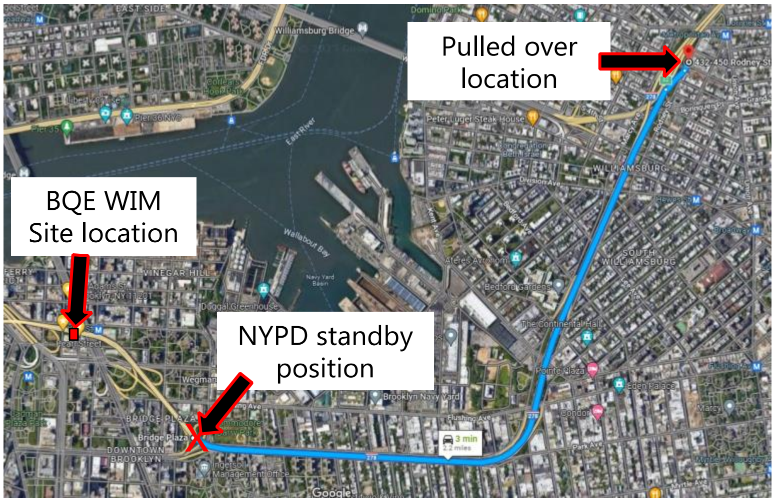


Figure 27: Real Time Police Report Protocol

The first violation case was logged at 8:34:42 A.M., and the violation report reached the standby officer in approximately 30 seconds. The NYPD officer received the violation report, promptly identified the overweight vehicle at the designated standby position, successfully intercepted the vehicle, and initiated a safe traffic stop on the local street. Figure 28 illustrates the first instance of NYPD enforcing the overweight (OW) trucks using real-time reports. The overweight truck underwent a comprehensive vehicle inspection. NYPD Highway Patrol officers conducted individual weight measurements of each wheel and inspected the vehicle's engine, tires, and brakes. To obtain axle-specific readings, the truck had to be repositioned on the scales multiple times during the inspection process.

NYPD measured each wheel's weight using two portable scales. It's important to note that these scales had underwent quarterly calibration to ensure accuracy, and the weight results were rounded up to the nearest hundred pounds. The entire vehicle inspection process took approximately one hour. The GVW difference between the two WIM records from two arrays and the portable scale was 5.96% and 1.13%, respectively, which was well below the 10% target GVW accuracy. Additionally, the axle weight errors did not exceed 20%, with maximum and average errors of 13.4% and 5.16%, respectively.

This demonstration highlights the system's ability to detect violations in real-time and generate reports for law enforcement officers, enabling them to promptly inspect potential violations. The real-time WIM violation detection system expedites enforcement actions, contributing to safer roads and more efficient law enforcement practices.

(a) (b)

Figure 28: WIM Validation by NYPD; (a) NYPD Inspecting Truck and (b) NYPD measuring Axle Weights using Portable Scale

After the initial demonstration, the NYPD has been practicing this procedure for several months, recording a total of 101 cases. The team collected all NYPD records and compared them to the WIM records per violation to evaluate the performance of the WIM system. Table 20 displays the number of cases complying with the 10% GVW target, while Figure 29presents the distribution of GVW errors. A total of 94 cases, or 93.1%, complied with the 10% GVW error requirement, while 7 cases, or 6.9%, exceeded the 10% GVW error threshold. The seven cases with GVW errors exceeding 10% were carefully examined. Notably, the weight difference in these cases was nearly equivalent to the weight of a single axle (10,000 ~ 20,000 lbs). It could be reasonably assumed that the officer might have inadvertently omitted one axle's weight when recording the data manually. Unfortunately, without access to the officer's actual field records, the team cannot confirm the specific cause of these discrepancies.

In conclusion, the data collected during the demonstration period has provided its potential as a reliable tool for weight violation detection, even in the presence of minor discrepancies. The real-time WIM violation detection system saves time and reduces the manpower required for identifying vehicle weight violations in traffic. The result analysis confirms its dependability and its substantial role in enhancing road safety and traffic enforcement while also highlighting areas for future improvement.

Table 20. Number of Cases per GVW Error Percentage

GVW Error	No. of Case	Ratio
≦ 10%	94	93.1%
> 10%	7	6.9%
Total	101	100%

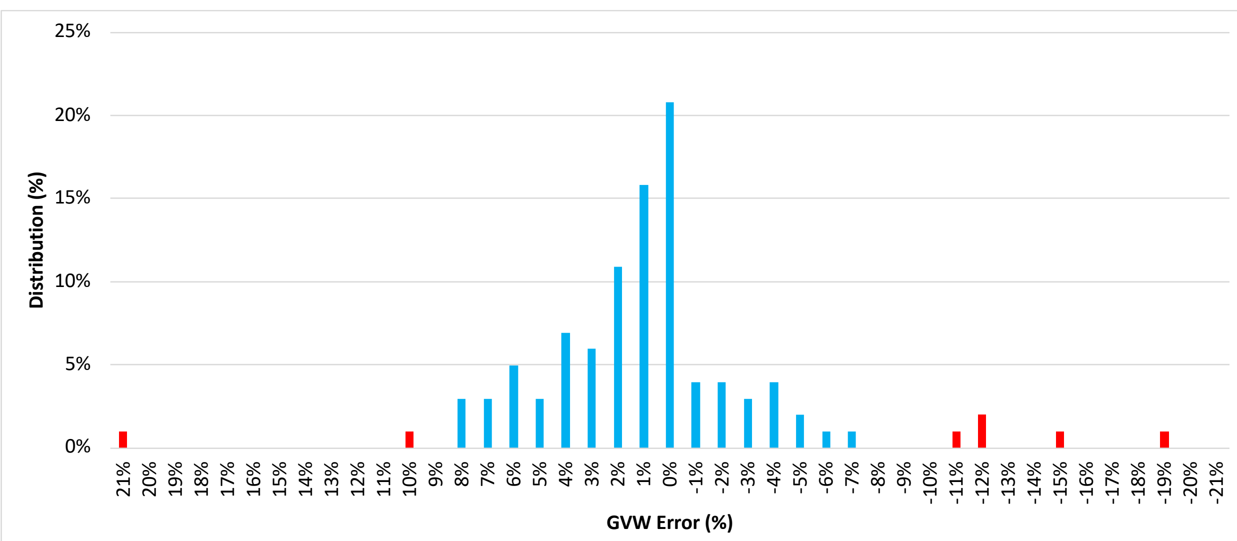


Figure 29: Distribution of GVW Errors

Section 6 – Conclusions and Recommendations

The team established a new testbed on the Brooklyn-Queens Expressway (BQE) for overweight enforcement. Initially, the team conducted a thorough evaluation of the BQE roadway profile, utilizing data from NYCDOT and Google Maps to identify the most appropriate segments that aligned with the ASEM E1318-09 standards. After considering various segments, the team chose a location between the Brooklyn Bridge and Manhattan Bridge due to the presence of an existing gantry and traffic patterns. To meet the legal requirement for a notice of liability (NOL), the team proposed two arrays of a double-staggered layout, ensuring uniformity in weighments by sharing the same pavement, traffic pattern, and other conditions. This layout was developed through a collaborative effort between Rutgers/C2SMART, NYCDOT, and Kistler Instrument Corp.

The team developed a calibration procedure by comparing four (4) standards, including two U.S. Standards (NIST HB44 and ASTM E1318-09), one European Standard (COST323), and one International Standard (OIML R134-1). This calibration process encompassed testing three prevalent truck types on the BQE at two GVWs (full and empty) and two speeds (post speed and crawling speed to simulate congestion scenarios) to prove consistent accuracy across different truck and traffic conditions. Following the sensor installation, the calibration procedure was executed, and the results indicated that the system met the accuracy requirements of ASTM E1318-09 Type III and COST 323 B(10), which mandated 95% compliance. However, it fell short of achieving the target accuracy for B+(7), primarily due to errors in single-axle weight, which were identified in three out of 353 runs. Furthermore, it was not feasible to meet the specified target accuracy in OIML R134-1 F(10) Verification.

The team evaluated the accuracy of the WIM system under congested conditions, with a specific focus on stop-and-go scenarios commonly encountered in urban traffic. Initially, they defined congestion using WIM data. Based on the WIM data, it was found that the maximum flow of the BQE corridor was 3138 vehicles and the average speed corresponding to the maximum flow was approximately 17 mph, establishing that congestion typically initiates when the average speed falls below this speed. Subsequently, the team designed a range of stop-and-go traffic scenarios to assess the system's accuracy during congested conditions. The results consistently indicated an underestimation of GVW measurements, with several cases showing less than a 5% overestimation.

The team collaborated with the NYPD Highway Patrol to validate the WIM accuracy. The team provided records of overweight trucks, including GVW, license plates, truck images, and more, while the NYPD verified the gross and axle weights of the violated trucks against legal limits. Based on these tests, the system demonstrated the capability to provide weight data with less than a 10% error in 93.1% of cases.

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