Exploring Air Resistance and its Effects on Acceleration

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Abstract

In this experiment we studied the effects of increasing the cross-sectional area of a cart on its acceleration and velocity. Through this, we proved that air resistance exists and is directly correlated to the cross-sectional area of an object, as well as its shape. Furthermore, we found that air resistance can be decreased by keeping cross-sectional area constant and changing the shape of an object.

Introduction

Throughout high school physics, we have been calculating the range of projectiles, the velocity of carts, and even the acceleration of planes - all by assuming that air resistance is negligible. In this experiment, we set out to prove that air resistance does exist, and that it has a significant impact on acceleration and velocity of an object relative to its cross-sectional area

Background

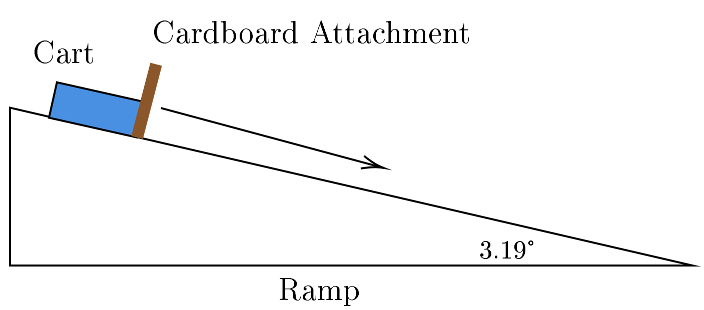


Figure 1. General experimental setup with a Smart Cart rolling down a ramp. Cross-sectional area of the cart is changed using a cardboard attachment.

Figure 1 shows the basic experimental configuration of this experiment. The cart was rolled down a ramp with an attachment on its front. Said attachment modified the cart's cross-sectional area as well as its aerodynamic properties.

We can break down the forces experienced by the cart into components 1 as shown in the free body diagram below.

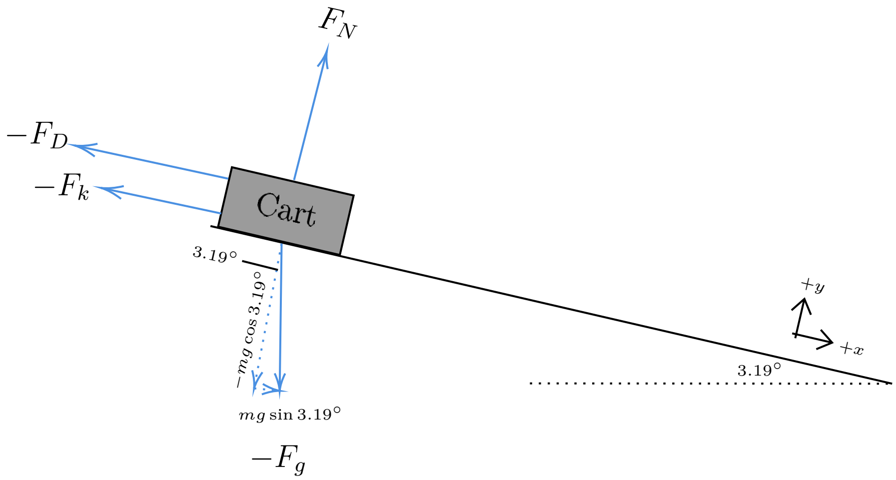


Figure 2. Free body diagram illustrating various forces acting upon the Smart Cart

In the free body diagram in figure 2, the cart is on the ramp, with the forces of air resistance (F_D) and kinetic friction (F_k) acting against the cart in the horizontal direction. The cart is also accelerated down the ramp by the horizontal component of gravity ($mg\sin(3.19°)$). Given that the force of air resistance upon an object with a drag coefficient of K is Kv^2, the following equation can be derived to solve for the drag coefficient where acceleration and velocity are a function of time.

$$F = mg\sin(\theta) - F_k \tag{1}$$

$$F_{\text{net}} = F - Kv(t)^2$$

$$ma(t) = F - Kv(t)^2$$

$$F - ma(t) = Kv(t)^2$$

$$K = \frac{F - a(t)m}{v(t)^2} \tag{2}$$

Methods

1. A 250g weight was taped onto the Smart Cart to make the effect of additional weight negligible
2. A 1.22m ramp was placed on top of a textbook so that it made a 3.19 degree angle with the lab bench counter
3. Depending on the trial being run, a cardboard attachment was measured and cut to proper dimensions and taped to the front of the Smart Car
4. The Smart Car's position, velocity, force, and acceleration were all recorded relative to time using Pasco Capstone software
5. Steps 3 and 4 were repeated eight more times until all trial data were successfully collected

Results

Table 1

K values relative to cross-sectional area and the shape of the attachment

Attachment	**Length**	**Width**	**Area (cm^2)**	**K**
None	3.	8.5	33.85	0.002
Orange	29	33	957	0.184
Cardboard	12	20.75	249	0.105
Cardboard	15.78	15.78	249	0.109
Orange Pocket	29	33	957	0.198
Equilateral Wedge	9.4	26.5	249	0.087
Sharp Wedge	9.4	26.5	249	0.050
Sharp Wedge on Orange	29	33	957	0.127

Discussion

Methodology

One unique part of our methodology that proved crucial to the statistical significance and accuracy of our data was the addition of a 250g weight on top of the Smart Cart. Adding the various cardboard attachments used to modify the aerodynamic properties of the Smart Cart would increase the total weight of our modified Smart Cart system. It would be possible to account for the variance in weight by measuring each cardboard attachment along with the tape used to affix it; however, a lack of time meant that it would be more efficient to make the additional weight negligible by increasing the overall weight of the Smart Cart itself. Although this may introduce some variance into our results, the relative effect of the additional weight is acceptable given how little the attachments weighed relative to the weighted Smart Cart.

Air Resistance

A major goal of this experiment was to determine whether or not air resistance actually existed, or if it had enough of an effect to affect our data in a manner that was statistically significant. If air resistance were to exist and be statistically significant with respect to the data collected, then there should be a statistically significant decrease in acceleration due to the increasing drag forces. After collecting multiple sets of data and removing outliers based on inter-quartile ranges, the data for each trial were individually plotted on a graph. Specifically, when acceleration relative to time was plotted for each trial, as well as a linear regression for acceleration relative to time, it becomes clear that when cross-sectional area is increased, there is a time-dependent, increasing drag force that decreases acceleration. Referring to A3, A4, A5, A2, A6, A7, and A8, each of their respective linear regressions of acceleration all have negative slopes and decrease with respect to time - signifying an overall deceleration. Furthermore, when referring to the base case, A1, it can be seen that the slope of the linear regression of acceleration is practically zero. The base case did not have a cardboard attachment nor an increased cross-sectional area. This shows that increasing cross-sectional area will affect the aerodynamic properties of the cart, which will create drag forces that decelerate the cart.

Calculating the Drag Coefficient ($\boldsymbol{K}$)

To calculate the drag coefficient for a given time, we can use equation 2. Since all the variables needed to solve for K at a given time are known, then these values can be substituted to solve for K at a given time - with the exception of F_k from equation 1.

Calculating the Force of Kinetic Friction

The friction forces on the cart are a system composed of static friction from the wheels on the ramp, and kinetic friction on the axles. It becomes difficult to find kinetic friction since it presents two unknowns: F_k and K. To determine F_k without needing to use two unknown variables, we let $K = 0$ in the base case where the cart had no additional attachments affecting its cross-sectional area. We were able to set K to zero in this case because in A1, the linear regression of acceleration for the base case was equal to zero, thus showing that the deceleration due to air resistance was also zero. To find for F_k given K, we can solve for F_k as a function of time by dividing acceleration by the mass of the cart and then average over the time interval of the respective trial. This will give us a numeric value for F_k.

$$F_k(t) = \frac{a(t)}{m}$$

$$F_k = \frac{\Sigma F_k(t)}{\text{Number of Measurements Taken}} \tag{3}$$

Appendix A

Trial Charts

Figure A1. Raw Data Collected from Smart Cart and Calculated K value - No Attachment

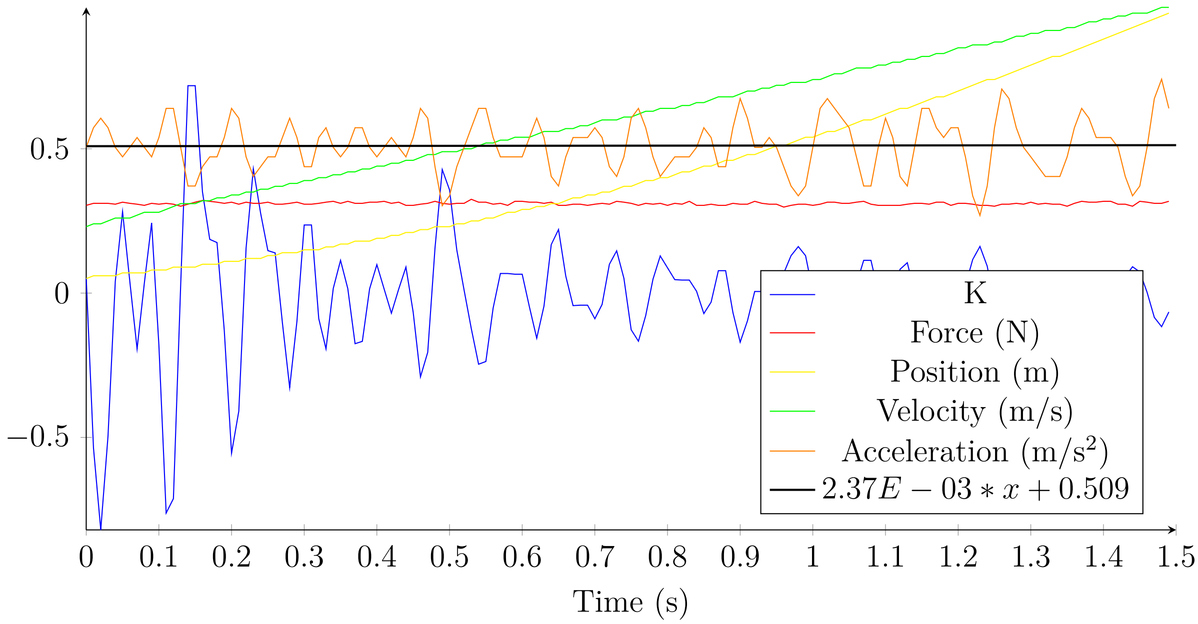


Figure A2. Raw Data Collected from Smart Cart and Calculated K value - Orange

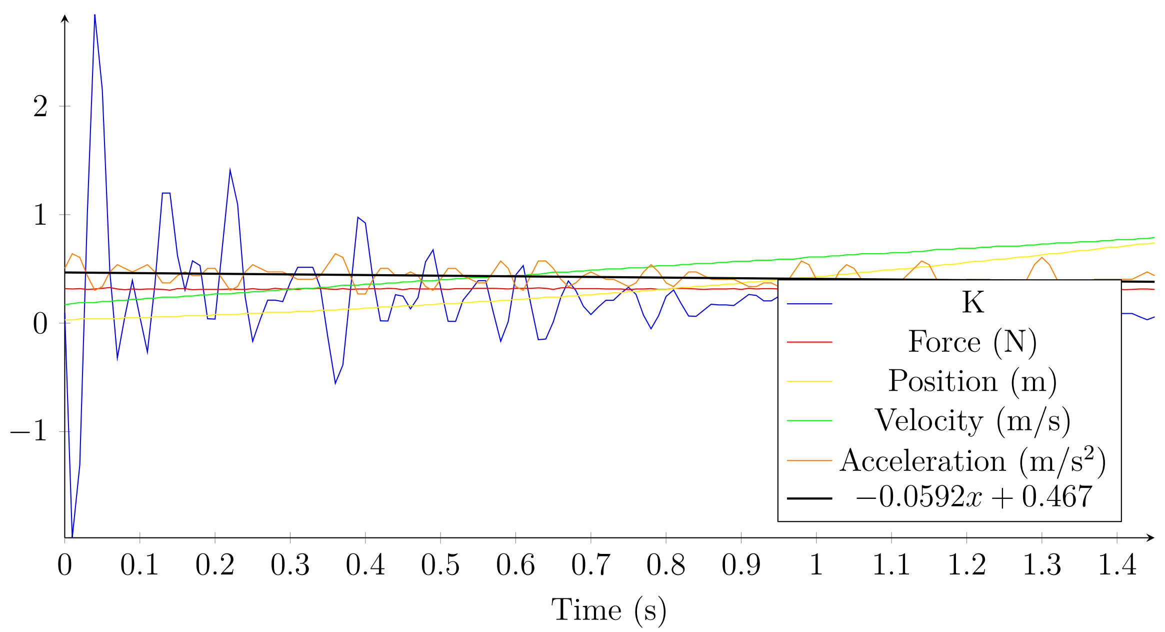


Figure A3. Raw Data Collected from Smart Cart and Calculated K value - Cardboard (12 x 20.75)

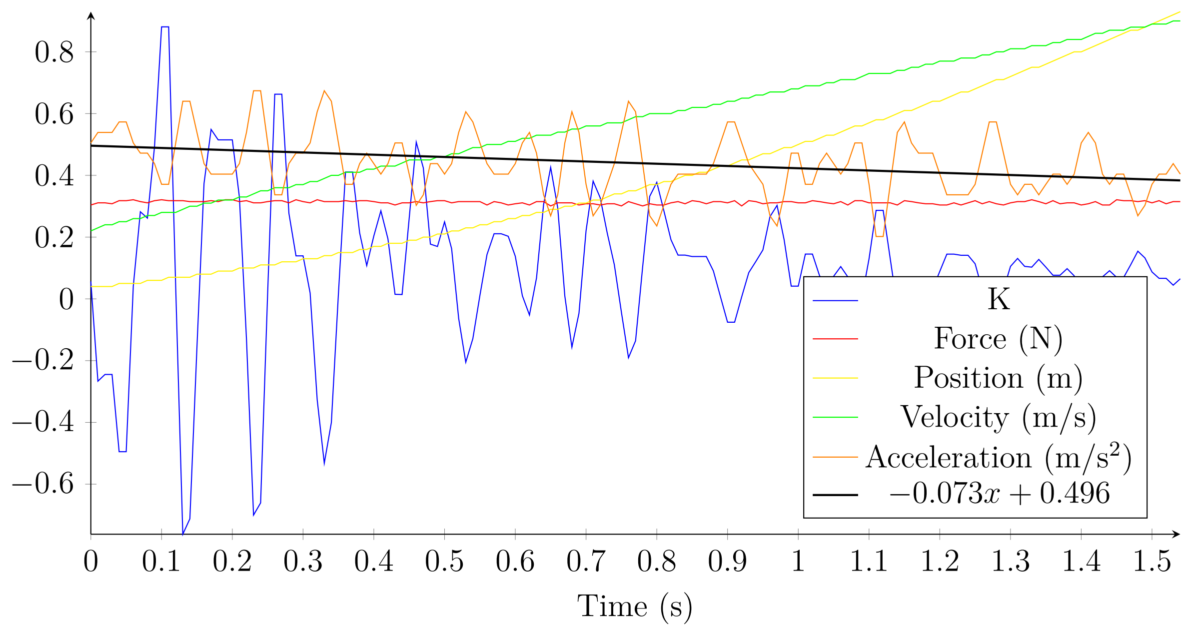


Figure A4. Raw Data Collected from Smart Cart and Calculated K value - Cardboard (15.78 x 15.78)

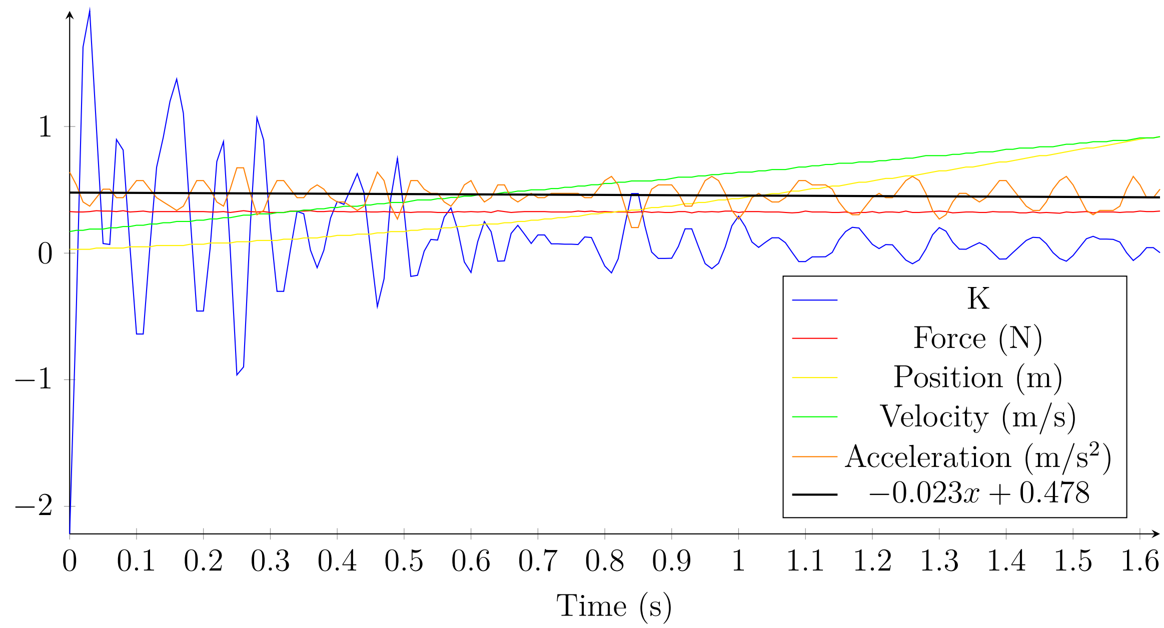


Figure A5. Raw Data Collected from Smart Cart and Calculated K value - Equilateral Wedge

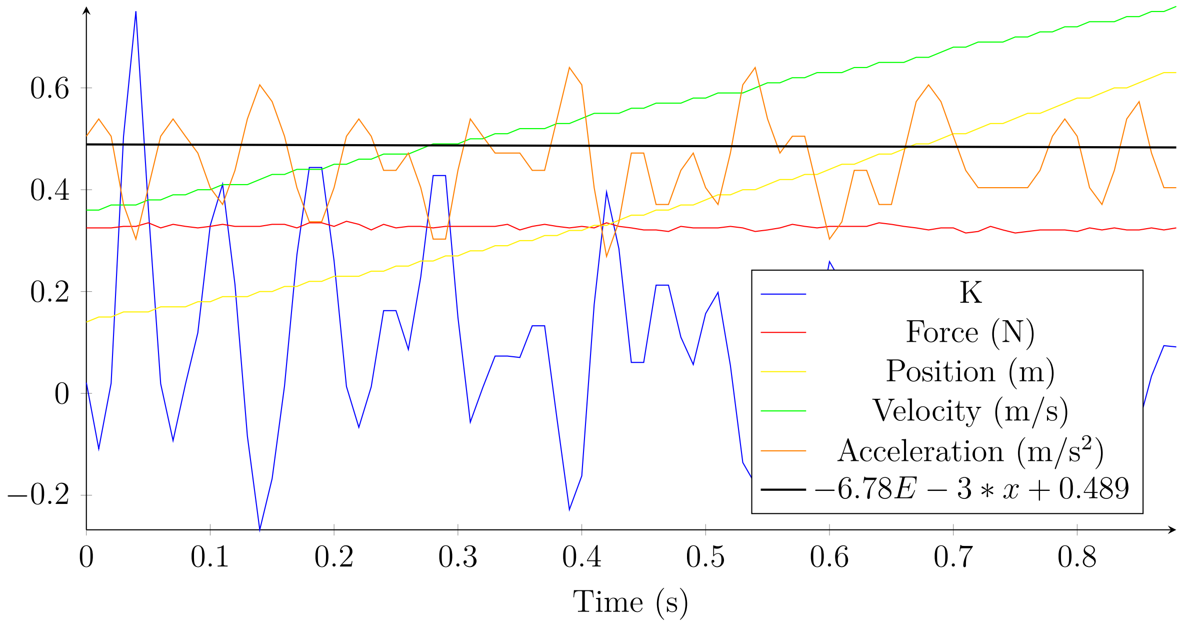


Figure A6. Raw Data Collected from Smart Cart and Calculated K value - Orange with Pocket

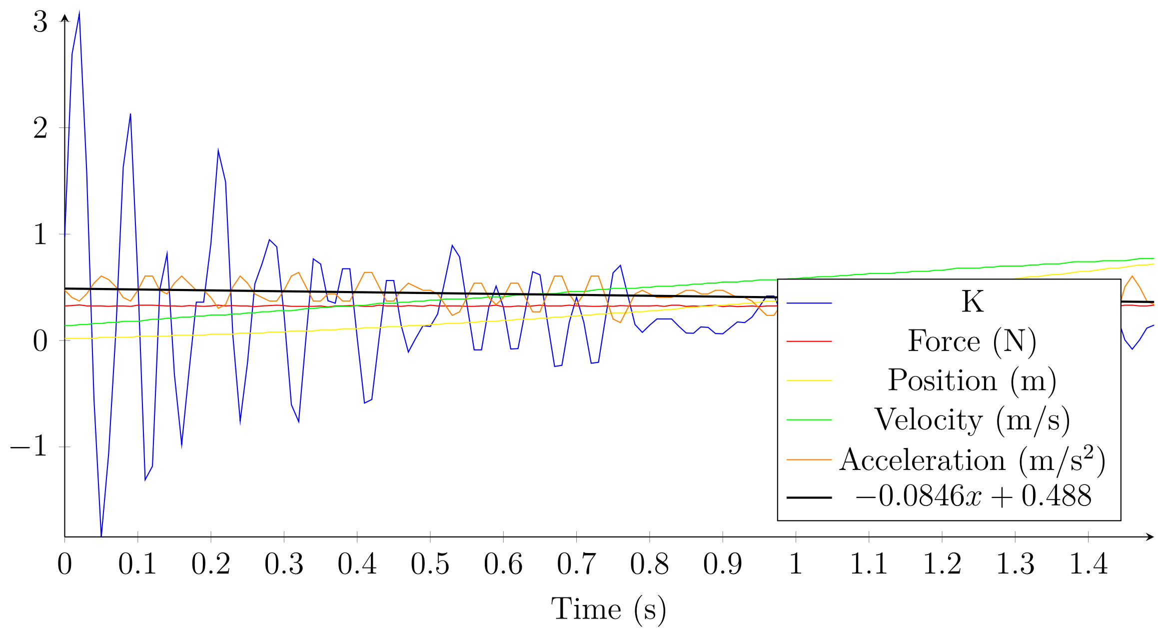


Figure A7. Raw Data Collected from Smart Cart and Calculated K value - Sharp Wedge

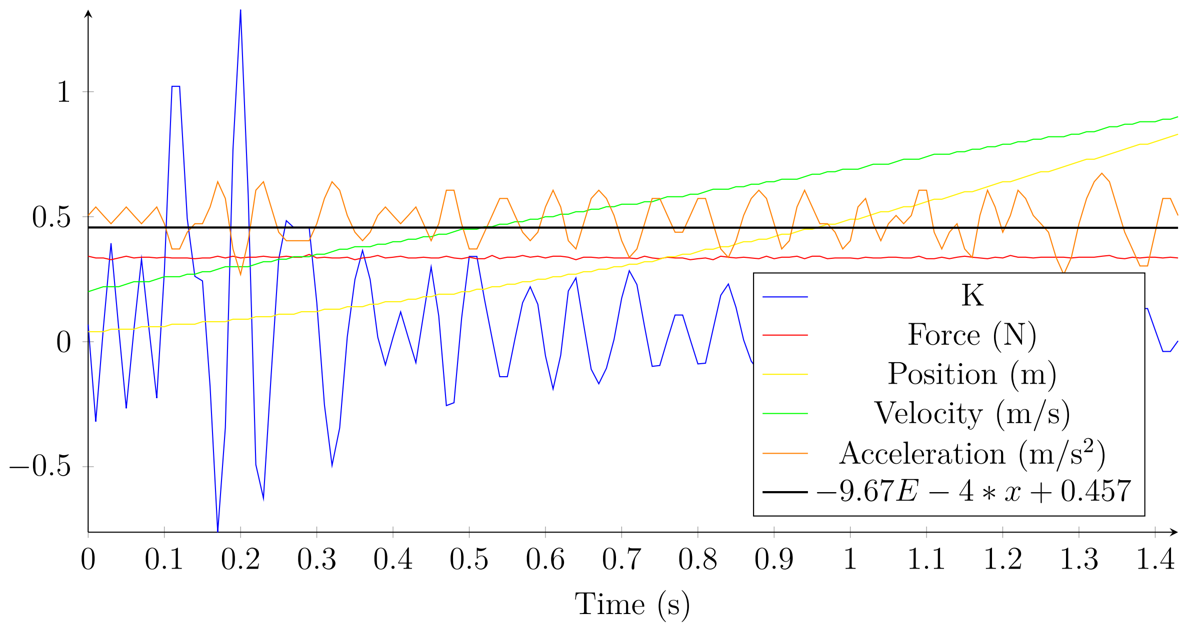
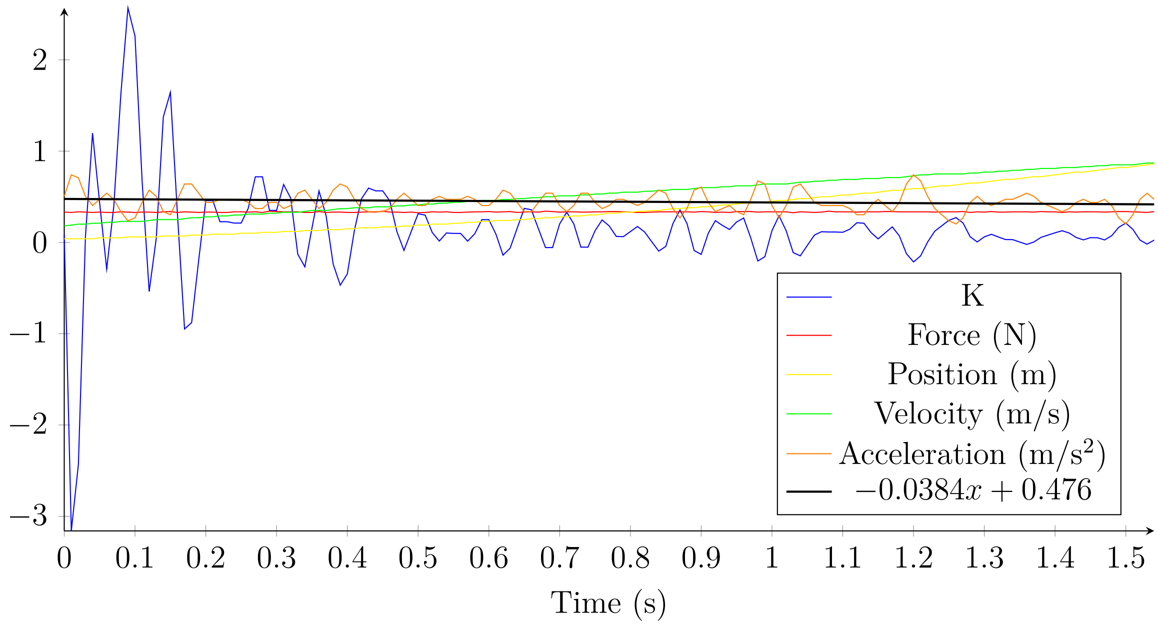


Figure A8. Raw Data Collected from Smart Cart and Calculated K value - Sharp Wedge on Orange



Appendix B

Sample Calculations

Average Range

$$\text{Average Range} = \frac{R_1 + R_2 + R3 + ... + R_n}{n} \tag{4}$$

$$\text{Average Range}_{\text{12.5cm}} = \frac{338 + 333 + 332 + 336 + 332}{5} \tag{5}$$

$$\text{Average Range}_{\text{12.5cm}} = 334.2 \text{ cm} \tag{6}$$