

# Evaluations of Connectors, Inlets, and Adapters

on Side-Load and Withstand Force



FEBRUARY 2026



## Disclaimer

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

This report was produced when the laboratory operated as the National Renewable Energy Laboratory (NREL). The laboratory is now the National Laboratory of the Rockies (NLR).

This report was prepared for the U.S. Department of Energy under DOE Idaho Operations Office Contract No: AC07-05ID14517, U.S. Department of Energy M&O Contract No: DE-AC36-08GO28308, and U.S. Department of Energy Office of Science Laboratory Contract No: DE-AC02-06CH11357. Funding was provided by the Joint Office of Energy and Transportation

## Authors

Marco Gaxiola, Isaac Tolbert, Andrew Meintz, and Kristi Moriarty (NLR).

## Contributors

Mariano Rigotti (Amphenol) and Joshua Major (NLR).

## Executive Summary

This report examines the mechanical forces that direct-current fast-charging electric vehicle supply equipment (EVSE) connectors and electric vehicle (EV) inlet ports experience during normal usage. The fast growth of a variety of EVs, charge port locations, and bigger and more powerful EVSE configurations, including the SAE J3400 North American Charging Standard, has increased the use of adapters with J3400 and J1772 compatibility. These new conditions contribute to increased mechanical forces because of their size, weight, and lever arm effect. This creates the need to study and compare these forces to the limits on UL 2251 and International Electrotechnical Commission (IEC) 62196-1 standards.

This report focuses solely on high-power direct-current charging EVSE connectors, EV inlets, and adapters for the specific compatibility cases of J3400 with J1772. The authors (we) first describe the details of the 100-newton (N) and the 750-N side-load evaluations as described in the standards, then present the data obtained by replicating these tests, include more details on the findings, and, last, provide our recommendations. The data gathered are related to the forces both during the connection of the mated parts and during the EVSE connector insertion and removal.

From three EVSE-EV location use cases (A1, B2, and C1 positions), forces on the connector/inlet remained below the 100-N misalignment force required by IEC 62196-1 and UL 2251 standards. However, in extreme scenarios such as the C1 position, where cables were stretched to their limit, forces exceeded 100 N, reaching up to 122 N in user evaluations. For this reason, we recommend increasing the UL 2251 Section 54C misalignment force standard from 100 N to 125 N to better reflect these conditions. Additionally, we found that adapters also increased rotational torque applied to the system (as a result of the length of the adapters increasing the length of the lever arm by which force was applied), suggesting that manufacturers should also account for this component design.

# Table of Contents

<b>Executive Summary</b> .....	<b>iii</b>
<b>1. Introduction</b> .....	<b>1</b>
<b>2. Background</b> .....	<b>2</b>
2.1 Significance .....	2
2.2 Summary of Relevant Portions of IEC 62196-1.....	2
<b>3. Design and Construction of the Evaluation Setup</b> .....	<b>6</b>
<b>4. Evaluations</b> .....	<b>9</b>
4.1 User Evaluation Setup.....	9
4.2 100-N Evaluation Setup .....	12
4.3 750-N Side-Load Evaluations .....	14
4.4 Results.....	18
4.4.1 Mated Forces.....	18
4.4.2 Insertion and Withdrawal Forces.....	24
4.5 Discussion .....	27
<b>5. Recommendations</b> .....	<b>29</b>
<b>References</b> .....	<b>30</b>
<b>Appendix A. Design and Construction of the Evaluation Fixture</b> .....	<b>31</b>
<b>Appendix B. EVSE Cord Fixture</b> .....	<b>32</b>
<b>Appendix C. EV Inlet Instrumentation Equipment</b> .....	<b>34</b>
<b>Appendix D. EV Inlet Construction</b> .....	<b>36</b>

# List of Figures

Figure 1. 750-N test apparatus per IEC 62196-1 .....3

Figure 2. Evaluation rig used to perform 100-N misalignment evaluation .....4

Figure 3. Purpose-built evaluation fixture showing different axes of force application .....5

Figure 4. View of the inlet force evaluation fixture .....7

Figure 5. Image of the EV inlet fixture seen from the front with a NACS inlet installed .....8

Figure 6. Graphical description of the three different positions used in the evaluations .....10

Figure 7. User participating in CCS-to-CCS evaluation .....12

Figure 8. Mated connector during NACS-to-NACS evaluation setup in the lab.....12

Figure 9. Purpose-built evaluation rig showing different axes .....13

Figure 10. Image of 100-N test setup conducted at a 0° angle .....13

Figure 11. Image of 100-N test setup conducted at 30° angle .....14

Figure 12. Image of the 750-N evaluation setup, showing the principal weight resting on a scale. 15

Figure 13. Y-axis linear forces and vertical rotational torques during "-Y" 750-N evaluation .....16

Figure 14. Overlapped video screenshots of the mated setup showing the "before" and "after" deformation during the applied 750-N load on the -Y-axis (down force) .....17

Figure 15. Overlapped images of the fully mated CCS to NACS assembly, showing loose tolerances when wiggling it up and down .....22

Figure 16. Side-by-side images of the same CCS to NACS fully mated assembly showing loose tolerances when wiggling it up and down .....23

Figure B-1. View of the EVSE fixture for holding the EVSE cable/connector assembly .....33

Figure C-1. Image of one Kyowa 1-kN load cell.....34

Figure C-2. Electrical diagram of the circuit to capture connector/inlet conductivity .....35

Figure D-1. Key location of the load cells across the fixture .....36

Figure D-2. Rear view of the EV inlet fixture showing the tensioning springs and adjusting hardware.....37

Figure D-3. View of the top Z-axis load cells being compressed by the springs .....37

Figure D-4. Neoprene round spring behind the sensor, allowing for a small amount of flexibility..38

Figure D-5. View of a cluster of three load cells—x, y, and z—at one of the corners of the inner frame.....38

Figure D-6. Final view of the inner frame wired up with all 12 load cells in groups of 3 at each corner, with the metal plate ready to have an EV inlet mounted .....38

# List of Tables

**Table 1. NACS/CCS User Evaluations ..... 11**  
**Table 2. Breakdown of Existing and Added Weights To Conduct the Evaluation ..... 15**  
**Table 3. 750-N Evaluation Linear Forces and Rotational Torques ..... 16**  
**Table 4. Maximum Transient Linear Force and Rotational Torques ..... 17**  
**Table 5. 100-N Evaluation Force and Torque Reference Values (0°)..... 19**  
**Table 6. 100-N Evaluation Force and Torque Values (0° vs. 30°)..... 19**  
**Table 7. Linear and Rotational Forces While Mated—A1 Position ..... 20**  
**Table 8. Linear and Rotational Forces While Mated—B2 Position ..... 20**  
**Table 9. Linear and Rotational Forces While Mated—C1 Position ..... 21**  
**Table 10. Force Replication Evaluations (122 N and 144 N) ..... 23**  
**Table 11. Linear and Rotational Forces During Insertion/Withdrawal—A1 Position..... 24**  
**Table 12. Linear and Rotational Forces During Insertion/Withdrawal—B2 Position (Normal Insertions) ..... 25**  
**Table 13. Linear and Rotational Forces During Insertion/Withdrawal—C1 Position (Normal Insertions) ..... 26**

## List of Abbreviations

Abbreviation	Description
CCS	Combined Charging System
DC	direct current
DUT	device under test
EV	electric vehicle
EVSE	electric vehicle supply equipment
IEC	International Electrotechnical Commission
N	newton
NACS	North American Charging Standard
Nm	newton-meter

# 1. Introduction

As electric vehicles (EVs) and public direct-current (DC) electric vehicle supply equipment (EVSE) are deployed in North America, the selection of available EVs and the location and configuration of supporting public DC EVSE expands. Available EVs feature charge ports in a variety of locations (e.g., front bumper, rear driver's quarter panel), and EVSEs feature charge cables of varying lengths and cable management techniques. Additionally, the recent introduction of the SAE J3400 North American Charging Standard (NACS) has led to an increase in the availability and usage of charging adapters, which allow an EV equipped with a J3400 inlet to charge on J1772 EVSE, or vice versa. This wide variety of vehicle types, charge connector types, and station locations and configurations leads to a large number of potential charging equipment combinations, requiring both EVSE and EVs to be equipped with rugged and adaptable charging cables and inlets.

In this report, the authors (we) examine the mechanical forces imparted onto EVSE charging connector cables and EV charging inlets during DC charging sessions. We compare these forces to the limits contained within the UL 2251 and International Electrotechnical Commission (IEC) 62196-1 standards to gain a better understanding of how accurately these force limits represent real-world forces that charging connectors and inlets could experience. If necessary, we also suggest updates to the UL 2251 and IEC 62169-1 standards force limits.

It is important to note DC equipment is designed to provide EV charging as fast as possible when properly used. Because DC EVSE operators are continuously improving and increasing power and charging speed capabilities, their charging cables might also see a considerable increase in size, weight, and length as they increase power. This then increases the forces experienced by EVSE cables and connectors and EV inlets with normal use. Further, the transition to J3400 has increased the use of adapters placed between the vehicle inlet and connector to convert the mechanical interface, adding to the length of the connector. These adapters are likely to increase both the probability of incidental contact and the "lever arm" effect of the connector, increasing the forces the EV inlet, the adapter, and the EVSE connector experience overall.

This report focuses on the forces involved in DC charging infrastructure for both SAE J1772 Combined Charging System (CCS) and SAE J3400 NACS. It does not investigate forces involved in lower-power and lower-weight alternating-current charging.

## 2. Background

The purpose of this report is to better understand what the forces are on EVSE connectors and EV inlets while mated and how these withstand certain situations such as long and heavy cables, tight connections resulting from limited available space, or misuse from EV drivers.

We first describe the existing standards and then compare them with the results obtained at our laboratory. The two targeted standards are IEC 62196-1, specifically for side-load forces affecting the mating connection integrity, and UL 2251 for misalignment.

### 2.1 Significance

IEC 62196-1 is used to support international references for the performance of EV and EVSE systems. However, these standards are not generally required in the United States, as the National Electrical Code refers directly to UL safety standards. UL 2251 notably does not include an evaluation similar to the IEC withdrawal test to ensure forceful removal of the connector does not result in exposure to electrical hazards, though it does reference IEC 62196-1 for other mechanical tests, including misalignment force.

These evaluations were written to allow for consistent laboratory evaluation of connectors and inlets, but little is currently known about how representative these evaluations are of the forces experienced in real-world scenarios. It is important to understand how effective these standards are in correctly defining the forces seen in the field and ensuring these forces are within what is expected through normal use by most EV users. We attempted to replicate the expected forces applied to connector, adapter, and inlets under typical use cases, and then we compared these forces to the safety standards.

### 2.2 Summary of Relevant Portions of IEC 62196-1

IEC 62196-1, *Plugs, socket-outlets, vehicle couplers and vehicle inlets—Conductive charging of electric vehicles*, covers a wide variety of electrical and mechanical requirements for EVs (IEC 2022). Two of these requirements are of interest for this report—a 750-newton (N) interlock withdrawal force and a 100-N misalignment force:

- **Interlock Withdrawal Force (IEC 62196-1, Section 14.1.6):** The connector and inlet are mated, with any retaining means opened, and without current flow. A principal and supplementary load are attached to the connector with a clamp, such that the total mass of clamp, connector, principal, and supplementary weight total 750 N (168.8 lb). The principal weight is applied without jolting, and the supplementary weight (75 N) is dropped onto the connector from a height of 5 centimeters (cm). This weight is maintained for 60 seconds. The mated devices are then rotated 90°, and the evaluation is repeated. The mated components are expected to experience no damage or circuit discontinuity, and the components

should not become unmated. Figure 1 shows an example of an apparatus for this evaluation.

- **Misalignment Force (IEC 62196-1, Section 36.3):** The connector and inlet are mated, and rated current flows through the devices until temperature stabilization is reached. Then, a mechanical load of 100 N is applied in each direction (-X, -Y, +X, +Y) for a minimum of 1 minute each, pausing for 10 seconds between each force application, and this cycle is repeated three times. The device is considered to have passed if, during the misalignment loading, the temperature did not vary from its steady-state value by more than  $\pm 5$  kelvin (K). Figure 2 shows an example of an apparatus used for this evaluation.

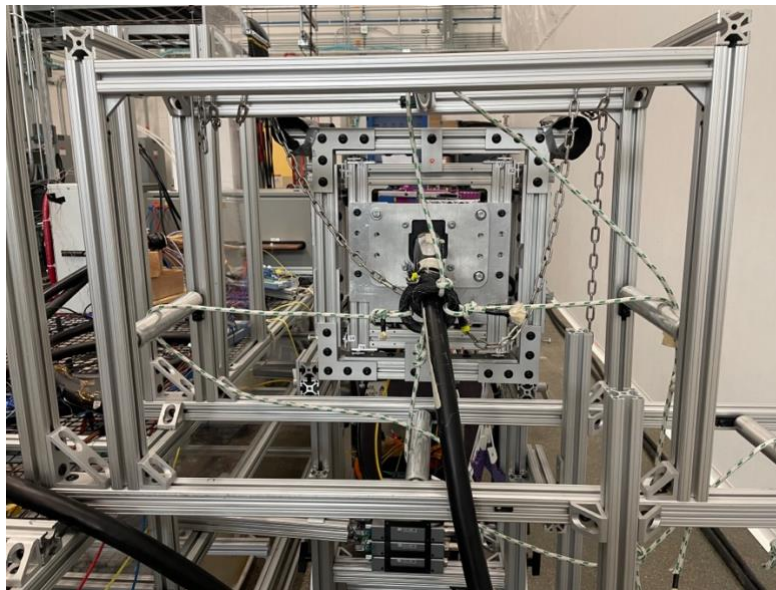
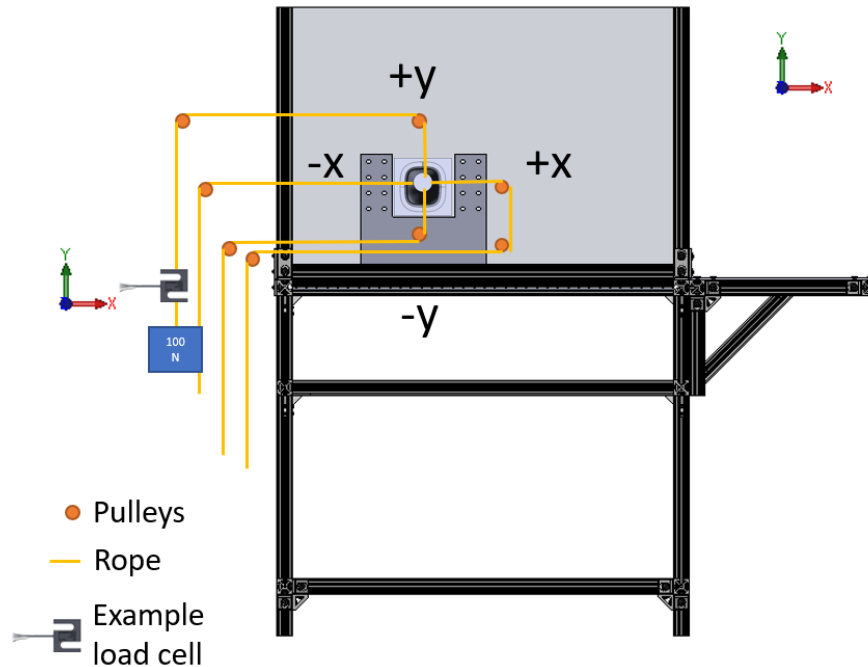


Figure 1. 750-N test apparatus per IEC 62196-1



**Figure 2. Evaluation rig used to perform 100-N misalignment evaluation**

UL 2251 (UL 2023) also incorporates the 100-N side-load misalignment force test described in IEC 62196-1, section 36.3. This misalignment test, described in UL 2251, *Plugs, Receptacles, and Couplers for Electric Vehicles*, Section 54C “Misalignment”, indicates the same force directions, durations, and physical device under test (DUT) configuration as described in IEC 62196-1.

Based on these tests and the mechanical requirements, we purpose-built an evaluation fixture (shown in Figure 3) in our laboratory, which allows us to introduce the required forces from the standards while monitoring and recording the forces on each axis.

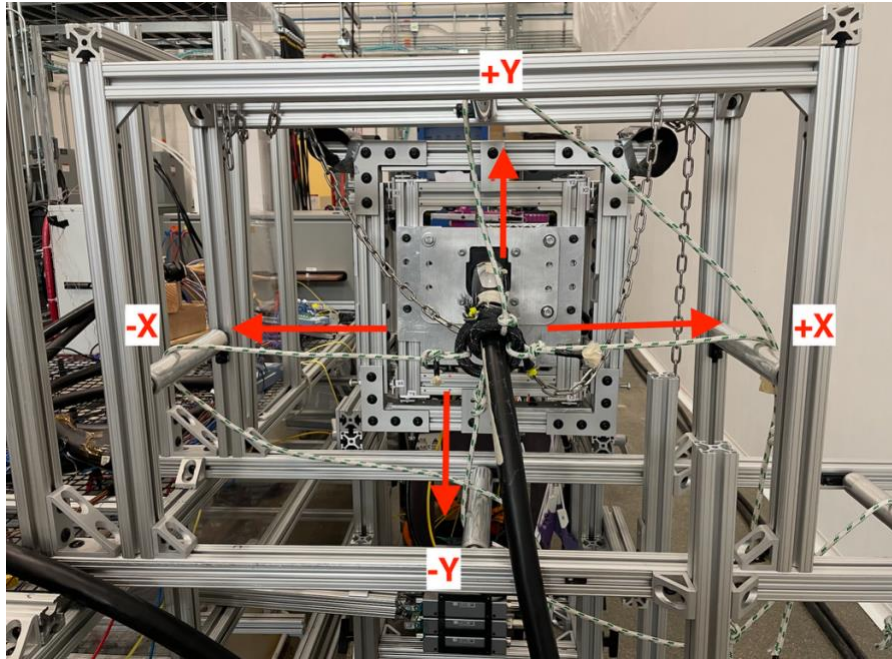


Figure 3. Purpose-built evaluation fixture showing different axes of force application

### 3. Design and Construction of the Evaluation Setup

To perform the evaluations described in this report—and because such an evaluation tool did not exist—our team at the National Laboratory of the Rockies (NLR) designed and built an instrumented evaluation fixture. This fixture can perform the force measurements on all different axes to allow us to capture in real time the forces involved at the EV inlet side while the EVSE connector is inserted, mated in place, and then removed. Additionally, this fixture allows us to monitor the continuity of the DC and signal connections between the connector and inlet, synchronized with the forces throughout all phases of the evaluation.

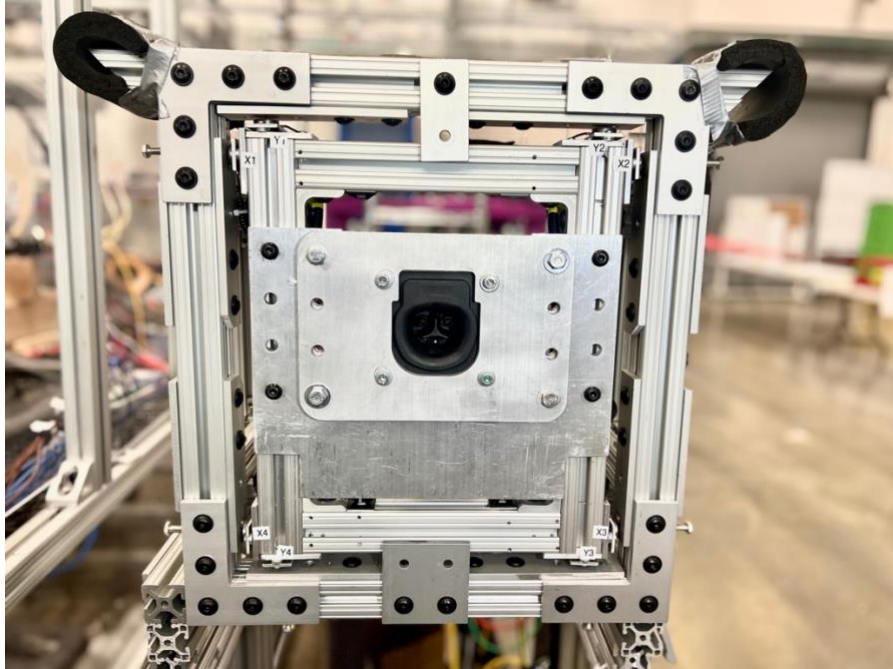
To capture all forces on each axis, the construction had to have all six degrees of freedom, allowing us to perform measurements of both linear forces on the x-, y-, and z-axes and torsional-rotational forces on each of these axes (pitch, yaw, and roll). The evaluation fixture and the six degrees of force measurements focused mainly on the EV inlet side. This part of the EV-EVSE setup is fixed to the EV experiencing these forces and was the easiest location to instrument for this purpose. The EVSE cable portion was built with no major complications, with the main goal of simulating the height of the EVSE cable mounting point as close as possible to what is normally found on public infrastructure. The EVSE cable mount was built to emulate the cable mounting configuration of an EVSE with no charging cable management system.

The most important part is the EV inlet mounting portion, shown in Figure 4. This holds the EV inlet to be used during the evaluations. This part is made of two subassemblies, which together allow us to measure the linear and torsional forces on all directions. There is also a base that allows us to adjust the height and angle of the inlet from 0° to 90° to represent special EV inlet ports (e.g., motorcycles).



**Figure 4. View of the inlet force evaluation fixture**

The two subassemblies are rectangular 80/20 aluminum frame structures, one inside the other. The inner frame holds the EV inlet (see Figure 5), and this frame is suspended through 12 different compression force sensors, or load cells, against the outer frame. These 12 load cells are strategically located to capture forces moving on any x, y, or z direction. They give us the ability to measure both positive and negative linear or rotational forces on all axes by adding or subtracting forces on each respective axis.



**Figure 5. Image of the EV inlet fixture seen from the front with a NACS inlet installed**

For a more detailed description of this EV inlet fixture, as well as the EVSE cable fixture, please refer to the appendices.

## 4. Evaluations

We performed several types of mechanical force evaluations. These included evaluations featuring several users performing insertions/withdrawals of connectors with different EVSE-EV placements, along with benchtop evaluations to examine how these user evaluations compared to the IEC- and UL-described force criteria. The setup, performance, and results of these evaluations are described in this section.

### 4.1 User Evaluation Setup

We analyzed several evaluation cases to identify which represent the typical use of the connector and inlet systems in the field. These different configurations were meant to cover the breadth of different vehicle inlet locations in addition to the EVSE installation relative to the parking stall positions.

Starting with the EVSE stall location, we narrowed our evaluation to two different locations:

- **EVSE Position 1:** The EVSE stall/cable interconnect is located at the center of the assigned EV parking space. This location is typical on charging stations where there is one EVSE stall per vehicle, per parking space.
- **EVSE Position 2:** The EVSE is located between two parking spaces, allowing two EVs to park and simultaneously charge from the same EVSE dispenser.

Following the EVSE stall and cable location, we defined three EV inlet port locations:

- **EV Inlet Position A:** Inlet is located on the front center of the vehicle (e.g., as on a Nissan Leaf).
- **EV Inlet Position B:** Inlet is located on the front left quarter panel (e.g., as on a Ford Mustang Mach-e), with the car pulled front-in to the parking space, or on the rear right quarter panel (e.g., as on a Hyundai Ioniq 5), with the vehicle backed into the parking space.
- **EV Inlet Position C:** Inlet is located on the rear left quarter panel (e.g., as on a Tesla Model 3), with the vehicle pulled front-in to the parking space, or on the front right quarter panel (as on a Nissan Ariya), with the vehicle backed into the parking space.

We then examined the different possible combinations of EVSE and EV inlet locations and selected three combinations that would represent a range of scenarios across both easy, low-force situations and difficult, high-force situations. Figure 6 displays a layout of all these locations:

- **Position A1:** EVSE is placed at the center of the parking space (position 1). Charge inlet is located at the front of the EV (position A), and the EV is pulled front-in to the parking space. This position was presumed to be that of lowest physical stress on the charging connector and inlet with a 1.14 m (45-inch) distance from point of station to EV inlet location. This position is fundamentally similar to a scenario with the inlet located in position B or C, with the EVSE

located directly beside the vehicle the vehicle closely parked (i.e., at a pull-through charging station).

- Position B2:** EVSE is located to the side of the parking space (position 2). The charge inlet is located at either the front left (with the vehicle pulled front-in) or rear right (with the vehicle backed in) (position B). This was assumed to be a position of low-to-medium physical stress on the charging connector and inlet with 1.955 m (77-inches) from the charging station cable to the center of the EV inlet. This position is also fundamentally similar to a scenario with the inlet located at position A, with the EVSE located directly beside the vehicle (i.e., a pull-through charging station).
- Position C1:** EVSE is placed at the center of the parking space (position 1). The charge inlet is located at either the rear left (with the vehicle parked front-in) or front right (with the vehicle backed in) (position C). This was the position of highest possible physical stress. In this position, the charge connector cable is stretched to its absolute maximum length, with the EV inlet as far away as possible (2.946 meters or 116 inches in our test case) but still able to be mated.



**Figure 6. Graphical description of the three different positions used in the evaluations**

In addition to the different EVSE stall locations and EV inlet port locations, we also performed different evaluations considering other factors during the connector insertion and removal. These were performed for each of the combinations mentioned previously.

The additional factors included inserting the connector into the EV inlet, completely removing the user's hands from the mated parts, leaving these untouched for at least 5 seconds, and then finally grabbing the connector and completely removing it from the EV inlet. We performed four different insertion types to capture a variety of different insertion/removal scenarios in position A1:

- Insertion, wait period, and removal of the connector, with no additional forces or special conditions

- Insertion, wait period, and removal of the connector, with added force angled to the right at all times while the user interacted with the connector
- Insertion, wait period, and removal of the connector, with added force angled to the bottom at all times while the user interacted with the connector
- Insertion, wait period, and removal of the connector, with the connector inserted and removed as fast as possible

For positions B2 and C1, only “normal” insertions were performed.

For the EVSE cable height, we used a fixed height of 2.28 m (7.5 ft) from the ground level and a cord distance of 4.0 m (13.12 ft). Similarly for the EV inlet charge port, we used a fixed height of 1.219 m (4 ft) from the ground to the center of the inlet (the maximum height allowed for an EVSE connector handle to be mounted by the Americans with Disabilities Act (ADA) (U.S. Access Board 2023)—with the assumption this is the maximum height a vehicle inlet would likely be placed). It is important to mention this height was chosen mostly because of technical considerations from our EV inlet fixture, but it offered a more realistic scenario when considering the probability of the EVSE cables not resting on the floor but instead mostly being supported by the inlet and the EVSE setups. The EV inlet fixture was fixed at a straight angle perpendicular to the floor to most closely match most of the EV configurations are currently in the market. This helped us simplify and reduce the number of combinations to perform the different evaluations. All the different evaluation types can be seen in Table 1.

**Table 1. NACS/CCS User Evaluations**

Inlet Position	EVSE Cable Height	EV Inlet Height	Insertion/Removal Type	CCS Users	NACS Users	CCS to NACS (Adapter)	NACS to CCS (Adapter)
A1	7.5 ft	4.0 ft	Normal insertion/removal	10 total users with an average of 2 samples per user for each case	5 total users with an average of 2 samples per user for each case	4 total users with average of 2 samples per user for each case	3 total users with average of 2 samples per user for each case
A1	7.5 ft	4.0 ft	Insertion/removal angled to the right				
A1	7.5 ft	4.0 ft	Insertion/removal angled to the bottom				
A1	7.5 ft	4.0 ft	Insertion/removal as fast as possible				
B2	7.5 ft	4.0 ft	Normal insertion/removal				
C1	7.5 ft	4.0 ft	Normal insertion/removal				

For this setup, we used commercial-grade, liquid-cooled CCS and/or NACS EVSE cables installed at the EVSE cable fixture. Then, at the EV inlet fixture, we also installed automotive-grade CCS and/or NACS EV inlets accordingly.

To obtain more realistic data, we invited several people from our laboratory to help us represent a typical EV user plugging in their vehicle. We had 10 guests with a varied mix of attributes (e.g., male, female, with EV experience, without any EV experience, of various heights). This helped us generate an extensive amount of data, of which we show only the most relevant examples in this report.

Figure 7 and Figure 8 represent the different evaluation scenarios performed in the laboratory.



**Figure 7. User participating in CCS-to-CCS evaluation**

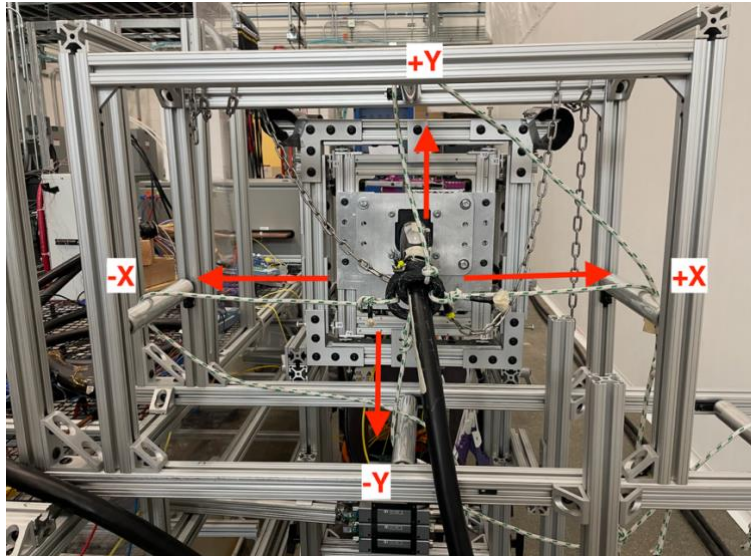


**Figure 8. Mated connector during NACS-to-NACS evaluation setup in the lab**

## 4.2 100-N Evaluation Setup

The 100-N evaluation setup consisted of a series of side-load tests following the IEC 62196-1, Section 36.3, and UL 2251, Sections 54C.1 to 54C.4, document guidelines. For this case, the EV inlet fixture was moved closer to a specially built 80/20 aluminum rectangular structure equipped with four adjustable rollers located at each corresponding axis (+x, -x, +y, and -y) and four connecting cords at the lower part of

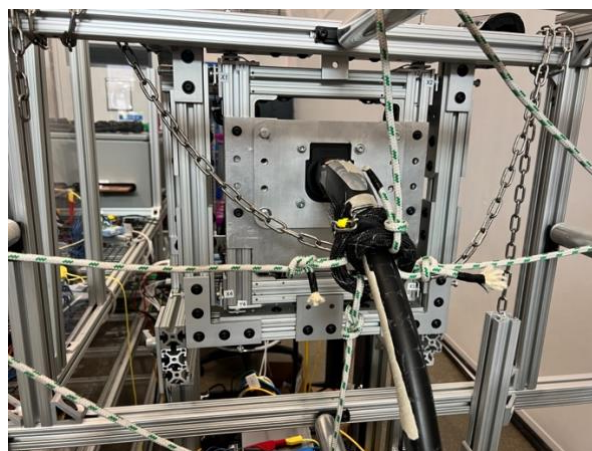
the EVSE connector handle, where the plastic connector handle housing meets the charge cable (Figure 9).



**Figure 9. Purpose-built evaluation rig showing different axes**

The evaluations were performed with the EVSE connector and the EV inlet in the mated position and as the standard suggests. Then, a 100-N load was introduced for approximately 30 seconds at each of the 4 axes following counterclockwise sequence (+x, +y, -x, -y).

Although the test defined in IEC 62196-1, Section 36.3, requests the inlet to be mounted at a 30° angle, our evaluations were performed at a 0° angle, as shown in Figure 10. Our main reason for this change was the inlets of most commercially available EVs are mounted at an angle much closer to 0° than 30°.



**Figure 10. Image of 100-N test setup conducted at a 0° angle**

However, we also conducted a 100-N side-load evaluation with the EV inlet at a 30° angle and obtained this data to compare it against the 0° angle test. See Figure 11 for details of the setup.

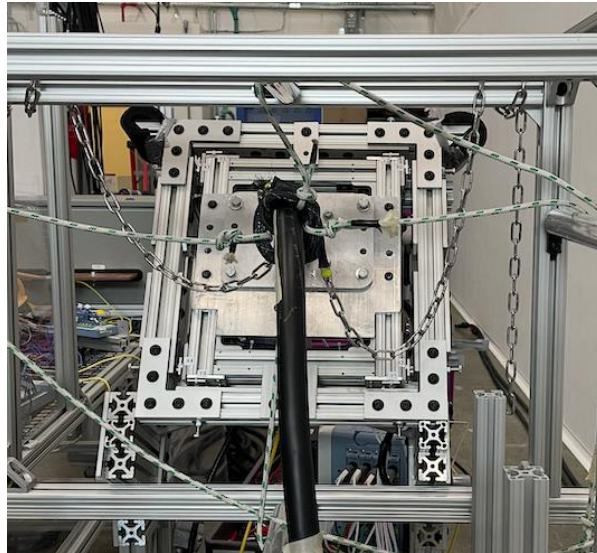


Figure 11. Image of 100-N test setup conducted at 30° angle

### 4.3 750-N Side-Load Evaluations

As part of the additional series of evaluations, we replicated the 750-N side-load evaluation as described in IEC 62196-1, Section 14.1.6, to understand the implications of such load on the mated parts.

For this evaluation, we used part of our current fixture—on this the EV inlet fixture was attached to the same X-Y cage used in the 100-N evaluation—which allowed us to introduce the desired loads on  $\pm x$ - or  $\pm y$ -axes. The setup is shown in Figure 12, with the primary modification being thicker, more robust straps to handle the additional weight load. The principal load, consisting of multiple bags of weighted pellets, is shown on top of a scale below the connector.



**Figure 12.** Image of the 750-N evaluation setup, showing the principal weight resting on a scale.

The existing and added weight is decomposed and shown in Table 2, where the *principal* is added first in a smooth incremental step and then the *supplementary* is being added with a 5-cm drop after the principal, as the IEC test prescribes.

**Table 2. Breakdown of Existing and Added Weights To Conduct the Evaluation**

Weight Breakdown	Weight (lb)	Force (N)
Targeted 750-N total weight	168.6 lb	750
Supplementary weight (10% of total, subtracted)	16.9 lb	75
EVSE cable, mating accessories and clamps weight (subtracted)	7.8 lb	34.7
Principal weight	143.9 lb	640.1

During this evaluation, the principal weight was gradually applied to the cable until all weights (except the supplementary weight) were applied to the cable. Then, the supplementary weight (75 N) was applied to the cable via a 5-cm drop, at which point

the DUT experienced the full 750 N of mechanical loading, and any oscillations in the forces were allowed to stabilize.

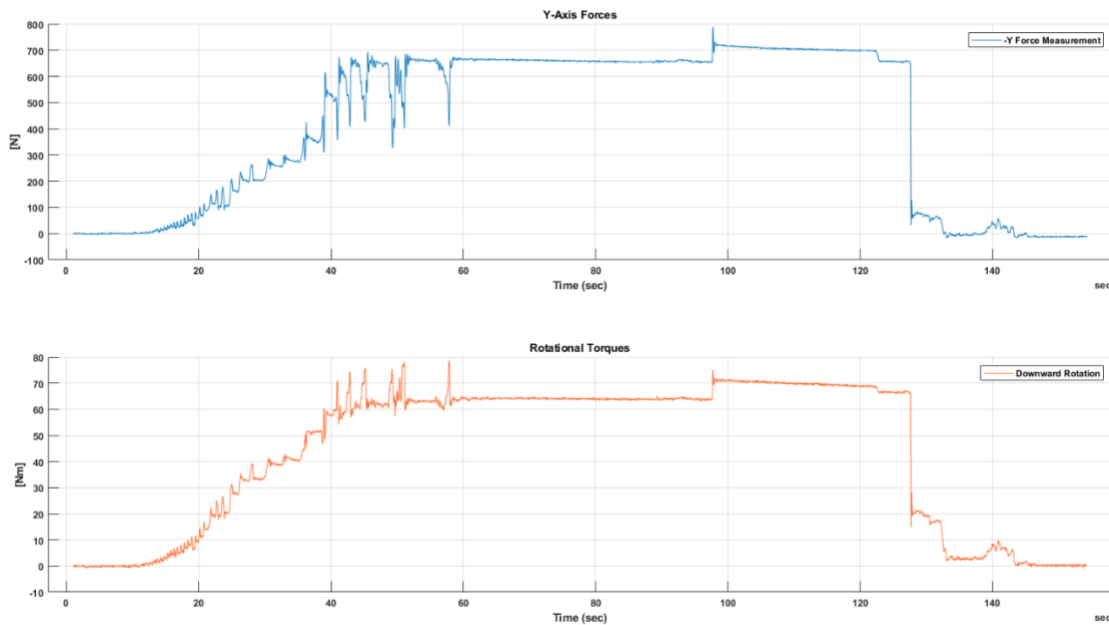
The linear forces and rotational torques experienced by the DUT during the 750-N evaluation, with the entire 750-N weight applied and the forces allowed to come to steady-state, are given in Table 3.

**Table 3. 750-N Evaluation Linear Forces and Rotational Torques**

Force	Pull Direction	Linear X-Axis Forces While Mated (N)		Linear Y-Axis Forces While Mated (N)		Lateral Rotational Torques While Mated (Nm)		Vertical Rotational Torques While Mated (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
750 N	+X	623	+X	159	-Y	50	Right	20	Down
750 N	-Y	50	-X	706	-Y	0	-	70	Down

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively. “Newton-meter” is shortened as “Nm.”

An example of the linear forces and rotational torques during an evaluation is given in Figure 13, which shows the Y-axis linear forces and vertical rotational torques throughout the entire “-Y 750N” evaluation.



**Figure 13. Y-axis linear forces and vertical rotational torques during “-Y” 750-N evaluation**

The “drop” portion of the evaluation, which featured the final 75-N weight being applied to the cable via a 5-cm drop, resulted in a brief transient force that was higher than the final steady-state force value. The maximum force observed during this drop is recorded in Table 4.

**Table 4. Maximum Transient Linear Force and Rotational Torques**

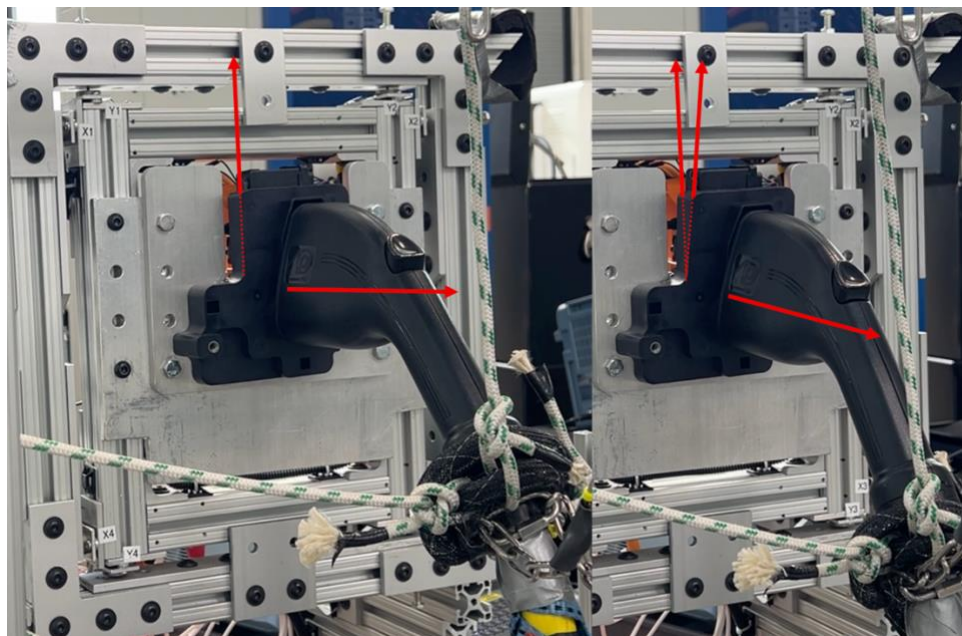
(675-N force + 75-N drop weight from 5 cm)

Force	Pull Direction	Max Linear X-Axis Forces While Mated (N)		Max Linear Y-Axis Forces While Mated (N)		Max Lateral Rotational Torques While Mated (Nm)		Max Vertical Rotational Torques While Mated (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
675 N+Drop	+X	643	+X	164	-Y	52	Right	20	Down
675 N+Drop	-Y	62	-X	789	-Y	0	-	75	Down

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

The 750-N results shown in Table 3 demonstrate a baseline level of force imparted by the 750-N evaluation, which we can compare against the maximum transient forces observed during insertion/withdrawal during the user evaluations. Additionally, we can see from Table 3, Table 4, and Figure 13 that the maximum transient linear force experienced during the 75-N, 5-cm drop portion of the evaluation is only slightly higher than the steady-state forces experienced with the full 750 N applied. This is possibly the result of the soft weights and ropes used to suspend the weights, which potentially dampened a portion of the mechanical impulse from the 75-N, 5-cm drop.

Although continuity was not broken during these tests, and both the connector and inlet stayed intact, we noticed a large amount of bending and deformation on the inlet housing as the full load was applied, as shown in Figure 14.



**Figure 14. Overlapped video screenshots of the mated setup showing the “before” and “after” deformation during the applied 750-N load on the -Y-axis (down force)**

## 4.4 Results

This section describes all the evaluations we performed in the laboratory. Section 4.4.1 discusses forces measured while the EVSE connector and EV inlet are mated, referencing the 100-N test per the IEC and UL standards mentioned previously. Section 4.4.2 discusses the measured forces during insertion and removal of the connector.

### 4.4.1 Mated Forces

Mated forces are the forces measured while the EVSE connector is mated with the EV inlet and with no additional external forces involved other than the EVSE cord weight and any possible side tension. These forces are the most representative of the 100-N force test described in IEC 62196-1 and UL 2251—they are static and applied for long periods, typically for the duration of the charge session, and are the forces that connectors would experience while transferring current.

During these intervals, both mated parts will observe the natural constant forces properly from the EVSE cable and EV inlet tension, including the cable weight and any of the EVSE cable management system (if it exists) and in case the cable were to be suspended. Additionally, forces can come from possible cable twisting along the way as a result of normal usage.

Because of the custom-made nature of the evaluation fixture, we performed several test runs to ensure the accuracy of our force and torque readings. We applied known weights of 100 N (22.4 lb) to the connector handle in sequence on each of the four linear axes (+x, +y, -x, -y), and observed the forces recorded by the evaluation fixture. Because of inherent mechanical losses within the evaluation fixture, it was necessary to apply an approximation factor to the recorded forces to more effectively compare the recorded forces to the actual applied forces. This approximation factor was calculated by determining the ratio between the measured linear force and the 100-N applied force, which, when the measured force was multiplied by the approximation factor, would match the actual applied force (in this case, 100 N). Thus, the data presented in this report represent an approximation of the linear forces as they relate to a 100-N weight applied to the connector handle (i.e., an indicated force of 110 N would indicate the connector/inlet pair is experiencing a force approximately the same as they would when a weight of 110 N is added to the connector handle).

For the rotational torques, the idealized torque applied to the fixture during the 100-N tests was calculated by determining the distance between the center of the inlet fixture plane and point of force application on the connector (i.e., the lever arm) and multiplying this distance by the applied force (in this case, 100 N). This idealized torque was then used to calculate the expected force applied to z-axis sensors, based on the vertical and horizontal distance between the z-axis force sensors and the center of the inlet fixture plane. This expected force was then used to calculate the approximation factor for the measured force on the z-axis sensors for rotational torques (upward, downward, leftward, rightward), and this approximated force could then be used to calculate the measured torques for each direction.

The approximated force and torque values for the 100-N evaluation with the inlet placed at an angle of 0° are given in Table 5.

**Table 5. 100-N Evaluation Force and Torque Reference Values (0°)**

Force	Pull Direction	Linear X-Axis Forces While Mated (N)		Linear Y-Axis Forces While Mated (N)		Lateral Rotational Torques While Mated (Nm)		Vertical Rotational Torques While Mated (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
100 N	+X	100	+X	-	-	21	Right	-	-
100 N	+Y	-	-	100	+Y	-	-	23	Up
100 N	-X	100	-X	-	-	23	Left	-	-
100 N	-Y	-	-	100	-Y	-	-	23	Down

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

To compare the forces between the 0° and 30° inlet angle cases, the team performed two evaluations, each at the 0° and 30° inlet angle with a weight of 100 N. The two evaluations at each angle were averaged together, and the results are provided in Table 6.

**Table 6. 100-N Evaluation Force and Torque Values (0° vs. 30°)**

Force	Pull Direction	Angle	Linear X-Axis Forces While Mated (N)		Linear Y-Axis Forces While Mated (N)		Lateral Rotational Torques While Mated (Nm)		Vertical Rotational Torques While Mated (Nm)	
			Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
100 N	+X	0°	100	+X	-	-	35	Right	2	Up
100 N	+X	30°	94	+X	-	-	29	Right	4	Up
100 N	+Y	0°	-	-	100	+Y	-	-	23	Up
100 N	+Y	30°	-	-	125	+Y	2	Right	20	Up
100 N	-X	0°	100	-X	-	-	23	Left	9	Up
100 N	-X	30°	97	-X	-	-	20	Left	12	Up
100 N	-Y	0°	-	-	100	-Y	-	-	23	Down
100 N	-Y	30°	-	-	113	-Y	-	-	16	Down

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

We can see from Table 6 that, for most forces, there is a relatively minor difference between forces in the 0° and 30° cases. In the vertical axis, the 30° case had noticeably higher linear ±y-axis forces than the 0° case, but it also had slightly lower linear ±x-axis forces. The rotational forces were generally similar on each axis.

The color scales in the following tables reflect the values’ relation to the “Reference” values as determined in the 100-N evaluation in Table 5. Values colored yellow are near 75% of the reference value measured during the 100-N evaluation, whereas values

colored red indicate a value greater than or equal to the reference value (e.g., a vertical torque value of 17.25 Nm will be colored yellow, whereas a value greater than 23 Nm would be colored red). The range of colors is referenced for this unique set of data within the table.

Table 7 presents forces seen while mated in position A1. These positions have the mated parts in a mostly relaxed condition, as the inlet is positioned very close to the EVSE.

**Table 7. Linear and Rotational Forces While Mated—A1 Position**

Item	DUT	Linear X-Axis Forces While Mated (N)		Linear Y-Axis Forces While Mated (N)		Lateral Rotational Torques While Mated (Nm)		Vertical Rotational Torques While Mated (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
1	CCS	13	-X	36	-Y	13	Left	12	Down
2	CCS	5	+X	39	-Y	-	-	5	Down
3	CCS	18	+X	45	-Y	9	Right	7	Down
4	CCS	14	-X	38	-Y	-	-	16	Down
5	NACS	9	-X	50	-Y	7	Left	11	Down
6	NACS	-	-	61	-Y	7	Right	9	Down
7	NACS	7	+X	66	-Y	10	Right	10	Down

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

In comparison to position A1, the forces presented in Table 8 at position B2 are slightly higher. Here, the most noticeable forces seen at the B2 evaluations are the ones conducted with adapters in between. Notice the lower forces overall were at mated parts from rows 1–6 (the CCS-to-CCS or NACS-to-NACS evaluations). Whereas in rows 7–13, with an adapter that is possibly creating bigger leverage down force added to the cable weight, we see higher tension particularly for the y-axis (down forces) and an increase in vertical rotational torque as well, likely a result of the adapter increasing the length of the force lever arm of the connector.

**Table 8. Linear and Rotational Forces While Mated—B2 Position**

Item	DUT	Linear X-Axis Forces While Mated (N)		Linear Y-Axis Forces While Mated (N)		Lateral Rotational Torques While Mated (Nm)		Vertical Rotational Torques While Mated (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
1	CCS	18	-X	45	-Y	-	-	18	Down
2	CCS	-	-	47	-Y	-	-	14	Down
3	CCS	14	-X	41	-Y	-	-	17	Down
4	NACS	22	-X	50	-Y	3	Left	14	Down
5	NACS	21	-X	54	-Y	4	Left	13	Down
6	NACS	17	-X	62	-Y	5	Left	16	Down

Item	DUT	Linear X-Axis Forces While Mated (N)		Linear Y-Axis Forces While Mated (N)		Lateral Rotational Torques While Mated (Nm)		Vertical Rotational Torques While Mated (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
7	CCS-NACS	5	-X	54	-Y	-	-	24	Down
8	CCS-NACS	9	-X	59	-Y	-	-	22	Down
9	CCS-NACS	15	-X	40	-Y	1	Left	7	Down
10	NACS-CCS	-	-	54	-Y	-	-	23	Down
11	NACS-CCS	15	-X	71	-Y	-	-	34	Down
12	NACS-CCS	16	-X	56	-Y	-	-	18	Down
13	NACS-CCS	13	-X	56	-Y	-	-	21	Down

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

Finally, Table 9 shows the mated linear and rotational forces as observed for an inlet at the C1 position. The table shows that many of these forces exceed both the 100-N linear force limits specified in IEC 62196-1 and the rotational torques observed during the 100-N evaluation.

**Table 9. Linear and Rotational Forces While Mated—C1 Position**

Item	DUT	Linear X-Axis Forces While Mated (N)		Linear Y-Axis Forces While Mated (N)		Lateral Rotational Torques While Mated (Nm)		Vertical Rotational Torques While Mated (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
1	CCS	92	-X	-	-	50	Left	23	Down
2	CCS	94	-X	-	-	50	Left	10	Down
3	CCS	94	-X	6	-Y	50	Left	21	Down
4	NACS	130	-X	-	-	47	Left	7	Down
5	NACS	127	-X	-	-	52	Left	8	Down
6	NACS	132	-X	-	-	47	Left	6	Down
7	CCS-NACS	67	-X	-	-	45	Left	28	Down
8	CCS-NACS	72	-X	40	-Y	44	Left	21	Down
9	CCS-NACS	69	-X	37	-Y	30	Left	16	Down
10	NACS-CCS	118	-X	14	-Y	53	Left	1	Up
11	NACS-CCS	137	-X	-	-	57	Left	2	Down
12	NACS-CCS	107	-X	-	-	62	Left	19	Down
13	NACS-CCS	122	-X	3	-Y	49	Left	3	Down

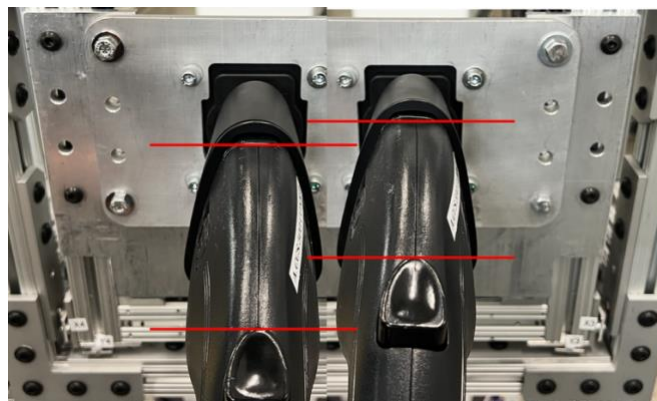
“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

Table 9 shows that mating the connector at the C1 position (where it is stretched to its limit) imparts significantly greater forces onto the connector/inlet pair than mating at a closer position, such as A1 or B2. These forces can exceed both the linear 100-N misalignment force given in IEC 62196-1 and UL 2251 and can impart a greater rotational torque onto the inlet as well, with torques of 50–60 Nm seen in this position (as compared to torques of 21–23 Nm seen during the 100-N misalignment test).

An important point to mention during the C1 evaluations from Table 9, specifically for the CCS-NACS adapter cases (7 through 9), was that we observed that the linear forces on the x-axis were considerably lower than the evaluations from rows 1 through 6 and 10 through 13 (the CCS, NACS, and NACS-CCS cases). This runs contrary to our initial expectation, which was that forces with an adapter would be greater, because of the increased leverage the adapter introduces.

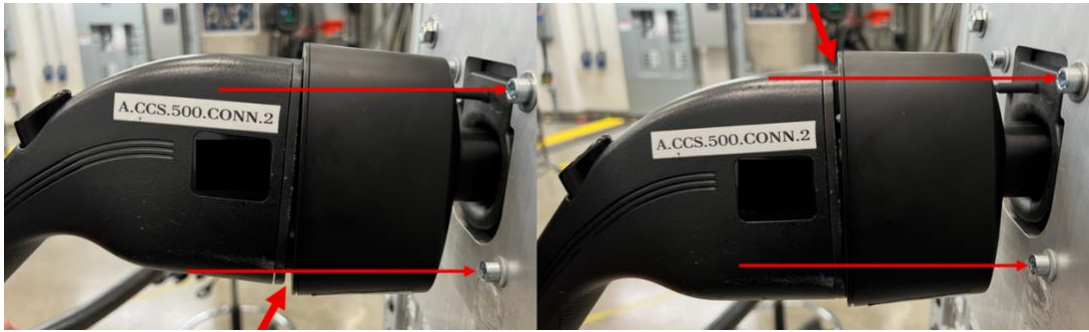
We initially thought we had misplaced our EV inlet fixture approximately 2.54 cm (1 inch) closer than the rest of the evaluations (creating less tension between the cable and the EV inlet). So, we repeated the evaluation three more times—the first one placing the EV inlet fixture at the right C1 location (at a distance of 116 in., as seen in Figure 6) and then two more moving the fixture 2.54 cm and 5.08 cm (2 inches) further away from C1 position, respectively, to increase the cable tension.

The results of these three evaluations were almost the same, with no relevant increase in forces. After reviewing images and videos of the evaluations, we realized the adapter had very loose mechanical tolerances, allowing the EVSE cable to relax much more and leading to lower tension than was observed on the CCS, NACS, or NACS-CCS evaluations. Figure 15 and Figure 16 show the large amount of slack in the system when side-loads are applied. On figure 16 in particular, we can appreciate (with thin arrows) how much of a slack happens when wiggling the setup up and down. The thicker arrows shows the gap that its created at the top & bottom because of this action. This reduced the amount of tension applied in this case, as compared to other evaluations performed at the same location. It also explains the much lower linear side-load forces shown in rows 7–9 of Table 9.



**Figure 15. Overlapped images of the fully mated CCS to NACS assembly, showing loose tolerances when wiggling it up and down**

Red lines help to indicate range of movement observed due to adapter mechanical tolerances.



**Figure 16. Side-by-side images of the same CCS to NACS fully mated assembly showing loose tolerances when wiggling it up and down**

Red lines help to indicate range of movement observed due to adapter mechanical tolerances.

Next, the team performed another set of bench evaluations, adding weight to the original 100-N force to determine the amount of weight needed to replicate the maximum forces seen during the user evaluations. The user evaluations featured forces on multiple axes at once, while the bench evaluations focused on applying force only on one axis at a time. Additional evaluations were performed with +5-lb (22.4-N) and +10-lb (44.8-N) weights, for a total force of 122 N and 144 N, respectively.

**Table 10. Force Replication Evaluations (122 N and 144 N)**

Force	Pull Direction	Linear X-Axis Forces While Mated (N)		Linear Y-Axis Forces While Mated (N)		Lateral Rotational Torques While Mated (Nm)		Vertical Rotational Torques While Mated (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
122 N	+X	133	+X	-	-	28	Right	-	-
122 N	+Y	-	-	137	+Y	-	-	45	Up
122 N	-X	134	-X	-	-	30	Left	-	-
122 N	-Y	-	-	130	-Y	-	-	37	Down
144 N	+X	175	+X	-	-	34	Right	-	-
144 N	+Y	-	-	160	+Y	-	-	51	Up
144 N	-X	165	-X	-	-	38	Left	-	-
144 N	-Y	-	-	153	-Y	-	-	27	Down

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

We see in Table 10 that, when applying a weight of 122 N, the rig measures a force of 133 N (likely because of some error/nonlinearities in the measurement rig design). This aligns well with the highest linear mated forces measured by the rig during user evaluations (137 N at position C1). Increasing this applied force slightly to 125 N would seem to give a good benchtop replication of the highest observed user forces in the linear domain. However, the increased weight did not increase the lateral rotational torques to the same degree seen during the user evaluations, with the maximum lateral torque at 122 N being 30 Nm (a relatively minor increase from the 23 Nm observed

during the 100-N evaluation, and significantly less than the roughly 50–60 Nm observed during the user evaluations). This suggests the current IEC/UL misalignment evaluation does not accurately represent rotational torque loading on the DUTs.

#### 4.4.2 Insertion and Withdrawal Forces

To provide more context on the acquired data with forces from different users at different EVSE-EV positions, this section includes the forces measured during insertion and removal of the EVSE connector. Although these forces are not as relevant as part of the IEC and UL side-load force test requirements, it is important to note these play an important role in connector-inlet wear-out. Here is where the forces observed were highest overall.

Table 11, Table 12, and Table 13 show the maximum transient linear forces and rotational torques experienced by the connector/inlet/adaptor DUT during connector insertion and withdrawal at positions A1, B2, and C1, respectively.

**Table 11. Linear and Rotational Forces During Insertion/Withdrawal—A1 Position**

Item	DUT	Insertion/ Removal Type	Max. Linear X- Axis Forces (N)		Max. Linear Y- Axis Forces (N)		Max. Lateral Rotational Torques (Nm)		Max. Vertical Rotational Torques (Nm)	
			Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
<b>Insertion</b>										
1	CCS	Normal	33	+X	99	+Y	48	Left	41	Down
2	CCS	Normal	28	+X	69	-Y	22	Right	22	Down
3	CCS	Normal	44	+X	100	+Y	57	Left	47	Down
4	CCS	Angled right	48	+X	117	+Y	48	Left	28	Down
5	CCS	Angled bottom	52	+X	178	+Y	34	Right	16	Down
6	CCS	Fast	20	+X	111	+Y	57	Left	47	Down
7	NACS	Normal	13	+X	76	-Y	31	Left	36	Down
8	NACS	Normal	15	+X	80	-Y	28	Left	25	Down
9	NACS	Normal	14	+X	52	-Y	26	Left	23	Down
10	NACS	Angled right	17	-X	76	-Y	33	Left	26	Down
11	NACS	Angled bottom	40	-X	126	+Y	39	Left	23	Down
12	NACS	Fast	14	+X	71	+Y	28	Left	28	Down
<b>Withdrawal</b>										
13	CCS	Normal	57	-X	191	-Y	17	Left	39	Up
14	CCS	Normal	15	+X	57	-Y	5	Left	7	Down
15	CCS	Normal	59	-X	52	+Y	19	Left	30	Up

Item	DUT	Insertion/ Removal Type	Max. Linear X- Axis Forces (N)		Max. Linear Y- Axis Forces (N)		Max. Lateral Rotational Torques (Nm)		Max. Vertical Rotational Torques (Nm)	
			Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
<b>Insertion</b>										
16	CCS	Angled right	56	-X	99	-Y	16	Right	42	Up
17	CCS	Angled bottom	41	-X	143	-Y	10	Right	24	Down
18	CCS	Fast	22	+X	60	-Y	7	Right	10	Down
19	NACS	Normal	34	-X	75	-Y	32	Right	36	Up
20	NACS	Normal	33	-X	196	-Y	46	Right	35	Up
21	NACS	Normal	12	+X	63	-Y	14	Right	12	Down
22	NACS	Angled right	70	+X	133	-Y	56	Right	27	Up
23	NACS	Angled bottom	41	-X	214	-Y	22	Right	17	Down
24	NACS	Fast	37	+X	205	-Y	51	Right	39	Up

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

**Table 12. Linear and Rotational Forces During Insertion/Withdrawal—B2 Position (Normal Insertions)**

Item	DUT	Max. Linear X- Axis Forces (N)		Max. Linear Y- Axis Forces (N)		Max. Lateral Rotational Torques (Nm)		Max. Vertical Rotational Torques (Nm)		
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	
<b>Insertion</b>										
1	CCS	54	+X	87	+Y	53	Left	62	Down	
2	CCS	21	-X	58	+Y	17	Left	20	Down	
3	CCS	36	+X	80	+Y	33	Left	28	Down	
4	NACS	19	-X	75	+Y	29	Left	21	Down	
5	NACS	42	-X	127	+Y	41	Left	33	Down	
6	NACS	26	-X	98	-Y	41	Left	45	Down	
7	CCS-NACS	18	+X	53	-Y	43	Left	38	Down	
8	CCS-NACS	22	+X	102	+Y	63	Left	49	Down	
9	CCS-NACS	12	-X	50	+Y	11	Left	7	Down	
10	NACS-CCS	32	+X	72	-Y	33	Left	30	Down	
11	NACS-CCS	45	+X	89	-Y	53	Left	60	Down	
12	NACS-CCS	16	-X	63	-Y	18	Left	19	Down	
13	NACS-CCS	32	+X	70	-Y	35	Right	36	Down	
<b>Withdrawal</b>										
14	CCS	42	-X	169	-Y	16	Left	27	Up	

Item	DUT	Max. Linear X-Axis Forces (N)		Max. Linear Y-Axis Forces (N)		Max. Lateral Rotational Torques (Nm)		Max. Vertical Rotational Torques (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
15	CCS	24	-X	60	-Y	11	Right	16	Down
16	CCS	20	-X	50	-Y	11	Right	18	Down
17	NACS	27	-X	66	-Y	18	Right	17	Up
18	NACS	26	-X	74	-Y	18	Right	14	Down
19	NACS	60	+X	90	-Y	55	Right	28	Up
20	CCS-NACS	28	+X	67	-Y	11	Left	20	Down
21	CCS-NACS	17	+X	63	-Y	15	Left	26	Down
22	CCS-NACS	24	-X	61	-Y	10	Right	9	Down
23	NACS-CCS	26	-X	62	-Y	20	Right	25	Down
24	NACS-CCS	43	-X	115	-Y	19	Left	36	Down
25	NACS-CCS	20	-X	57	-Y	5	Left	18	Down
26	NACS-CCS	45	+X	61	-Y	24	Right	22	Down

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

**Table 13. Linear and Rotational Forces During Insertion/Withdrawal—C1 Position (Normal Insertions)**

Item	DUT	Max. Linear X-Axis Forces (N)		Max. Linear Y-Axis Forces (N)		Max. Lateral Rotational Torques (Nm)		Max. Vertical Rotational Torques (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
<b>Insertion</b>									
1	CCS	23	-X	32	+Y	20	Left	9	Down
2	CCS	97	-X	115	+Y	60	Left	40	Down
3	CCS	102	-X	59	+Y	64	Left	57	Down
4	NACS	142	-X	154	+Y	60	Left	42	Down
5	NACS	179	-X	181	+Y	89	Left	64	Down
6	NACS	141	-X	113	+Y	52	Left	56	Down
7	CCS-NACS	120	+X	205	+Y	97	Left	108	Down
8	CCS-NACS	83	-X	110	+Y	60	Left	68	Down
9	CCS-NACS	75	-X	113	+Y	30	Left	23	Down
10	NACS-CCS	166	-X	80	+Y	66	Left	33	Down
11	NACS-CCS	146	-X	84	-Y	62	Left	44	Down
12	NACS-CCS	122	-X	72	-Y	73	Left	57	Down
13	NACS-CCS	136	-X	131	+Y	67	Left	49	Down
<b>Withdrawal</b>									

Item	DUT	Max. Linear X-Axis Forces (N)		Max. Linear Y-Axis Forces (N)		Max. Lateral Rotational Torques (Nm)		Max. Vertical Rotational Torques (Nm)	
		Mag.	Dir.	Mag.	Dir.	Mag.	Dir.	Mag.	Dir.
14	CCS	244	-X	360	-Y	94	Right	124	Up
15	CCS	106	-X	130	+Y	53	Left	46	Up
16	CCS	101	-X	103	-Y	52	Left	42	Up
17	NACS	135	-X	64	+Y	48	Left	30	Up
18	NACS	135	-X	46	+Y	54	Left	58	Up
19	NACS	138	-X	79	-Y	48	Left	23	Up
20	CCS-NACS	103	-X	100	-Y	70	Right	102	Up
21	CCS-NACS	76	-X	120	-Y	45	Left	24	Down
22	CCS-NACS	94	-X	129	-Y	35	Left	41	Down
23	NACS-CCS	123	-X	119	+Y	55	Left	27	Up
24	NACS-CCS	152	-X	79	+Y	63	Left	35	Up
25	NACS-CCS	138	-X	74	-Y	63	Left	22	Down
26	NACS-CCS	144	-X	65	-Y	79	Left	54	Up

“Magnitude” and “direction” are shortened as “Mag.” and “Dir.,” respectively.

As a result of these evaluations and after comparing the data, we observed that for both A1 and B2 positions, insertion and removal forces are wide and variable across most evaluations, with variations depending on the actual user and the force they used when interacting with the setup.

In the A1 and B2 positions, where the connector is in a relatively relaxed, easy-to-insert position, we can see that the linear forces in these positions are mostly related to the user’s behavior (e.g., whether they inserted with the connector misaligned to the right or bottom, or whether they inserted unusually quickly/forcefully compared to a normal insertion, etc.).

For the C1 position, there is a clear increase in the insertion and removal force used, which in some cases doubled or tripled the 100-N mark for the linear x- and y-axes. This is the result of the user applying an extra force (sometimes using their own body weight) to fight the EVSE cable tension mostly during the insertion. We observed a considerable increase in the rotational forces (torque) both on the lateral and vertical axes mainly because of the added forces to the existing cable tension on the C1 position.

## 4.5 Discussion

An important observation is that the addition of an adapter to the system can potentially affect the forces impacting the system, as the adapter introduces additional length, which increases the total lever arm of the forces transferred to the inlet. In the

evaluations performed with an adapter, an increase was observed in the leverage forces the EV inlet experiences.

Based on the gathered data, it can be appreciated that, although forces stayed relatively the same for either the A1 or B2 positions during the mated event, all forces were always under 100 N on every direction. And in a few interesting cases, the EVSE cable had some twist before being inserted, and/or depending on the person inserting it (right- or left-handed), some rotational forces on the y-axis were noted.

Additionally, we can see that adding an adapter to the system noticeably increases the rotational torque applied to the inlet. We can see in Table 8 that at position B2, the cases with an adapter noticeably increased the vertical rotational torque applied to the inlet. Similarly, we can see in Table 9 that the lateral rotational torques are increased with a NACS-CCS adapter. This is likely the result of the length of the adapter increasing the effective length of the lever arm, which applies the force pulling the connector to the inlet. In the B2 case, the primary force is gravity, pulling the connector downward (vertically); in the C1 case, the primary force is the tension on the connector pulling the connector laterally. The lower-than-expected force and torque values in the CCS-NACS adapter case might be explained by the adapter's large mechanical tolerances, as shown in Figure 15 and Figure 16.

Forces observed during insertion and removal are the highest recorded throughout the complete datasets on all connector-inlet configurations. These forces are wide and highly variable based on the user height, with or without EV experience, and so on, and also depending on the user's temperament. Most of these forces were random, except for positions A1 or B2. Additionally, another observed behavior was highly dependent on the user type—some users wiggled the connector sideways to remove it, but others moved it up and down, creating different force behaviors at the EV inlet.

For the C1 position and despite the user type, we observed an increase on these forces during insertion and removal, but due to differences between the users' techniques, the forces were not as predictable as the observed forces during the mated portion. Additionally, in cases such as the NACS to CCS, in which an adapter had to be used, a considerable increase in forces was seen as a result of the increased lever arm length.

## 5. Recommendations

With actual evaluations performed and data gathered from both users and the side force weight evaluations, we now have a better understanding of how these forces relate to real-world applications. As expected, we saw that scenarios in which the charging connector is stretched to its limit (as in the position C1) impart higher forces onto the inlet during insertion/removal and while mated.

These learnings help us directly compare the forces seen throughout our evaluations versus the misalignment test required in UL 2251, Sections 54C.1–54C.4. We can see that throughout most of the normal use cases (i.e., positions A1 and B2), the forces on the connector/inlet pair are less than the 100-N misalignment force required by the current IEC 62196-1/UL 2251 standards. However, in the most extreme scenarios (i.e., position C1), in which the user stretches the cable to its limit to “make it fit,” forces can exceed the current 100-N standard. As discussed in Section 4.5.1, performing the IEC 62196-1/UL 2251 misalignment test with a force of 122 N closely replicates the highest linear forces observed during the user evaluation (with the replicated benchtop forces coming in only slightly under the user evaluation forces). Based on these findings, we recommend the misalignment force weight in UL 2215 Section 54C be increased from 100 N to 125 N.

Additionally, we saw that adding an adapter between the connector and inlet led to an increase in the rotational torque applied to the inlet, even if the linear forces are not noticeably increased. Connector and inlet manufacturers should consider the increased torque caused by an adapter in the system when designing components. Because of this, we recommend future work should examine potential additions to IEC 62196-1 and UL 2251 to account for rotational-specific force/torque requirements.

We found that the high, transient forces observed during insertion/withdrawal for the x and y linear axes were less than the actual forces read on the 750-N side-load evaluation, but the forces observed on the lateral and vertical rotational forces were considerably higher than the ones from the 750-N test. This introduces another valid point—user randomness at the time of insertion and removal also adds the rotational portion that both the 100-N and 750-N test cannot capture.

In summary, our recommendations are:

1. The misalignment force weight in UL 2215 Section 54C should be increased from 100 N to 125 N.
2. Future work should examine potential additions to IEC 62196-1 and UL 2251 to account for rotational-specific force/torque requirements.

## References

International Electrotechnical Commission (IEC). 2022. *Plugs, socket-outlets, vehicle connectors and vehicle inlets – Conductive charging of electric vehicles – Part 1: General requirements*. IEC 62196-1 (2022-05 Ed4.0).

<https://webstore.iec.ch/en/publication/59922>.

UL. 2023. *Plugs, Receptacles, and Couplers for Electric Vehicles*. UL 2251.

<https://www.shopulstandards.com/ProductDetail.aspx?UniqueKey=33653>.

U.S. Access Board. 2023. “Design Recommendations for Accessible Electric Vehicle Charging Stations.” July 17, 2023. <https://www.access-board.gov/tad/ev/>.

## Appendix A. Design and Construction of the Evaluation Fixture

After several technical proposals and some experimentation, we developed a functional and compact fixture that allowed us to evaluate the forces experienced by the charge connector and inlet in various scenarios.

Appendix B describes the EVSE fixture to simulate where the cord of the EVSE hangs from the unit. This allowed us to recreate different height scenarios to represent the different EVSE manufacturers in the market.

Appendix C and Appendix D describe the EV inlet fixture and how it was designed, built, and calibrated. This includes the six degrees of force measurements, as well as the circuitry for the continuity measurements.

## Appendix B. EVSE Cord Fixture

This fixture consists of an approximately 10-ft-tall rigid structure made of the popular 80/20 extruded aluminum T-slotted style. This unit is made of two parts: The first is a long and tall rectangular frame fixed to the building's structure that provides support for the second part—a smaller rectangular structure mounted on sliders, allowing it linear movement up and down. This allows us to obtain the desired EVSE cable height. This adjustment is usually performed before the test and stays there throughout the entire evaluation.

This structure is permanently fixed to the lab, and its only movable part is operated only during the fixture height adjustment of this part of the setup. Once the desired height is set, the moving section is secured by two hand-operated lock levers at the 80/20 rails. An additional safety cord is also tightened up to a part on the wall.

This part has no electrical or mechanical stored energy once it is set up. This EVSE fixture is pictured in Figure B-1.

In this study, we used a fixed EVSE cable height of 2.28 m (7.5 ft), with a cable length of 4.0 m (13.12 ft) from the EVSE cable glands to the CCS or NACS connector for each case.



**Figure B-1. View of the EVSE fixture for holding the EVSE cable/connector assembly**

## Appendix C. EV Inlet Instrumentation Equipment

To capture the linear and rotational forces of all six axes, we used three four-channel sensor interface modules (PCD-400B series) made by Kyowa,<sup>1</sup> purposely intended for strain gauges and strain gauge transducers. Each of these modules was connected to four of our compression load cells. Because we had four sensors on each axis, we assigned one of these modules to each (Figure C-1).

The Kyowa PCD-400 design allowed us to stack up to four of these units to make a 16-channel system. We stacked three of these, as we only needed 12 sensors for our approach, with one unique USB-A-type port for data collection.

Additionally, for the 12 sensors or compression load cells, we used the LMA-A series, also from Kyowa.<sup>2</sup> This is a very robust and small-size compression cell capable of up to 1 kilonewton (kN) (approximately 225 lb) each in a 20-mm-diameter coin design.



**Figure C-1. Image of one Kyowa 1-kN load cell**

Additionally, for the electrical circuit continuity during the evaluations, we used a multichannel digital oscilloscope with data logging function—in this case, the DL850 ScopeCorder from Yokogawa.<sup>3</sup> This unit gave us the ability to accurately monitor and record continuity of all the DC power lines (DC+ and DC-), control pilot (CP) and proximity pilot (PP), and ground circuits and log the exact time of circuit connect and disconnect events during the evaluation.

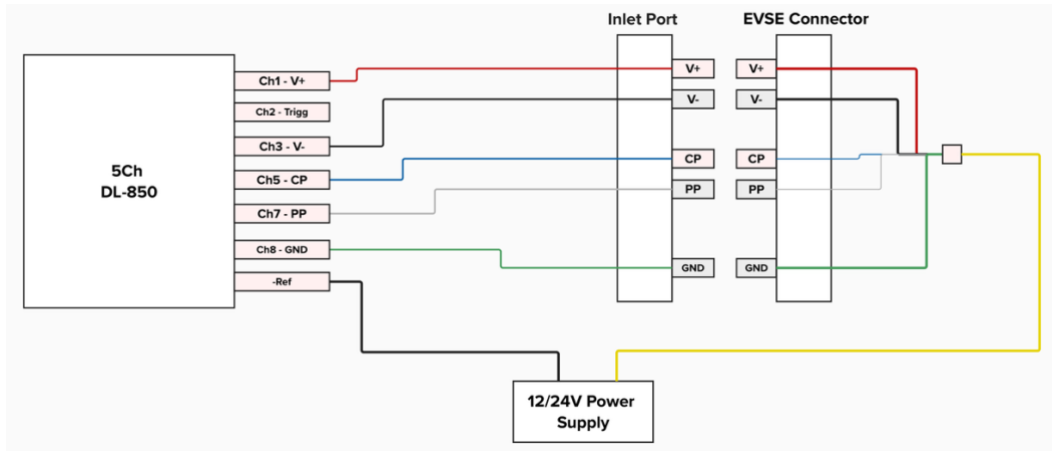
Additionally, we used a regular 12-V bench power supply to feed a 12-V signal, which was purposely set at a very low current (around 200 mA) throughout all of the EVSE cable circuits and the EV inlet. We used this to close the circuit and bring the 12-V signals into the Yokogawa DL-850 ScopeCorder during the evaluations. This allowed us to capture the rising and falling times of each of the circuits during the connector insertion and removal, respectively.

Figure C-2 is the electrical circuit to perform such readings. Additionally, we added a momentary push-button switch connected to a separate ScopeCorder channel that was used as a trigger on our data logging, which helped us separate the useful data from the rest.

<sup>1</sup> [https://product.kyowa-ei.com/en/products/data-loggers/type-s\\_pcd-400\\_series?tab=features](https://product.kyowa-ei.com/en/products/data-loggers/type-s_pcd-400_series?tab=features).

<sup>2</sup> [https://kyowa-ei.meclib.jp/library/books/e2022/book/#target/page\\_no=92](https://kyowa-ei.meclib.jp/library/books/e2022/book/#target/page_no=92).

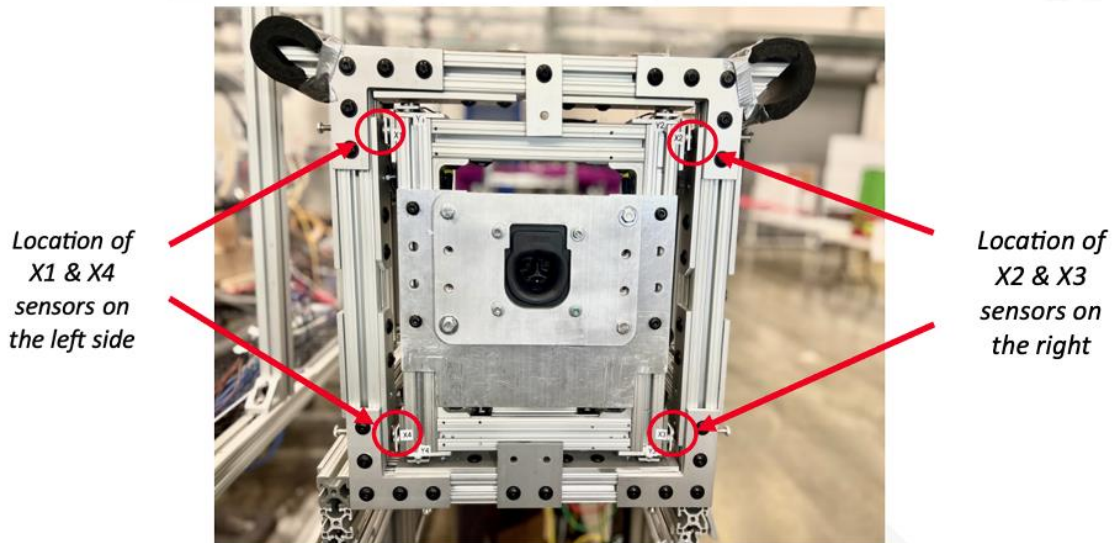
<sup>3</sup> <https://tmi.yokogawa.com/us/solutions/discontinued/dl850dl850v-scopecorder/>.



**Figure C-2. Electrical diagram of the circuit to capture connector/inlet conductivity**

## Appendix D. EV Inlet Construction

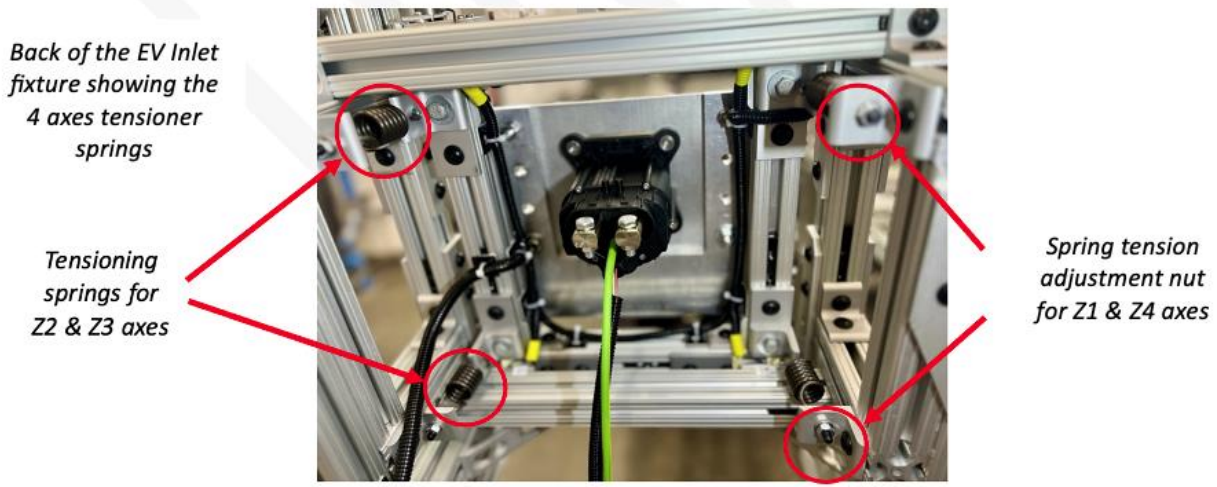
We constructed two subassemblies made of 80/20 material, creating a dual rectangular frame system. The outer frame served as the main structural support, and the inner frame is “floating,” suspended by the compression load cells sensing on the x- and y-axes. There were four sensors allocated at each of the x- and y-axes, totaling eight for these two. For the x-axis, two on the left side and two on the right side in between the two frames allowed us to capture linear movements on each x-axis direction. See Figure D-1.



**Figure D-1. Key location of the load cells across the fixture**

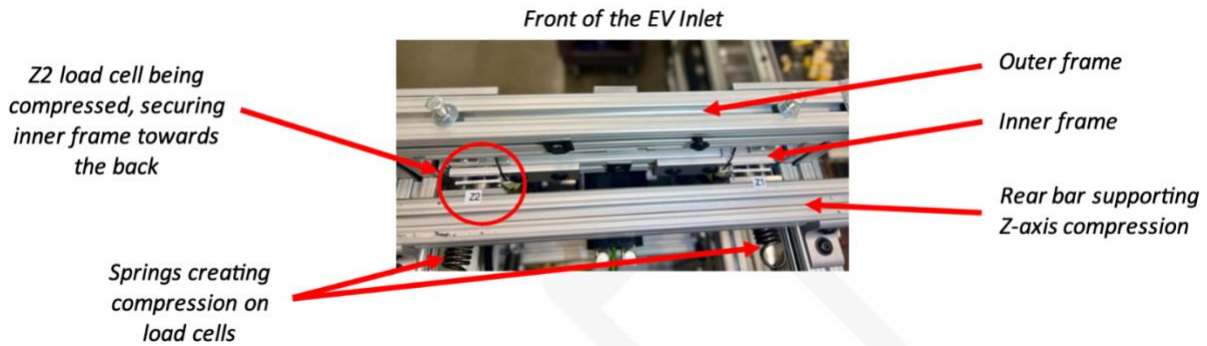
Similarly, the four sensors for the y-axis were allocated at the top and bottom, allowing us to capture the forces going up and down.

The eight sensors allocated for both x- and y-axes prevented the inner frame from escaping the main structure if forces actuated on any of these axes. However, the z-axis forces could push or pull the inner frame out of its cavity between the outer frame, and the front and rear of the plate was required to mount the EV inlet and access its electrical connections. Therefore, we needed the inner frame to be free of obstacles to simulate the EV inlet. That is one reason why we designed the z-axis a bit differently by mounting the correspondent sensors at the back of the inner frame (Figure D-2), right on each of the corners. We also used four sensors, but different from the x-y approach, where the inner frame cannot move outside its limits, we added two horizontal 80/20 bars at the back of the inner frame and four tensioning springs, one at each corner, compressing the z-axis sensors against it.



**Figure D-2. Rear view of the EV inlet fixture showing the tensioning springs and adjusting hardware**

This way, no matter how strong the forces pushing the EV inlet were, the rear bar would not allow more movement toward that direction. On the opposite side, forces pulling the EV inlet in the z-axis would have to be stronger than the tension of the four springs (Figure D-3). We added a small locking piece in the front for such an extreme case.



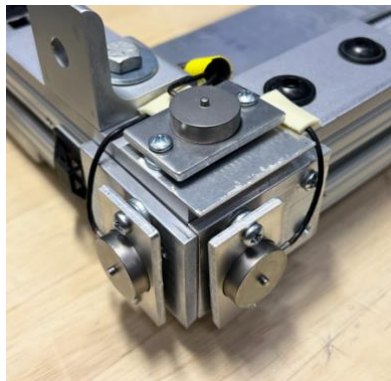
**Figure D-3. View of the top Z-axis load cells being compressed by the springs**

Because the load cells are only positive pressure sensors, a certain amount of tension was added to all the sensors. In the case of the x- and y-axes, a special neoprene round spring was placed underneath the sensor, creating a flexible bed for the setup to add compression to the sensors while still allowing some movement (Figures D-4, D-5, and D-6). After some compression was added, then a calibration was performed, and all the sensors were set to a digital net-zero force afterward.

For the z-axis, a certain tension was added via the spring to create a compression force toward the back of the fixture, like the other sensors. Then a zero-value was calibrated, allowing us to measure positive and negative forces from this point.



**Figure D-4. Neoprene round spring behind the sensor, allowing for a small amount of flexibility**



**Figure D-5. View of a cluster of three load cells—x, y, and z—at one of the corners of the inner frame**



**Figure D-6. Final view of the inner frame wired up with all 12 load cells in groups of 3 at each corner, with the metal plate ready to have an EV inlet mounted**



## About the ChargeX Consortium

The National Charging Experience Consortium (ChargeX Consortium) is a collaborative effort between Argonne National Laboratory, Idaho National Laboratory, National Laboratory of the Rockies, electric vehicle charging industry experts, consumer advocates, and other stakeholders. The ChargeX Consortium's mission is to work together to measure and significantly improve public charging reliability and usability by June 2025.

For more information, visit [chargex.inl.gov](http://chargex.inl.gov).

FEBRUARY 2026

