## Steering Force Test

We ran a test to determine the toque required to turn the steering wheel. We used this data for our preliminary calculations so we could down-select between the geared or belt-driven steering system options to determine our design direction. After conducting the test an applying a conservative safety factor, we will design our steering system to apply a 28 N-m torque to the steering column.

**Test setup:**

The test setup, shown in Figure H-1, has a force gauge attached to the steering wheel, at a known distance from the center of the steering column.

Figure 1. Shows test setup with a force gauge attached to the steering wheel to measure the force necessary to turn the wheel when the cart is at a standstill.

The test was conducted by pulling the force gauge directly tangent to the steering wheel until there is slight movement of the tires. At this point, we recorded the measured force from the force gauge. We repeat the test 5 times to find ensure the results are consistent.

The tests were performed on smooth concrete with the cart at rest with all original vehicle components in the cart as well as the provided DC servo motor. We repeated the tests with and without an additional 17 N weight which simulates the added weight of our gearbox, linear motor, and mounts.

The test surface of smooth concrete was chosen because this is a neutral and consistent surface. The safety factor that is applied after the data is collected accounts for variation in surface roughness, considering that the cart may be run on asphalt or grass. Additionally, the tests were conducted with the cart at rest because this is the speed at which the steering column requires the greatest torque to rotate the tires. By conducting the tests in this state, we are ensuring that this is the maximum torque that will be required.

**Results and Analysis:**

We calculated required steering torque using Equation 1:

$$T = Fr, \tag{1}$$

where $T$ is the Torque (in N-m), $F$ is the measured force (in Newtons), and r is the radius in mm. The radius is the distance between the force gauge and center axis of the steering column. The results from the test are summarized in Table H-1.

Table 1. Shows the steering wheel force test results summary.

| | | |
|---|---|---|
| **Additional Weight in the Cart [N]** | 17 | 0 |
| **Measured Force [N]** | 17 | 14 |
| **Measured Arm Length [m]** | 0.42 | 0.42 |
| **Calculated Torque [N-m]** | 7.14 | 5.88 |

**Conclusion:**

This test helped us determine that the cart (with a simulated 17N weight) requires a torque of 7.15 N-m on the steering column to rotate the tires while the cart is at rest on smooth concrete. We will use a safety factor of 4 to account for the potential error in these tests which arise from our test equipment and setup. Additionally, our safety factor accounts for the test surface; we conducted the tests on smooth concrete, whereas higher friction surfaces such as asphalt or grass will increase the required steering torque. As a result, we will use 28 N as our required steering torque for the preliminary system design calculations and concept selection process.

## Full Range Steering Test

The purpose of this test is to measure the range of motion of the steering system to ensure that the gearbox and related mechanical systems did not reduce our original capabilities. This test examines the mechanical function of the steering system. It involves every component of the steering subassembly, except for the rotary encoder.

**Procedure:**

1. Assemble the steering system of the vehicle. Wire the steering motor and ensure that you can control the motor rotation to steer the wheels left/right.
2. Elevate the vehicle on blocks so that the wheels are not in contact with any external objects and can rotate and steer freely. Align the steering wheel base plate so that it points straight forward.
3. Coat the top of the output shaft in black permanent marker so the scribe marks can be seen easily.
4. With the wheels point straight forward, scribe a line on the output shaft that goes down the centerline of the gearbox. The screws for mounting the encoder should be a good visual reference.
5. Rotate the steering column to the right until the system has reached the limit of its travel. Take a picture of the current position.
6. Rotate the steering column to the left until the system has reached the limit of its travel. Take a picture of the current position.
7. Repeat steps 7 and 8 until you have 15 measurements in each direction.
8. Export the photos to OneNote. Using the ruler tool, measure the angle between the scribed line and the centerline of the gearbox.

**Results and Analysis:**

For this test, we started by identifying the centerline of the gearbox as a reference line, as shown in Figure 1-A. This was then scribed onto the output shaft to provide a visual reference, as shown in Figure 1-B.

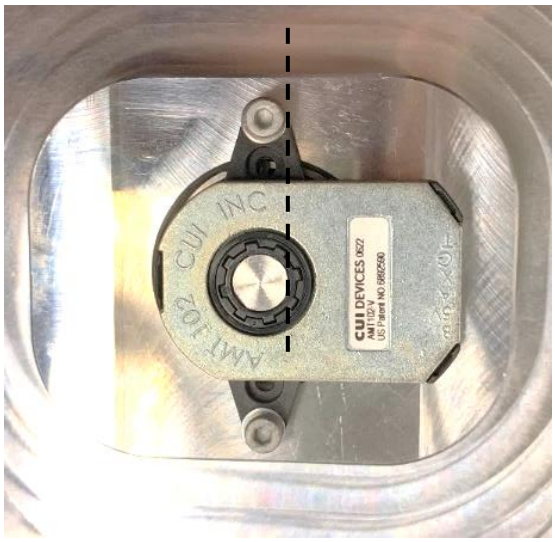


Figure 2. Top View of Gearbox Showing Centerline


Figure 3. Top View of Gearbox Showing Scribed Centerline on Output Shaft

Table 2. Raw Data Showing the Range of Motion in Both the Left and Right Directions

| **Trial** | **Range of Motion** | |
|---|---|---|
| | **Left** [deg] | **Right** [deg] |
| 1 | 43 | 44 |
| 2 | 47 | 44 |
| 3 | 49 | 45 |
| 4 | 52 | 43 |
| 5 | 38 | 42 |
| 6 | 41 | 43 |
| 7 | 58 | 48 |
| 8 | 43 | 49 |
| 9 | 44 | 46 |
| 10 | 40 | 37 |
| 11 | 40 | 46 |
| 12 | 46 | 55 |
| 13 | 47 | 51 |
| 14 | 46 | 42 |
| 15 | 46 | 45 |

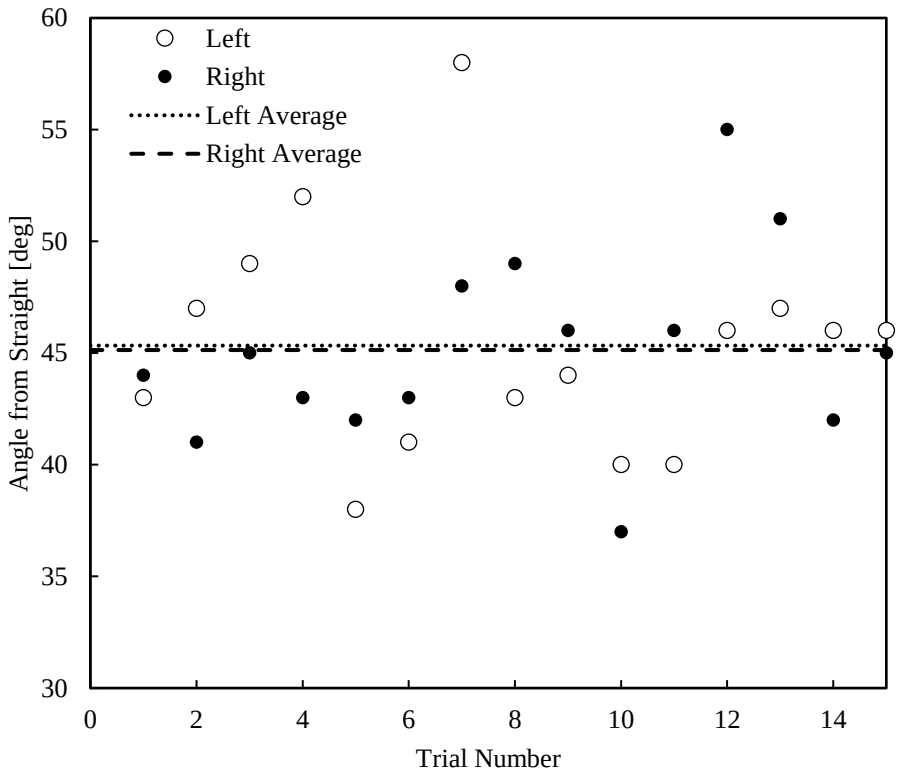


Figure 4. Displaced Angle Measured in Each Trial

## Steering Time Test

The purpose of this test is to measure the time required to move through the full range of motion of the steering system. This test examines the mechanical function of the steering system motor. It involves every component of the steering subassembly including the wired motor.

**Procedure:**

1. Assemble the steering system of the vehicle, ensure that the motor can be controlled electronically.
2. Test the system by controlling the motor movement to achieve full range of motion of the steering system. The system will reach a mechanical stop when it cannot turn further. Make sure to not push the motor past what is physically possible.
3. Elevate the vehicle on blocks so that the wheels are not in contact with any external objects and can rotate and steer freely. Align the steering wheel base plate so that it points straight forward.
4. Coat the top of the output shaft in black permanent marker so the scribe marks can be seen easily.
5. With the wheels point straight forward, scribe a line on the output shaft that goes down the centerline of the gearbox. The screws for mounting the encoder should be a good visual reference.
6. Place a stopwatch next to the top of the output shaft. Record a video so that both the scribed output shaft and stopwatch are visible in the view of a camera.
7. Use the full power of the motor to move throughout the range of motion of the steering system, pausing as each limit (left or right) is reached.
8. Repeat this movement 15 times, capturing this all in the same video.
9. At the end of the test, slowly move through the video and note the start and stop times for each section of movement.
10. Repeat the test with the cart sitting on smooth concrete.

**Results and Analysis:**

For this test, we started by identifying the centerline of the gearbox as a reference line, as shown in Figure 1-A. This was then scribed onto the output shaft to provide a visual reference, as shown in Figure 1-B.

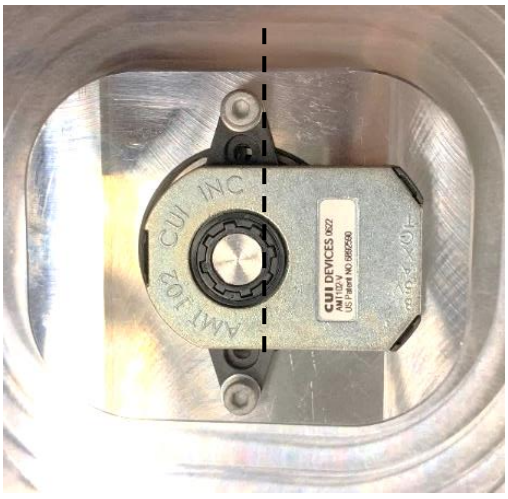


Figure 5. Top View of Gearbox Showing Centerline


Figure 6. Top View of Gearbox Showing Scribed Centerline on Output Shaft

Table 3. Raw Data for Showing Time to Steer Through Full Range of Motion

| Run | Movement Direction | Wheels on Concrete | Wheels Elevated |
|---|---|---|---|
| | | [sec] | [sec] |
| 1 | Left | 1.42 | 1.97 |
| 2 | Left | 1.58 | 1.48 |
| 3 | Left | 1.81 | 1.59 |
| 4 | Left | 1.58 | 1.29 |
| 5 | Left | 1.88 | 1.42 |
| 6 | Left | 1.7 | 1.44 |
| 7 | Left | 1.62 | 1.96 |
| 8 | Left | 1.66 | 1.43 |
| 9 | Left | 2.23 | 1.42 |
| 10 | Left | 2.01 | 1.55 |
| 11 | Left | 1.93 | 1.68 |
| 12 | Left | 1.79 | 1.55 |
| 13 | Left | 2.38 | 1.29 |
| 14 | Left | 1.72 | 1.58 |
| 15 | Left | 1.9 | 1.54 |
| 1 | Right | 1.62 | 1.79 |
| 2 | Right | 1.85 | 1.36 |
| 3 | Right | 1.48 | 1.7 |
| 4 | Right | 1.78 | 1.47 |
| 5 | Right | 1.59 | 1.73 |
| 6 | Right | 1.93 | 1.6 |
| 7 | Right | 1.88 | 1.65 |
| 8 | Right | 2.03 | 1.86 |
| 9 | Right | 2.53 | 1.52 |
| 10 | Right | 1.78 | 1.5 |
| 11 | Right | 1.68 | 1.69 |
| 12 | Right | 1.85 | 1.8 |
| 13 | Right | 1.74 | 1.46 |
| 14 | Right | 2.1 | 1.23 |
| 15 | Right | 1.52 | 1.51 |

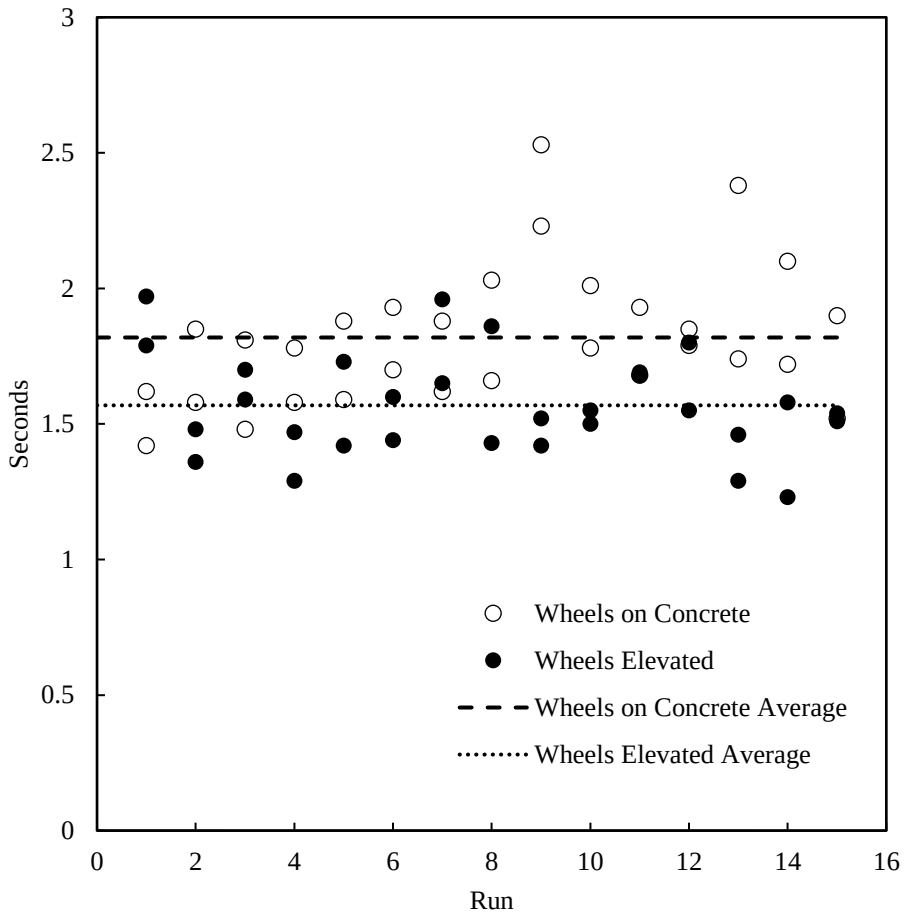


Figure 7. Time to Steer for Each Trial