Isaac Newton and the 3rd Law of Motion: PocketLab Voyager/Phyphox

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Isaac Newton

Isaac Newton is well-known for the apple that hit his head and the discovery of gravity. His three Laws of Motion, however, are among the most famous laws of physics. In this lesson, we are especially interested in Newton's Third Law of Motion—all forces between two objects are equal in magnitude and opposite in direction. We will be studying collisions between two identical carts that are bouncing back-and-forth, much like a Newton's cradle with just two steel balls. Repelling magnets attached to the front bumpers of each of the carts allow for noncontact collisions.

A PocketLab Voyager on each cart measures x-acceleration during the collisions. Phyphox software records the acceleration data. It creates a real-time scatter plot of the acceleration of one cart versus the other cart. Observable statistical trends on the graph provide strong evidence for the Third Law of Motion. The figure below shows a bird's eye view of the apparatus setup for this experiment. The red arrow indicates the positive x-direction for each of the two Voyagers.

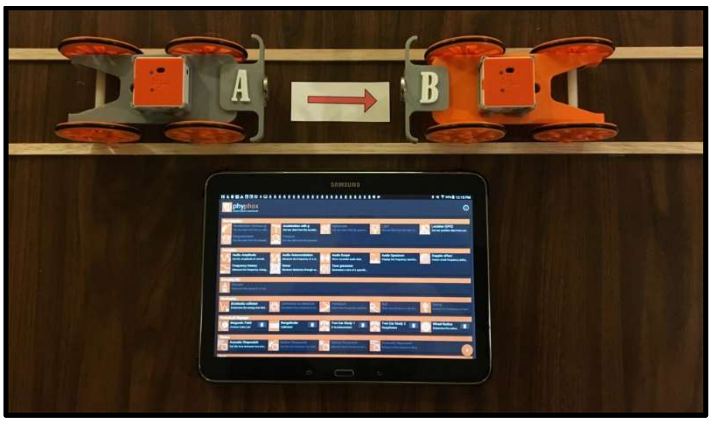

Figure 1

Phyphox Software

Phyphox (***phy***sical ***pho***ne e***x***periments) is a free app developed at the 2nd Institute of Physics of the RWTH Aachen University in Germany. The author of this lesson has been working with a pre-release Android version of this app that supports BLE (Bluetooth Low Energy) technology to transfer data from multiple Voyagers to the Phyphox app. It is important to understand that this capability of Phyphox may not be available to the public until the July 2018 anticipated beta release.

The experiment of this lesson is in a file named *TwoCarStudy1.phyphox* and will be made available from the author when the Phyphox beta is released. This file can then be opened in Phyphox and will appear in the *PocketLab Voyager* category of the main screen, similar to that in Figure 2. For anyone who may be interested in doing a conservation of momentum experiment with a similar setup using Voyager rangefinders, please follow this link for the "Two Car Study 2" experiment.

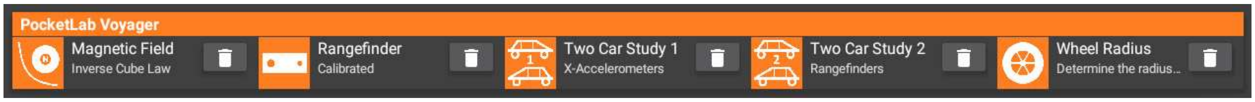

Figure 2

Performing the Experiment

The first screen that you will see after selecting the *Two Car Study 1* experiment is shown in Figure 3. The top graph indicates that PocketLab Voyager A will make use of its x-accelerometer. The middle graph indicates that PocketLab Voyager B will also make use of its x-accelerometer. Both of these graphs plot x-acceleration vs. time. The bottom graph is a plot of B's acceleration versus A's acceleration and will be a real-time scatter plot. A message in the center of the screen tells you that it is scanning for Bluetooth devices with the name "PL Voyager" and asks you to pick a device. At this point you should turn on PocketLab A, on the cart on the left. "PL Voyager" will appear in the message. Click on "PL Voyager" and a message will tell you that Bluetooth is connecting to the device. You will be asked a second time to pick a device—this time turn on the Voyager mounted on the top of the cart on the right. You can now start data collection with the pulsating start triangle in the upper right corner of the screen. You would then alternate pushing the carts toward one another in a manner shown in the accompanying video.

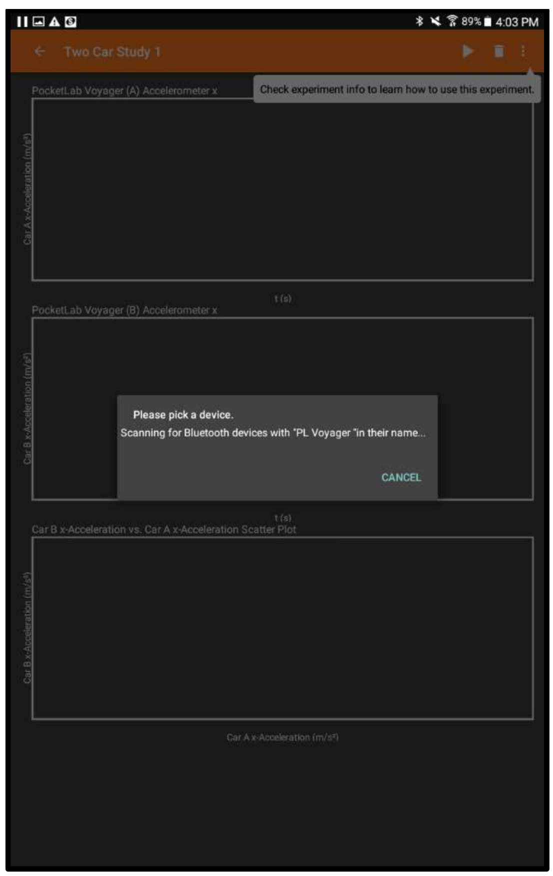

Figure 3

It is important to remember that Voyager A be selected *first*, and Voyager B be selected *second*. If they are not selected in the correct order, then the two graphs will be matched to the wrong Voyagers. Figure 4 shows what the graphs could look like after data collection is complete.

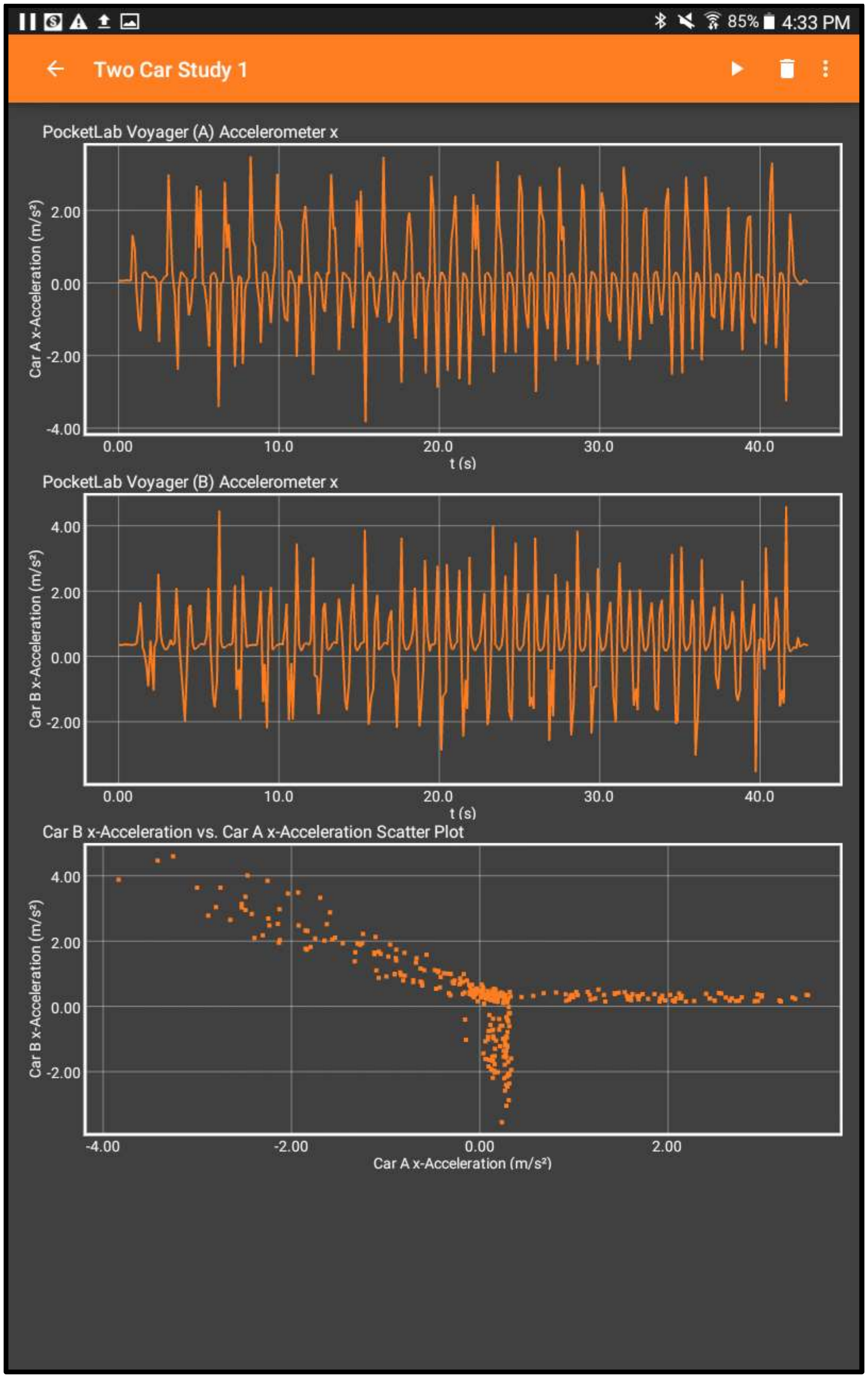

Figure 4

In order to export the data, all you need to do is click the ellipsis in the upper right corner of the screen and select *Export Data* from the drop-down menu. You can then choose the desired data format (Excel, CSV) and pick a method for sharing the data (Google Drive, Dropbox, Email, etc.) See Figure 5.

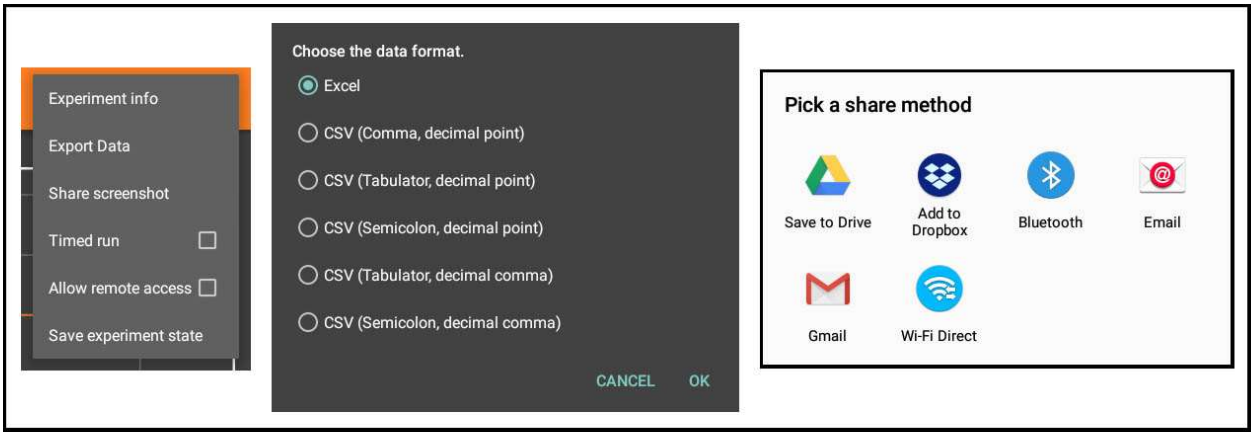

Figure 5

Procedures and Analysis

There are many ways that one can approach procedures and analysis of data in this experiment. The author suggests the following ordered steps in a comprehensive study.

1. *Zeroing the Accelerometer Sensors*

   This is a critical step in the successful analysis of the experimental data, as accelerometer zeros will vary from one Voyager to another. This can be accomplished by doing a quick run of the Phyphox experiment with both carts at rest for about a minute. The Excel graph of Figure 6 shows data collected by the author. All data in latter steps in this analysis should be adjusted based upon the values for the zeros. From data in the graph, acceleration data for cart A needs to be reduced by 0.105 m/s^2, and data for cart B needs to be reduced by 0.588 m/s^2.

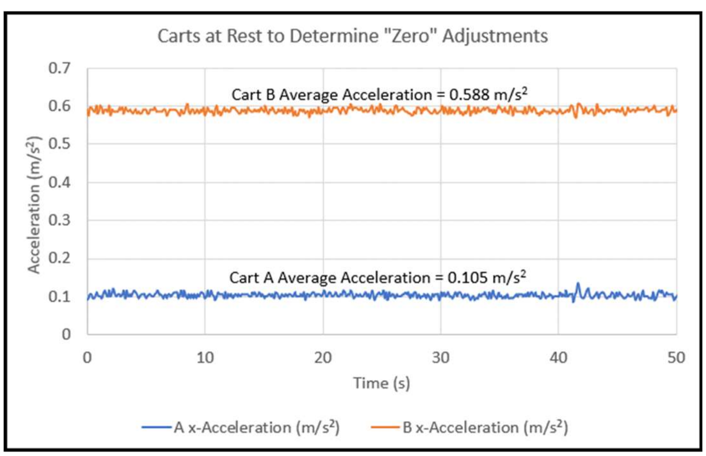

Figure 6

2. Collecting the x-Acceleration Data for Multiple Collisions

It is suggested that an experiment run with about 100 collisions be recorded. It is not necessary to count the number of collisions, but you will want enough to see some patterns in the acceleration scatter plot. Figure 7 shows a data run done by the author. The scatter plot on the left is the raw data, and the scatter plot on the right is the data after zeroing.

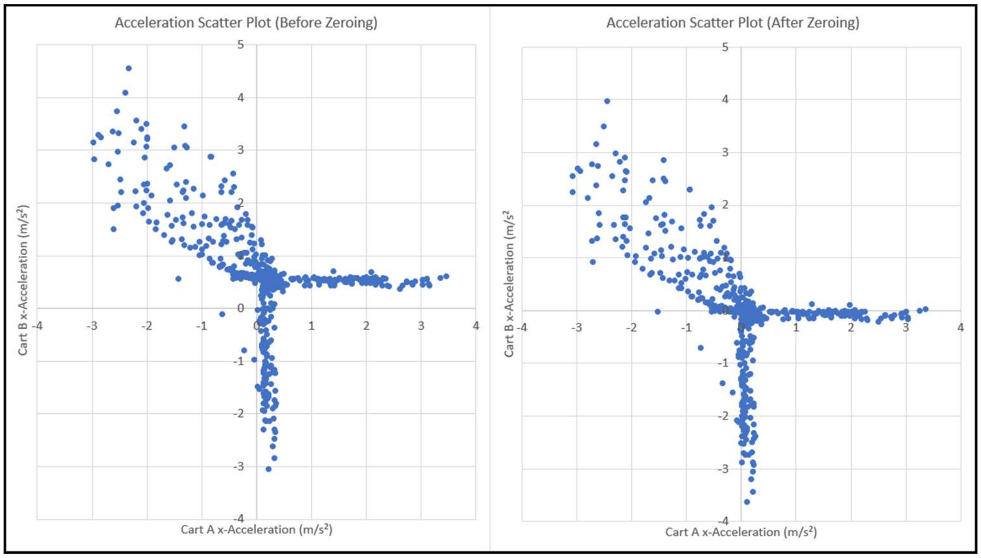

Figure 7

3. Explaining the Scatter Plot Patterns

There are three patterns of interest in the scatter plot:

A. The cluster of points on the A acceleration axis for which B's acceleration is near zero.
B. The cluster of points on the B acceleration axis for which A's acceleration is near zero.
C. The cluster of points in the top left quadrant.

In order to explain these patterns, it helps to view a graph of acceleration vs. time for each cart. The graph should show only one collision of cart A into B and one collision of B into A, as shown in the annotated graph of Figure 8. A colliding with B is shown with white annotations. B colliding with A is shown with light blue annotations. Note that these raw data graphs from Phyphox are not zeroed, so you need to *imagine* that they are. Here are the explanations for cluster patterns A, B, and C:

A. When A is pushed toward B, B is at rest and B's acceleration is therefore zero, regardless of what A's acceleration is. This explains the cluster of points on the A acceleration axis for which B's acceleration is near zero.
B. When B is pushed toward A, A is at rest and A's acceleration is zero, regardless of what B's acceleration is. This explains the cluster of points on the B acceleration axis for which A's acceleration is near zero.
C. Now consider the cases when A rebounds backward while B moves forward in reaction, or when B rebounds forward while A moves backward in reaction. In both cases, A's

acceleration is negative while B’s acceleration is positive. So regardless of what the accelerations are, the data points would lie in the top left quadrant.

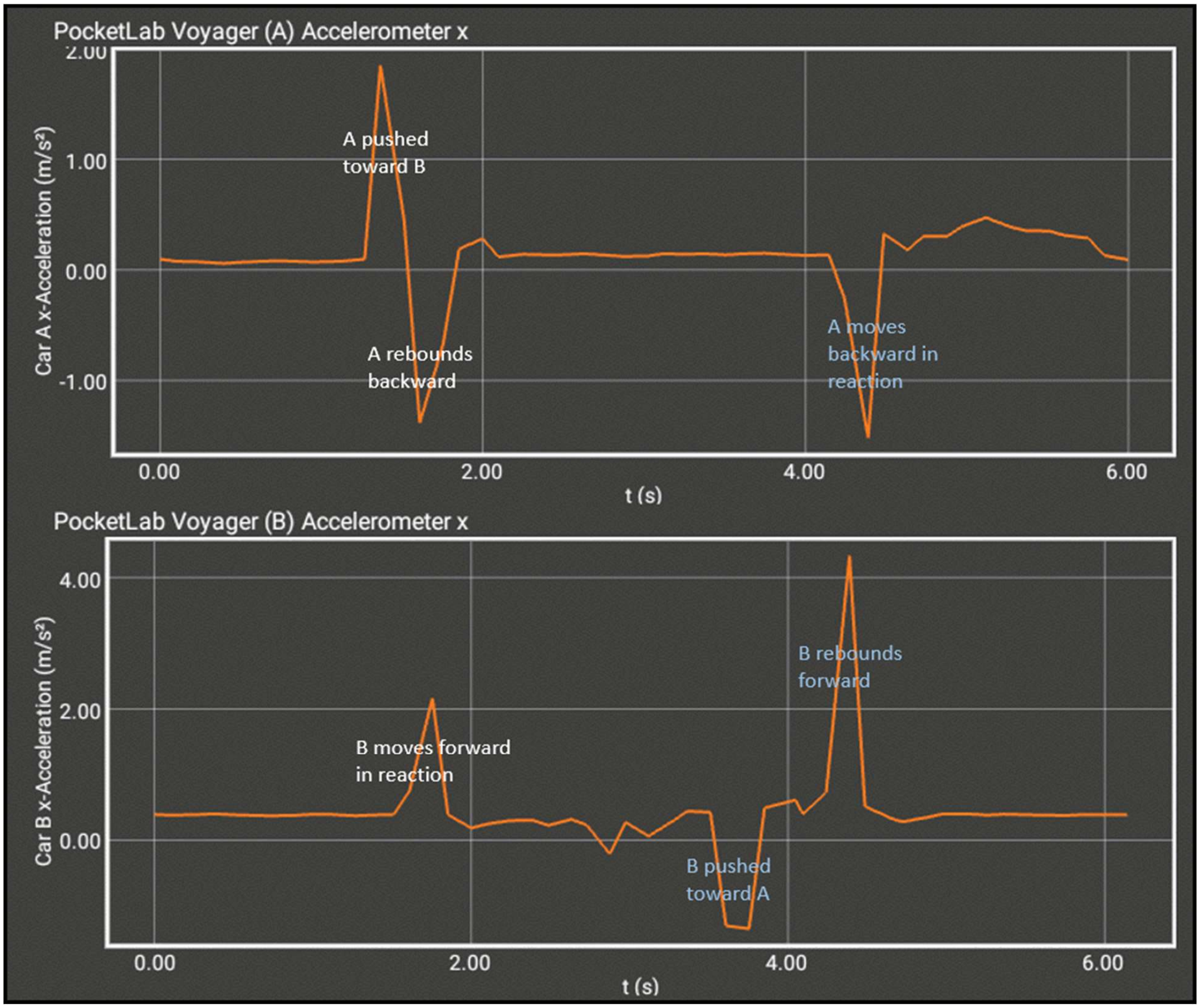

Figure 8

4. *Explaining Why A and B Accelerations During Collisions Are Not the Same*

You have probably noticed that the accelerations of the carts during the collisions are opposite in direction as we would expect from Isaac Newton’s 3rd Law of Motion. But they are *not equal* according the graphs of Figure 8. Since the carts are nearly the same in mass, we would expect the accelerations to be equal. How can this be explained?

Plotting a graph showing *data points* zoomed in on one collision is the first step in answering this question, as shown in Figure 9. You will notice that only eight data points are displayed per second. The actual collision is seen to be about 3/8 second. The timing of data collection of these points will vary with the time between pushes of the carts. The height of the “peaks” could then vary significantly within a given collision as well as from one collision to the next. It is reasonable that if we collected data on enough collisions, say a minute or two worth of collisions (about 100), we could statistically see a pattern justifying equality of A and B accelerations. This is precisely what we see in the right-hand graph of Figure 7!

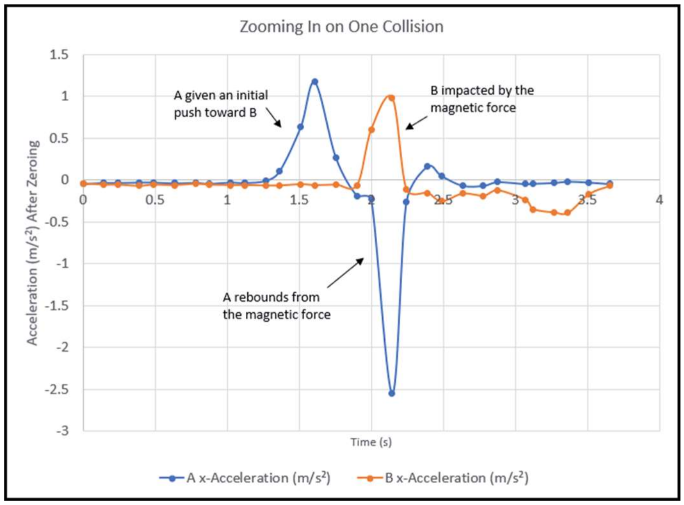

Figure 9

5. Performing a Regression Analysis

The analysis from step 4 suggests that performing a regression analysis of the data points in the top-left quadrant in the rightmost graph of Figure 7 could be fruitful. It certainly appears that these points are centered on the line "*y = -x*", or equivalently, on the line "*B acceleration = - A acceleration*". Figure 10 shows an Excel graph with a linear regression on those points. The dotted blue line is the straight line of best fit (*y = -0.9058x*) when forcing it through the origin. The R^2 value is not close to 1, but that is to be expected since there is a great deal of variation in the data. The important thing here is that the R^2 value is *not near zero*. If it were near zero, then the straight line of best fit would have been nearly horizontal.

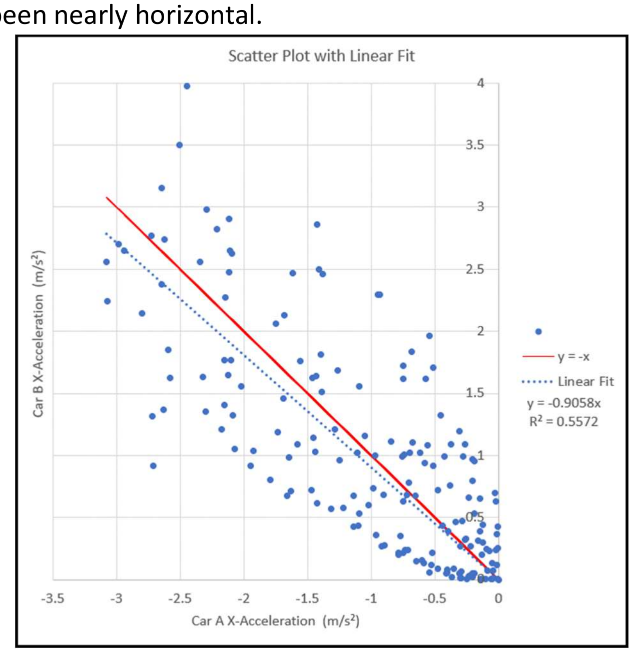

Figure 10

The red line is the line *y* = -*x*. We see that the red and blue lines are quite close together. This gives clear evidence that Newton's 3rd Law of Motion is valid, in spite of the high variability of data within a collision and from one collision to the next. Figure 10 shows us that, in the long run, forces between the two carts are equal in magnitude but opposite in direction.