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Mid-Range Data Acquisition Units Using GPS and Accelerometers

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Abstract

In the 2016 SAE publication "Data Acquisition using Smart Phone Applications," Neale et al., evaluated the accuracy of basic fitness applications in tracking position and elevation using the GPS and accelerometer technology contained within the smart phone itself [1]. This paper further develops the research by evaluating mid-level applications. Mid-level applications are defined as ones that use a phone's internal accelerometer and record data at 1 Hz or greater. The application can also utilize add-on devices, such as a Bluetooth enabled GPS antenna, which reports at a higher sample rate (10 Hz) than the phone by itself. These mid-level applications are still relatively easy to use, lightweight and affordable [2], [3], [4], but have the potential for higher data sample rates for the accelerometer (due to the software) and GPS signal (due to the hardware). In this paper, Harry's Lap Timer™ was evaluated as a smart phone mid-level application. Used in conjunction with the external antenna Sky Pro GPS, the speed, acceleration and position recorded by Harry's Lap Timer™ tracking technology is compared to a well-known and validated data acquisition unit. The speed, position, and acceleration data of Harry's Lap Timer™ was compared to the VBOX 20 Hz VB20SL3 with a RLVB IMU 03 3-axis accelerometer. The research presented here demonstrates that mid-level tracking software like Harry's Lap Timer™ collects comparable data at a sample rate between 1-10 Hz for many testing situations.

Introduction

The method of obtaining position, distance, speed, and acceleration data through smart phone applications is advantageous because the devices are lightweight, affordable, and easy to setup and use. The mid-level applications can potentially acquire better speed, acceleration, and positional data than basic applications because they differ in the way they sample the data and report it. In previous testing, Neale et al. showed that conventional health fitness applications such as Map My Fitness allows sampling of GPS data every one to two seconds [5]. A reason for this longer interval in fitness applications is that sampling at shorter intervals requires more data storage as well as battery usage and generally is not required for exercise activities that take 20 or 30 minutes. Also, exercise activities typically have speeds much lower than a motorized vehicle. Furthermore, the data is reported through a website which is accurate for that sample rate but does require extra steps on the part of the user to extract, process, and utilize the data.

Though it is not utilized fully by the fitness applications, the authors found that smart phones can sample the GPS signal at a much higher rate. The phones are also equipped with an accelerometer that can sample at higher rate. Mid-level smart phone applications are designed to access the phone's internal accelerometers and a higher sampling rate for position can be achieved through an external GPS antenna. This paper evaluates Harry's Lap Timer™, to determine the reliability of mid-level smart phone applications to report speed and distance as well as acceleration. Several tests were performed where data is collected and compared to a VBOX data acquisition unit. The tests are designed to evaluate the use of Harry's Lap Timer™ for accident reconstruction purposes, and thus include a variety of vehicle maneuvers such as slow turns, slalom, hard acceleration and hard braking. These maneuvers were tested over both short and long durations.

For each of these tests, the results from Harry's Lap Timer™ was compared to the VBOX. The Race Logic VBOX VB20SL3 Data Acquisition Unit and the IMU accelerometer were set up in parallel with Harry's Lap Timer™ in each test. The VBOX was chosen as the control for this testing due to its use in the automotive industry and in accident reconstruction, and it is specifically designed to monitor and record vehicle movement [6]. Other data acquisition systems can sample at higher data rates, and may be required for reconstruction events where data needs to be sampled greater than 20 cycles per second, such as a crash test. Additionally, if the location where the test is taking place does not have satellite coverage then the use of different systems, or combination of systems, may be needed.

The phone and external antenna are small and easy to set up on a variety of vehicles or moving objects. They can document speed, distance, and acceleration at a sample rate useful for many accident reconstruction purposes. From our testing and research, it was determined that Harry's Lap Timer™ and similar functioning applications and accessories that access the device's accelerometers and GPS systems can perform comparably to the VBOX in many situations. The paper also presents results where the external antenna was not used. Even without the antenna accessory (where Harry's Lap Timer™ was limited to 1 Hz), the data collected still showed good correlation to the VBOX data in most of the tests for speed, distance, and acceleration.

Harry's Lap Timer': Grand Prix Edition

Harry's Lap Timer™ has four different versions: Rookie Edition, Petrolhead Edition, ToGo Edition, and Grand Prix Edition. For the testing preformed in this study, the Grand Prix Edition was used. The Grand Prix Edition allows for an external GPS sensor that can record up to 20 Hz, can use multiple cameras, and produces a video reference lap.

The application is one of several that are designed to record a vehicle's speed, position, distance, and acceleration. Some other applications designed for similar purposes are Track Attack, Track Master, Dynolicious, and Track Addict. These applications vary in their features, costs, and phone operating system, as well as what data is collected. Additional differences include file format types and availability of video logging.

Harry's Lap Timer™ was tested because it is available on both iOS and Android platforms, can record video, uses the phone's internal accelerometer, and uses Doppler shift to determine the vehicle's speed. Doppler shift is also used by the VBOX data acquisition system which has been proven to be accurate and reliable [7].

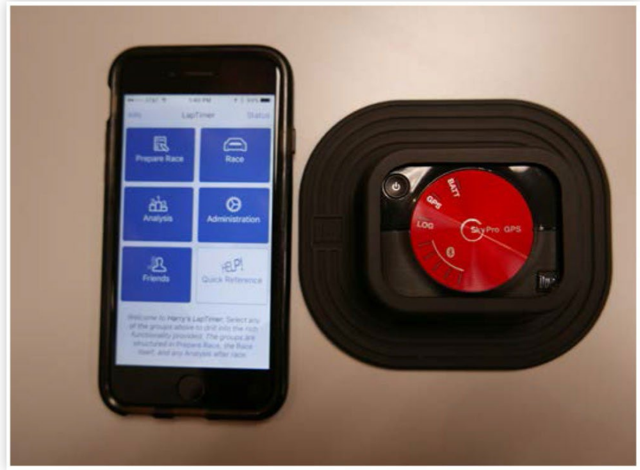
Harry's Lap Timer™ can also overlay the speed, position and acceleration data onto video. The video overlay feature allows the speed and acceleration data to be synchronized with the video as a real-time feedback. The video can be recorded separately, as its own video file, or as a video file with the data imprinted in the lower left corner. The video features are described in detail in the section "Evaluation of the Video Sync".

Harry's Lap Timer: Data Acquisition

Two different configurations of the Harry's Lap Timer™ program were tested. One configuration limited the reported data to only 1 Hz for the GPS and accelerometer. The second configuration added an accessory to the phone to increase the sample rate to 10 Hz. This accessory was the Sky Pro GPS, a small, lightweight Bluetooth-enabled GPS antenna that has a maximum sample rate of 10 Hz with a specified accuracy of ±2.5 m (8.2 ft) [8]. Harry's Lap Timer™ will access the highest available sample rate through the external GPS; for example, if a different antenna had a sample rate of 20 Hz, Harry's Lap Timer™ would track speed and position at 20 Hz.

Figure 1 shows the Harry's Lap Timer™ Phone Application home screen along with the Sky Pro GPS accessory antenna. For both configurations (with and without the accessory antenna), Doppler shift is used to calculate speed from the

FIGURE 1 - Harry's Lap Timer™ Home Screen and Sky Pro GPS XGPS160



GPS data. Also, the phone's accelerometers are accessed by Harry's Lap Timer™ to determine acceleration during the testing.

Global Position System (GPS) - During previous testing, it was found that the GPS sample rate for any smart phone tested was a maximum of 1 Hz [9]. For some phone applications, the sample rate was even lower, 1/3 Hz to 1/5 Hz.

What limits the sample rate for these more basic applications is the onboard GPS receiver in the phones themselves, which allows only 1 Hz to be reported. Applications such as Harry's Lap Timer™ allow the pairing of third-party GPS receivers which can sample at a higher rate. Some of the third-party GPS receiver providers are Dual XGPS ($85-$135), Racelogic VBOX Sport ($320), Push Smartgauge ($400), Garmin GLO ($96), and Qstar BT-Q818 XT ($89). The testing in this paper utilized the Sky Pro GPS model XGPS160 manufactured by Dual shown in Figure 1.

The XGPS160 uses both the US and Russian satellite systems to determine position and then transmits wirelessly via Bluetooth to the supported smartphone devices and applications. The receiver samples the location of the device up to 10 times per second (10 Hz) with an accuracy of 2.5 m (Circular Error Probable) [10]. The XGPS160 can connect to five Bluetooth devices with a range up to 33 feet. [11]. The phones used in the testing included Android and Apple phones running the Harry's Lap Timer™ application.

Accelerometer - The specific smart phones used in this testing were the iPhone 6 Plus and the Motorola Droid Turbo 2. The phones are equipped with an internal magnetometer, 3-axis gyroscope and 3-axis accelerometer which can track the motion and acceleration of the phone. In the previous testing of the fitness applications, the accelerometer was only accessed when the GPS signal was lost. Even then, the data used from the accelerometer was only used to estimate speed by comparing the accelerometer patterns to a database that suggests a speed based on the activity type [12].

Harry's Lap Timer™ accesses the phone's accelerometer to measure the acceleration of the device directly. The accelerometers in the smart phones have a higher sample rate than the GPS system utilized in our testing. The accelerometer sensor in the iPhone 6 Plus, for instance, is a InvenSense MP67B (MPU-6500) which samples at 200 Hz. The accelerometer has a user-programmable full-scale range of ±2 g, ±4 g, ±8 g, or ±16 g. The gyroscope has a programmable full-scale range of ±250, ±500, ±1000, or ±2000 degrees/sec [13]. The accelerometer in the Droid has tri-axis Kionix KXTF9 with a programable range of ±2 g, ±4 g, or ±8 g. The sample rate for the accelerometer is 25 to 800 Hz, with a typical output of 50 Hz [14]. When Harry's Lap Timer™ accesses the acceleration data, it samples the data to match the sample rate of the GPS, which is lower. For example, if the GPS is sampling at 10 Hz, the accelerometer samples at 10 Hz. Harry's Lap Timer™ recorded frequency is limited by the GPS sample frequency.

Procedure and Test Setup

Testing was performed a 2004 Chevrolet Malibu. To consider any differences between phone platforms, both an iPhone running iOS 9.3.4 and a Droid running the Android 6.0 were mounted on the inside of the windshield. The Bluetooth Sky Pro GPS antenna connected to the Droid was placed on the roof of the test vehicle above the vehicle's previously measured center of gravity and as close to the VBOX GPS receiver as possible. The data from Harry's Lap Timer™ that was recorded on each phone was compared to the VBOX data. The VBOX determines speed using a GPS-based system but can also measure acceleration using an add-on accelerometer. The VBOX accelerometer was mounted to a rigid plate directly above the vehicle's airbag control module. An image of the test vehicle is shown in Figure 2 and the interior of the vehicle showing the location of the test phones and VBOX accelerometer is shown in Figure 3.

Harry's Lap Timer Setup - In the Harry's Lap Timer™ application, there is a help section that shows how to set up the phone to record data and there are also multiple guides and instructional videos on the application's web site [15]. However, the process is relatively straightforward and requires minimal setup, such as connecting the phone via Bluetooth to the GPS antenna. Once the phones were paired with the sensors, both phones were then positioned onto independent mounts and rotated to have a level landscape orientation with a view through the windshield. Leveling the phones in the vehicle prior to testing insures that the longitudinal and lateral accelerations are zero. This can be accomplished by using the acceleration circle on the bottom left of the video display as shown in Figure 4.

The phones were located laterally as close to the center line of the vehicle as possible and mounted to the windshield though a suction style mount. Once the VBOX system and the phones were ready to collect data, they were initialized and the car was held stationary for approximately 5 seconds. This was done for two reasons: to establish a zero state for the entire system before testing which enables a base line for data comparison, and Harry's Lap Timer™ needs a few seconds at the beginning to reach the maximum sample rate. From initial testing, it was observed that Harry's Lap Timer™ would record at less than the 10 Hz for the first 2-3 seconds (when connected to an external GPS sensor), therefore a protocol of staying stationary for the first 5 seconds was established.

FIGURE 2 Exterior of Test Vehicle

FIGURE 3 Interior of Test Vehicle

FIGURE 4 Acceleration Circle

Testing - The tests were performed on a closed course, allowing various maneuvers to be performed. There were four groups of tests performed: 1) long distance, 2) slalom maneuvers, 3) left and right turns, and 4) hard acceleration and braking. An aerial view of the testing outlining the location of each test is shown in Figure 5.

The right turns were performed traveling clockwise around the loop and the left turns were performed driving counterclockwise. The slalom, braking, acceleration and distance testing were performed on the straight section of road south of the loop. A sample of the GPS mapping for one of the left turn tests is shown in Figure 6. The three colors are visualizations of the paths of the three different devices (Droid, iPhone, and VBOX) during the run.

Figure 6 shows the VBOX path in red, the Droid sampling at 10 Hz in yellow, and the iPhone sampling at 1 Hz in green. The vehicle began each run traveling North (up) on the straight portion of the track, heading towards the loop. At the loop, the vehicle was driven either counterclockwise (left turn) or clockwise (right turn) for two full laps then returned to the initial position.

Review of the GPS positional data between both the phones and the VBOX shows that the location of the vehicle does not match exactly, but it does give sufficient information to determine the approximate location and path of the vehicle relative to the roadway. The error associated with the GPS positions was not analyzed because it did not affect the measured acceleration, speed or calculated distances of the vehicle. For example, the acceleration is measured by the internal sensor in the phone, the speed is calculated with the use of Doppler shift and the distance is based on speed and time. However, the accuracy of the GPS positional data as stated by the manufacture is 3 m (9.84 ft.) [16] for the VBOX and 2.5 m (8.2 ft.) for the external GPS [17].

Data Export - Prior to exporting the data collected from Harry's Lap Timer™, the speed, acceleration, and path data was overlaid onto the recorded video using the application. The raw and overlay video along with the recorded data were exported and analyzed. An example of the file produced from the left turn test is shown in Table 1.

The exported data includes several columns of information, some of these columns are: Date, Time, Lap Time (Time_Lap), Latitude, Longitude, Speed (in both kph and mph), Elevation (in meters and feet), Heading, Distance (in km and miles), and Lateral and Linear Acceleration in g. Additionally, data can be obtained through a Bluetooth On-Board Diagnostics II (OBD II) reader that gathers information from the Controller Area Network (CAN) can be exported.

FIGURE 5 Aerial View of Testing Area

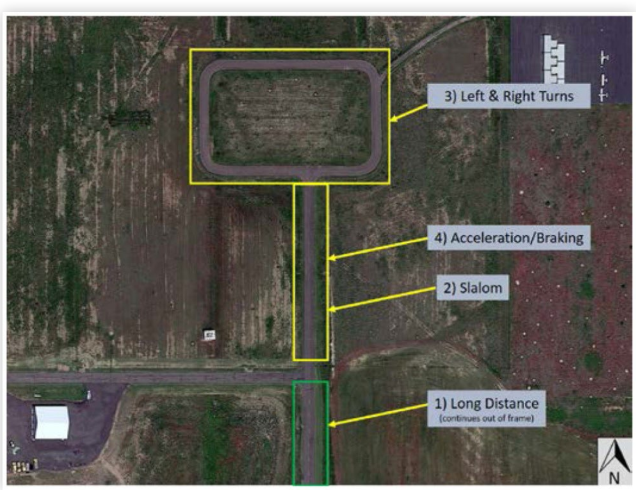


FIGURE 6 GPS Tracking of Left Turn Run 1

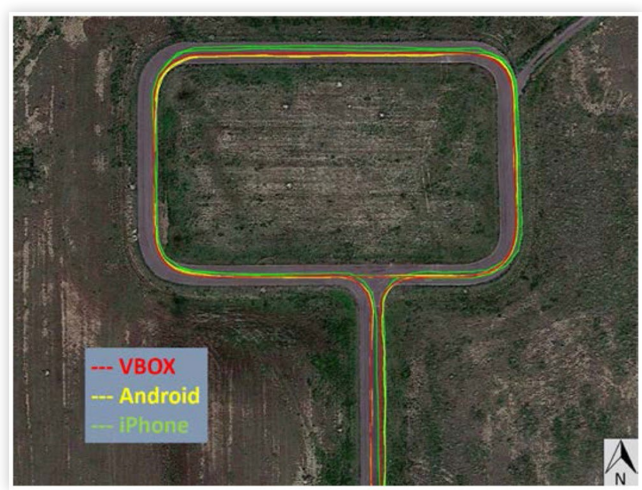


TABLE 1 Partial Harry's Lap Timer™ Exported Data

DATE	TIME	TIME LAP	LATITUDE	LONGITUDE	SPEED_KPH	SPEED_MPH
8/15/2016	5:26:46 PM	10.6	39.78624	-104.516577	7.4	4.598147
8/15/2016	5:26:46 PM	11.2	39.786242	-104.51656	10.1	6.275849
8/15/2016	5:26:46 PM	11.3	39.786242	-104.516557	10.6	6.586535
8/15/2016	5:26:46 PM	11.4	39.786242	-104.516552	10.9	6.772946
8/15/2016	5:26:47 PM	11.6	39.786243	-104.516545	11.7	7.270043
HEIGHT_M	**HEIGHT_FT**	**HEADING_DEG**	**DISTANCE_KM**	**DISTANCE_MILE**	**LATERALG**	**LINEALG**
1668.9	5475.393709	89	0.0016	0.000994	-0.04	0.18
1668.9	5475.393709	83	0.003	0.001864	-0.05	0.17
1668.9	5475.393709	82	0.0032	0.001988	-0.07	0.16
1668.9	5475.393709	81.2	0.0036	0.002237	-0.08	0.16
1669	5475.721793	80	0.0041	0.002548	-0.1	0.15

The information obtained from the CAN data is related to engine parameters and was not the focus for this study, therefore this ability of Harry's Lap Timer™ was not evaluated.

VBOX

The VBOX 20 Hz VB20SL3 - Triple Antenna (SL3) data logger with accelerometer was used for comparison with data recorded with Harry's Lap Timer™. The VBOX is an industry accepted data acquisition system that has been widely accepted in the accident reconstruction community for measuring GPS location, speed, acceleration in all 3 axes, yaw, pitch, and roll angles, heading, and elevation changes [18], [19], [20]. This unit is calibrated once per year to ensure accuracy. The calibration sheet provided by Racelogic shows an accuracy in the recorded speed of ±0.06 mph. In the testing performed for this paper, one antenna and an accelerometer was utilized for the VBOX. Figure 7 is a photograph of the VBOX unit used.

Results

A total of 13 tests were performed and are listed in Table 2 below. Each test was designed to evaluate a specific parameter such as longitudinal/lateral acceleration, speed, and distance. After the testing was performed, the data was then analyzed and compared to the VBOX.

FIGURE 7 Image of VBOX

TABLE 2 Testing List

Group	Maneuver	Number of Runs
1	Long Distance	4
2	Slalom	3
3	Left Turn	2
	Right Turn	2
4	Straight Line Acceleration and Braking	2

Data Filtering

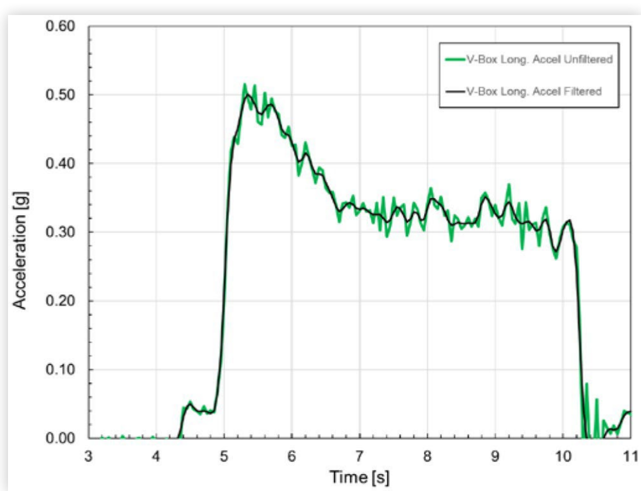
Data for each test was recorded and downloaded from both the VBOX and Harry's Lap Timer™. In all the data collected, filtering was only performed on the acceleration data from the VBOX. A Butterworth 4-channel lowpass filter with a cutoff frequency of 3.3 Hz was used on the acceleration data. Even though the accelerometer of the VBOX was collecting data at 20 Hz, the inherent noise made filtering necessary for a comparison of the data. The acceleration from Harry's Lap Timer™ is smoothed by the software using a 3-point moving average; this feature cannot be turned off. Speed and distance data collected by Harry's Lap Timer™ was not filtered nor was the speed and distance data from the VBOX. The reported speed data from both sources is smooth and therefore does not need to be filtered. Figure 8 is a comparison sample of the VBOX accelerometer data unfiltered and filtered.

Data Synchronization and Error Calculations

At the onset of each test, the VBOX and both phones began recording data at slightly different times. The VBOX was started first, then one phone, then the other phone. With the difference in start times and the different rates that which each device recorded data, a time offset to synchronize the data needed to be determined.

Harry's Lap Timer™ records video, however the VBOX used in the testing did not, therefore video synchronization was not an option. The first step to synchronizing the data was to make an initial time offset for the data collected by Harry's Lap Timer™. This offset was done using the initial steady state condition created when the vehicle sat at rest for the 5 seconds prior to testing. This offset would shift all the Harry's Lap Timer™ data to match with the data collected by the VBOX. All of the data being collected at different rates

FIGURE 8 VBOX Accelerometer Data Filtered and Unfiltered



would make it unlikely that a time stamp on a VBOX data point would match an exact time stamp to a Harry's Lap Timer™ data point, therefore the time needs to be synchronized to allow a comparison.

A linear interpolation between the VBOX data points was used so that the exact time of the Harry's Lap Timer™ data point could be compared to the VBOX. Now having the data synchronized, the data points from Harry's Lap Timer and VBOX were compared and the differences found. The total error was calculated by the sum of the square root of the differences squared from each data point.

The total error was divided by the number of data points to get the average error per point. The solver function in Excel was then used to adjust the initial time offset to minimize the error in the data set.

Coefficient of Determination

The coefficient of determination (R^2) was calculated using Excel. To determine the R^2 value for each test the data point collected by Harry's Lap Timer™ was compared to a linear interpolation of the VBOX data so that a comparison at the same time could be made. For the function to work in Excel, the arrays need to be the same size, therefore only the data points collected by Harry's Lap Timer™ were used in the R^2 calculations.

Tracking Results: Distance

Distance testing was performed on both phones, one at 1 Hz (iPhone) and the other at 10 Hz (Droid). Review of the distance data showed a larger difference than expected. Table 3 shows the comparison of the VBOX distance data and the Harry's Lap Timer™ distance data that was recorded during the left and right turn tests.

It was determined that the difference was due to the way the distances were calculated by VBOX and by Harry's Lap Timer™. Distance reported by the VBOX is calculated based on speed and time. However, Harry's Lap Timer™ determines the distance by using the Haversine formula which calculates the distance between discrete GPS points. With the associated error inherent with any GPS system, the Haversine method used by Harry's Lap Timer™ can have an error exceeding 3 to 5% over a small distance (under 350 feet). Therefore, due to the error, another method was used to allow a direct comparison of Harry's Lap Timer™ distance to the distance calculated by VBOX.

TABLE 3 Comparison of the distances from VBOX to Harry's Lap Timer™

Distance [ft]				
	Left Turn		Right Turn	
Method	Run 1	Run 2	Run 1	Run 2
Reported from Harry's	3532	3532	3527	3577
Vbox	3637	3634	3672	3676
% Difference	2.9%	2.8%	3.9%	2.7%

Using the measured speed and time from Harry's Lap Timer™, we independently calculated a distance and compared this to the VBOX data. Table 4 shows a comparison between the distance reported directly from Harry's Lap Timer™ to our calculated distance using speed and time from Harry's Lap Timer™.

TABLE 4 Comparison of the reported and calculated distances from Harry's Lap Timer™

Distance [ft]				
	Left Turn		Right Turn	
Method	Run 1	Run 2	Run 1	Run 2
Reported from Harry's	3473	3532	3527	3577
Calculated from Harry's	3629	3621	3680	3681
% Difference	4.3%	2.5%	4.1%	2.8%

As can be seen in Table 4, the difference in the reported distance to the calculated distance can start to exceed 4%. The calculated distances from Harry's Lap Timer™ were then compared to the reported values from the VBOX are shown in Table 5.

TABLE 5 Comparison of the reported distances from VBOX to Calculated distances from Harry's Lap Timer™

Distance [ft]				
	Left Turn		Right Turn	
Method	Run 1	Run 2	Run 1	Run 2
Calculated from Harry's	3629	3621	3680	3681
Vbox	3637	3634	3672	3676
% Difference	0.2%	0.3%	0.2%	0.1%

When comparing the calculated distances from Harry's Lap Timer™ to the VBOX, the difference was reduced to under 0.4%. Therefore, it is recommended that distance from Harry's Lap Timer™ should be calculated from speed and time rather than the distance directly reported by Harry's Lap Timer™.

Tracking Results: Speed

In the testing presented here, two different systems were used to track the speed. One setup (iPhone) only allowed Harry's Lap Timer™ to access the built-in GPS receiver for the phone, limiting the sample rate to 1 Hz. The second setup (Droid) allowed Harry's Lap Timer™ to access the higher GPS sample rate of an external antenna which increased the sample rate to 10 Hz. Data from both configurations is presented here. For all speed tracking, both the VBOX and Harry's Lap Timer™ use Doppler shift to determine speed, regardless of the sample rate. Doppler shift is the same method the VBOX uses to determine speed, and it has been verified and tested to be accurate. The VBOX has a reported accuracy of ±0.06 mph. The VBOX was calibrated by the manufacturer prior to use, and was verified to fall within the stated accuracies of the device.

Tracking Results-Speed at 1 Hz

A plot of the vehicle's speed comparing the unfiltered VBOX data to the Harry's Lap Timer™ test (Run 1 - left turn) taken at 1 Hz (iPhone) is shown in Figure 9. This sample was chosen because of the change in speed throughout the run. The VBOX data is shown in black and Harry's Lap Timer™ is shown in green.

Figure 10 is a close-up view of the speed comparison shown in the square in Figure 9. The data from the 1 Hz (iPhone) when overlaid to the unfiltered VBOX data, shows a close correlation even at 1 Hz. The average difference of Harry's Lap Timer™ collecting data at 1 Hz was ±0.09 mph with a R^2 of 0.9986. As with Figure 9, the unfiltered VBOX data is shown in black and Harry's Lap Timer™ data is shown in green.

FIGURE 9 Comparison of the unfiltered speed at 1 Hz from Run 1 - left turn test.

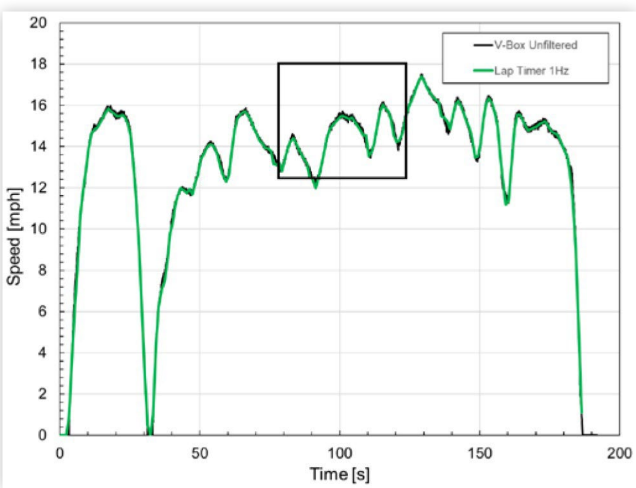
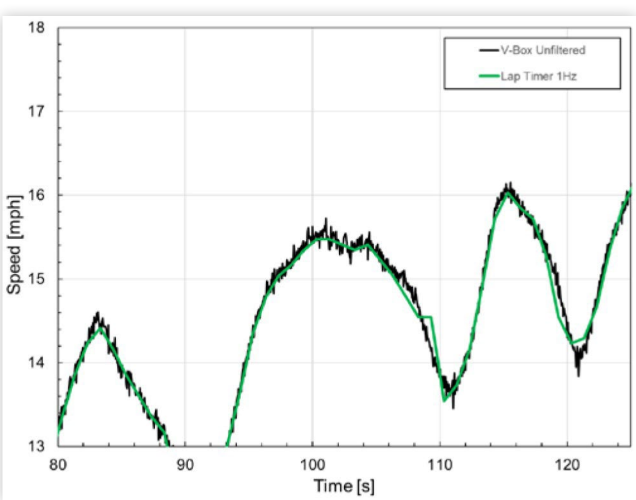


FIGURE 10 Close-up view comparison of the unfiltered speed at 1 Hz from Run 1 - left turn test (from 80-125 seconds)



Tracking Results: Speed at 10 Hz

When Harry's Lap Timer™ accessed the external antenna, the sample rate increased to 10 Hz. Review of the 10 Hz data also shows an improvement in correlation between Harry's Lap Timer™ and the unfiltered VBOX data over the 1 Hz data. Figure 11 shows the comparison results for the test data collected at 10 Hz from Run 1 - left turn test. Figure 12 shows a close-up view of this data outlined by the square box in Figure 11. The VBOX data is in black and Harry's Lap Timer™ is shown in red. The average difference of Harry's Lap Timer™ collecting data at 10 Hz was ±0.07 mph, with a R^2 value of 0.9991.

FIGURE 11 Comparison of the unfiltered speed data at 10 HZ from Run 1 - left turn test

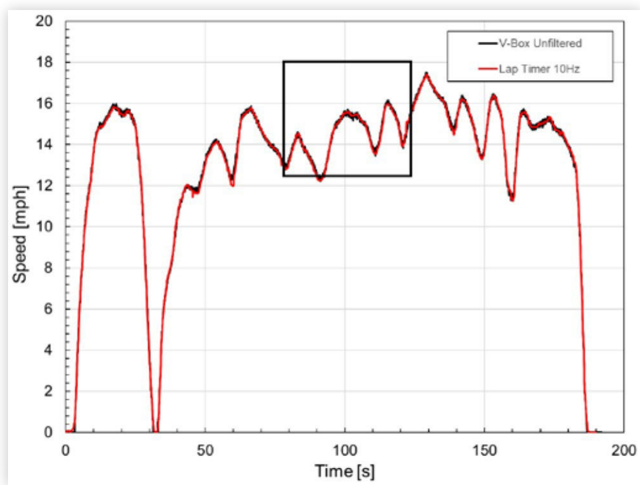
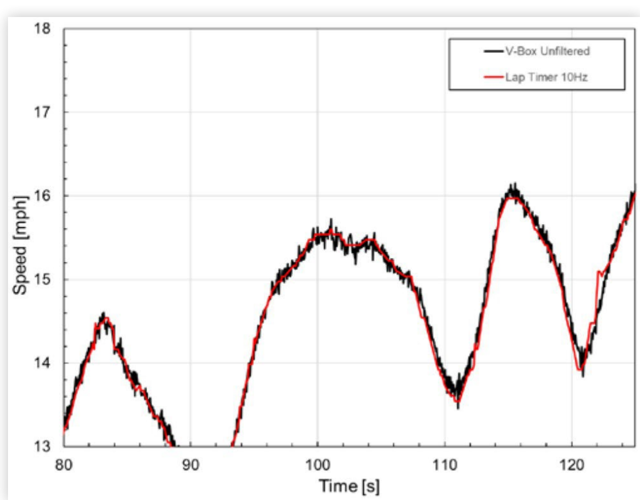


FIGURE 12 Close-up view of the unfiltered speed data at 10 HZ from Run 1 - left turn test (from 80-125 seconds)



Summary of Error: Speed at 1 Hz and 10 Hz

The speed recorded from every test was analyzed for correlation. Table 6 lists the coefficient of determination for speed from each test.

The R^2 value for the speed data shows a good correlation. For the 1 Hz tests, all the data fit well except for the speed in the hard acceleration and hard braking tests. During the 1 Hz hard acceleration and braking testing, Harry's Lap Timer™ stopped recording the speed data for what was later to be determined to be a hardware issue. Upon further testing, this event did not reoccur. Speed data is not recorded if there is a loss GPS signal; it was determined this was the cause of the missing speed data. However, if the R^2 value for the 1 Hz during that testing was recalculated up to the point where the data dropped off, the value increased to 0.9845 for run 1 and 0.9870 for run 2. Therefore, based on testing, the 1 Hz speed data recorded accurately when compared to the VBOX.

The 10 Hz data showed a good correlation with the lowest R^2 value of 0.98. This would indicate that for all test conditions, the 10 Hz captures speed data accurately. From the testing performed, speed data can be accurately collected with the use of Harry's Lap Timer™.

Tracking Results: Acceleration

In addition to the distance and speed comparison, the testing included comparing lateral and longitudinal accelerations from Harry's Lap Timer™ to the VBOX. Some of the tests were specifically designed for longitudinal accelerations, such as the hard acceleration and hard braking, while others were designed to look at the lateral accelerations, such as the left or right turn maneuvers. In each test performed, acceleration data was analyzed. For the comparison, the VBOX acceleration data was filtered as previously discussed, and Harry's Lap Timer™ is smoothed by the software. The following outlines the findings from the both a left turn, hard acceleration/braking tests, and slalom. For all of the acceleration figures, the VBOX data was filtered and the Harry's Lap Timer™ data was left unfiltered. The data from Harry's Lap Timer™ was presented as points without interpolation between the points. Presenting Harry's Lap Timer™ data as points allows for a discrete evaluation of the data due to the difference in sample rates.

TABLE 6 Coefficient of Determination (R^2) for Speed

Speed				
Speed Data Coefficient of Determination (R^2)				
Group	**Maneuver**	**Test**	**1 Hz**	**10 Hz**
2	Slalom	Run 1 (lat.)	0.9541	0.9971
		Run 2 (lat.)	0.9490	0.9981
		Run 3 (lat.)	0.9428	0.9967
3	Left Turn	Run 1 (lat.)	0.9986	0.9991
		Run 2 (lat.)	0.9983	0.9985
	Right Turn	Run 3 (lat.)	0.9966	0.9991
		Run 4 (lat.)	0.9640	0.9989
4	Acceleration & Braking	Run 1 (long.)	0.8842*	0.9826
	Acceleration & Braking	Run 2 (long.)	0.7898*	0.9960

* Harry's Lap Timer™ stopped recording during these runs. R^2 Value is reported for the entire run. If the R^2 value was recalculated for only the section where speed was reported the values fall with the range of the other tests.

Tracking Results: Lateral Acceleration at 1 Hz

A plot of the lateral accelerations collected at 1 Hz from Run 1 - left turn test compared to the filtered VBOX is shown in Figure 13. The test was performed making 90 degree left turns while attempting to maintain a relatively constant speed.

In Figure 13, Harry's Lap Timer™ data is shown by the blue triangles while the VBOX data is shown by the solid black line. Harry's Lap Timer™ did well tracking the lateral acceleration of the test vehicle. The average difference for the lateral acceleration during testing was ±0.02 g with a R^2 of 0.81. As with what could be expected with a sample rate of 1 Hz it is highly possible the peak accelerations would be missed.

A plot of the lateral accelerations collected at 1 Hz from Run 1 - Slalom test compared to the filtered VBOX is shown in Figure 14. The test was performed making a slalom maneuver at approximately 35 mph with cones spaced 100 ft apart.

In Figure 14, Harry's Lap Timer™ data is shown by the blue triangles while the VBOX data is shown by the solid black line. Harry's Lap Timer™ did well at capturing accurate lateral accelerations of the test vehicle at the points sampled. The average difference for the lateral acceleration during testing was ±0.05 g with a R^2 of 0.96. Even though the data collected was accurate at 1 Hz when compared to the VBOX, the lower

FIGURE 13 Comparison of Lateral Accelerations at 1 Hz from Run 1 - left turn test

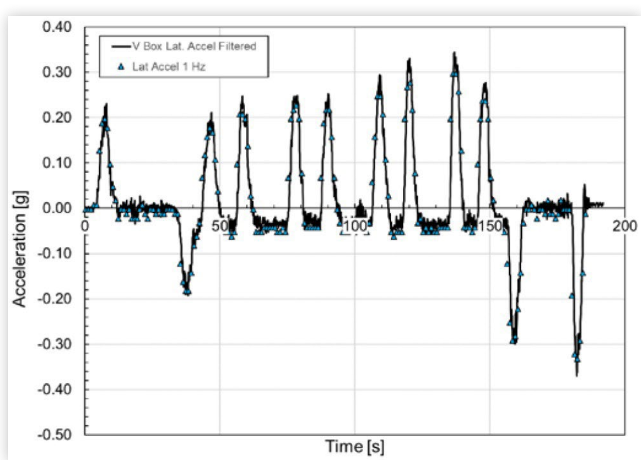
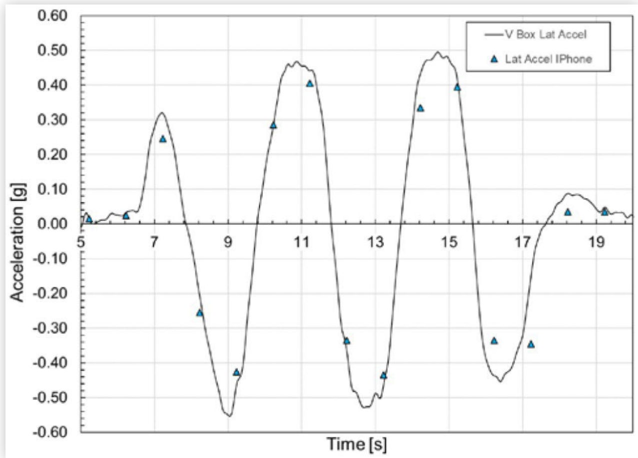


FIGURE 14 Comparison of Lateral Accelerations at 1 Hz from Run 1 - Slalom



sample rate makes it likely that the peak accelerations will not be recorded. Also, a complete picture of the vehicle motion would be missed from the 1 Hz sample rate, and with the smoothing done by Harry's Lap Timer™ the peaks are underreported.

Tracking Results - Lateral Acceleration at 10 Hz

Figure 15 is the lateral acceleration reported at 10 Hz from Run 1 - left turn test. The filtered VBOX data is shown in black and Harry's Lap Timer™ data is shown in red squares.

As with the 1 Hz data, the 10 Hz data was consistent with the data recorded from VBOX. As expected, the 10 Hz data had a lower error rate when compared to the 1 Hz sample rate. The average difference of the data collected at 10 Hz was ±0.01 g with a R^2 of 0.96. As with the 1 Hz data, it is possible the peak accelerations are missed because of the lower sample

FIGURE 15 Comparison of Lateral Accelerations at 10 Hz from Run 1 - left turn test

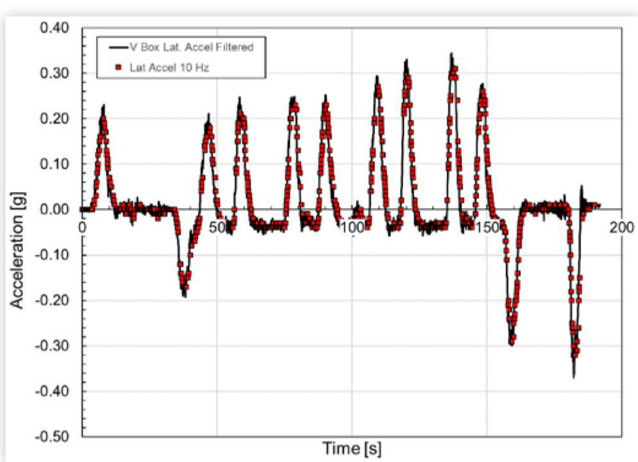
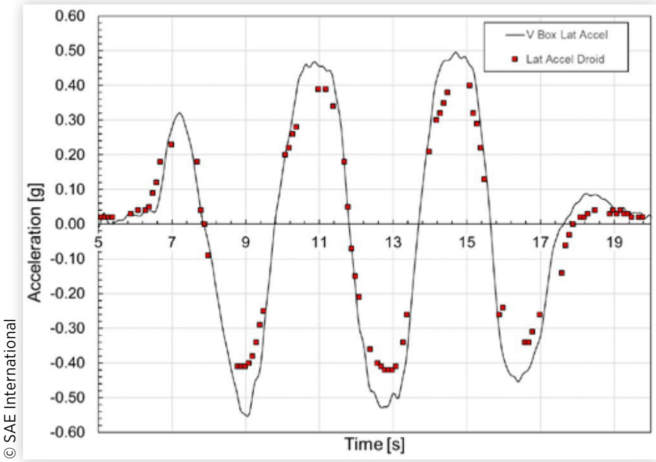


FIGURE 16 Comparison of Lateral Accelerations at 10 Hz from Run 1 - Slalom



rate. Also the smoothing that is incorporated into the software may cause the peaks to be underreported.

Figure 16 is the lateral acceleration reported at 10 Hz from Run 1 - Slalom test. The filtered VBOX data is shown in black and Harry's Lap Timer™ data is shown in red squares.

As with the 1 Hz data, the 10 Hz data was consistent with the data recorded from VBOX, however the peaks are underreported by 22% (0.1 g). The 10 Hz data had a lower error rate when compared to the 1 Hz sample rate. The average difference of the data collected at 10 Hz was ±0.04 g with a R^2 of 0.98.

The 10 Hz sample rate was sufficient to collect data at the reported time when the peak accelerations occurred but underreported the peak acceleration values. The reason for this error was partially due to the location of the phones compared to the VBOX accelerometer. The phones are mounted on the windshield, approximately 1.5 ft higher than the VBOX accelerometer. The difference in locations combined with the body roll induced with high lateral accelerations likely contributed to the error. The other source of the error would be contributed to the smoothing that is built into Harry's Lap Timer™. When smoothing is used the peaks are underreported.

Tracking Results: Longitudinal Acceleration at 1 Hz (Hard Acceleration and Hard Braking)

A plot of the longitudinal acceleration at 1 Hz from the hard acceleration and hard braking Run 1 is shown in Figure 17 and Figure 18 respectively. It should be noted that at the 15 to 16 second mark in Figure 18 (outlined by the circle) the data shows vehicle oscillation, which was a result of the oscillation of the test vehicle when coming to an abrupt stop and the subsequent rocking of the vehicle.

The hard acceleration in Figure 17 shows that from approximately 3 to 4.2 seconds, the vehicle is at rest and then accelerated. This sudden jump in acceleration over a span of one second does not give the phone (sampling at 1 Hz) sufficient time to collect the data. This condition is called jerk which will be discussed later in this paper. Although the peak at the initial onset of acceleration is missed, the vehicle settles out to a more constant acceleration from 6.5 to 9.5 seconds for an average of approximately 0.33 g from the VBOX and 0.36 g from Harry's Lap Timer™. The average difference at 1 Hz was ±0.02 g with a R^2 of 0.93.

The hard-braking deceleration in Figure 18 demonstrates a trend similar to what was observed in the acceleration data. The vehicle is traveling at a constant speed and then the brakes are rapidly applied approximately at 12 seconds. Again the 1 Hz is insufficient to sample the data quickly enough and misses the peaks. However, once the vehicle achieves a relatively constant deceleration around 12.5 to 14.3 seconds, the data has a better fit reaching an average deceleration of 0.78 g from the VBOX data and 0.72 g from Harry's Lap Timer™. The average difference at 1 Hz was ±0.01 g with a R^2 of 0.99.

FIGURE 17 Comparison of Hard Accelerations at 1 Hz, Run 1

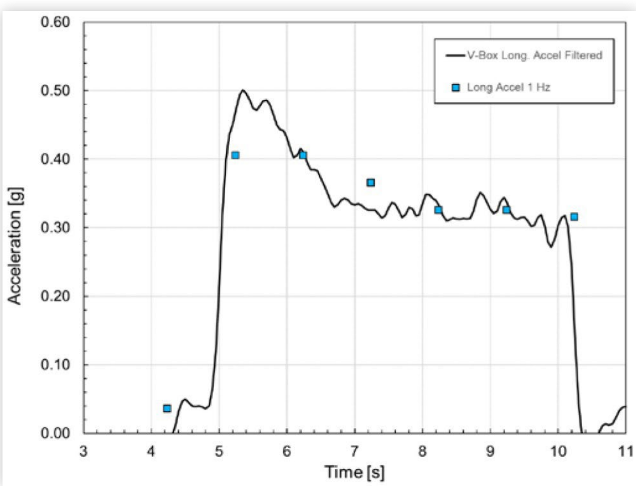
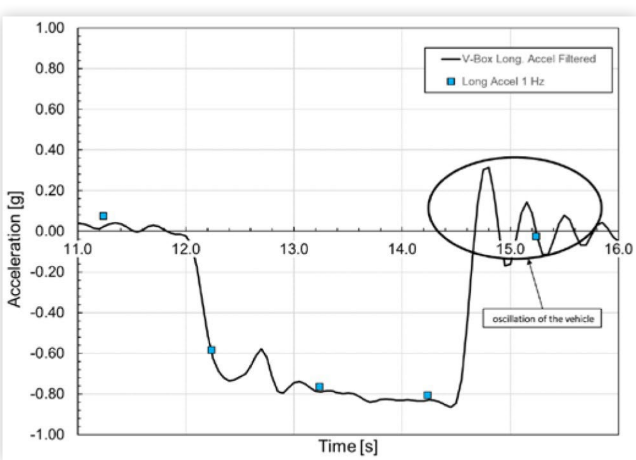


FIGURE 18 Comparison of hard Braking Deceleration at 1 Hz, Run 1



Tracking Results: Longitudinal Acceleration at 10 Hz (Hard Acceleration and Hard Braking)

The same hard acceleration and hard braking from Run 1 is shown in Figures 19 and 21 respectively, however with the data from the 10 Hz sample rate.

The hard acceleration data in Figure 19 again shows the initial acceleration from 4.1 to 5.1 seconds does not track well. The sudden squatting of vehicle during acceleration induces a rearward pitch of the vehicle which momentarily throws off the synchronization of the VBOX to Harry's Lap Timer™ due to their relative mounting positions. After the vehicle pitches forward to a level position at 7 to 10 seconds, the acceleration

FIGURE 19 Comparison of Longitudinal Accelerations at 10 Hz, Run 1

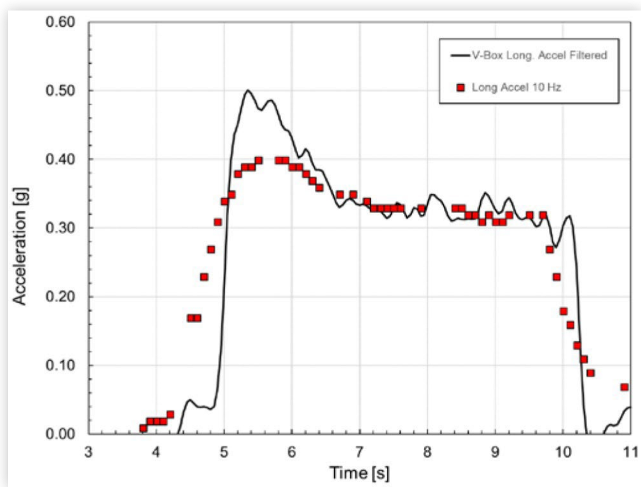


FIGURE 20 Comparison of Longitudinal Decelerations at 10 Hz, Run 1

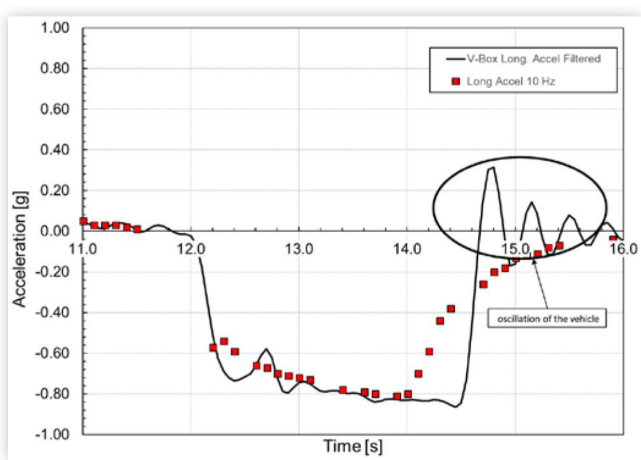


FIGURE 21 Droid and iPhone mounted to the windshield

reaches a steady state condition resulting in an average acceleration of 0.33 g from Harry's Lap Timer™ compared to the VBOX at 0.33 g. The average difference associated with the longitudinal steady state acceleration at 10 Hz was ±0.05 g with a R^2 of 0.87.

The fit of the data during the hard braking at 10 Hz was a bit surprising as shown in Figure 20. What was surprising was the fit of the data during steady state at 12.5 and 14.2 seconds. Even though the data is sampled at the higher rate of 10 Hz, the data from Harry's Lap Timer seems to trend at a lower average deceleration than what was recorded at 1 Hz. The VBOX has a deceleration average of 0.78 g whereas Harry's Lap Timer™ reported an average of 0.71 g, resulting in an average difference for braking at ±0.05 g with a R^2 of 0.84.

Further analysis of hard acceleration and braking data shows that the location of the phones during the testing compared to the location of the VBOX accelerometer is a contributing factor in the data fit, along with the smoothing done by Harry's Lap Timer™. The phones were mounted on the windshield while the VBOX accelerometer was mounted on the floorboard of the vehicle. During events where the accelerations are relatively low, such as 0.3 to 0.4 g, the body of the vehicle stays relatively flat. However, during heavy acceleration and braking where the vehicle saw accelerations over 0.5 g, the body pitch became much more pronounced. The location of the phones on the windshield creates a moment arm away from the location of the VBOX accelerometer when the vehicle squats during acceleration or dives during braking. Therefore, the data does not track exactly with the VBOX data during hard acceleration and braking due to the body pitch and the location of the phones on the windshield. With 3 point moving average utilized by Harry's Lap Timer™, the peaks will be underreported from the nature of the smoothing function.

The data from Harry's Lap Timer™ has a good correlation with the data collected by the VBOX on all sampling, however some of the peaks are missed depending on the how quickly the acceleration changes. For our purposes of accident reconstruction, it is the average accelerations that are often used for analysis. Therefore, a comparison was done between the averaged accelerations for each maneuver. An example of when average accelerations are important would be the use of Daily's lane change or swerve equations. The average acceleration is used in those calculations and not peak acceleration [21].

The lateral acceleration averages were calculated using the slalom, left and right turn tests. The straight acceleration and braking tests were used for the average longitudinal accelerations. The average was determined for each pulse (zero to peak back to zero) and then it was separated into positive accelerations or negative accelerations. The average for each group was calculated by summing the all the data and dividing by the total number of points. The results of the calculated average accelerations are shown in Table 7.

Table 7 shows that the differences in average accelerations between the reported data from the VBOX and Harry's Lap Timer™ are approximately 3%. However, there are differences which are greater, such as in the Run 2 Brake test where the VBOX reported 0.85 average g, compared to 0.78 g at 1 Hz and 0.77 g at 10 Hz. The hard braking shows a 9.5% difference.

TABLE 7 Average Accelerations and Max Jerk

Average Accelerations [g]						
Group	**Maneuver**	**Test**	**Vbox**	**1 Hz**	**10 Hz**	**Max Jerk [g/s]**
2	Slalom	Run 1 (Left) (lat.)	0.28	0.27	0.25	1.04
		Run 1 (Right) (lat.)	-0.33	-0.36	-0.32	
		Run 2 (Left) (lat.)	0.27	0.30	0.27	1.18
		Run 2 (Right) (lat.)	-0.34	-0.39	-0.33	
		Run 3 (Left) (lat.)	0.36	0.38	0.34	2.39
		Run 3 (Right) (lat.)	-0.45	-0.48	-0.41	
3	Left Turn	Run 1 (lat.)	0.17	0.17	0.17	0.41
		Run 2 (lat.)	0.32	0.32	0.30	0.9
	Right Turn	Run 3 (lat.)	-0.26	-0.25	-0.26	0.55
		Run 4 (lat.)	-0.40	-0.41	-0.40	1.02
4	Acceleration & Braking	Run 1 Acceleration (long.)	0.33	0.36	0.33	1.23
		Run 1 Brake (long.)	-0.78	-0.72	-0.71	3.25
	Acceleration & Braking	Run 2 Acceleration(long.)	0.33	0.35	0.33	1.92
		Run 2 Brake (long.)	-0.85	-0.78	-0.77	3.93

Further analysis of the data showed that when the acceleration changed too quickly, the data became less accurate at the point of greatest change in acceleration or jerk. Jerk [g/s] is defined as the sudden change in acceleration. The jerk is the derivative of the acceleration, so it reaches a maximum where the greatest changes in acceleration occur. This is usually found in the onset of a maneuver. An example would be the 4.8-5.2 seconds of the hard acceleration plots in Figures 17 and 19.

When dealing with peak accelerations, the error starts to become larger with the 1 Hz sample rate, but the error does stay under 10% with a jerk of less than 2.5 g/s and 14% error rate when above 2.5 g/s. The 10 Hz sample had an error from 2% to 10% in all runs. A 1 Hz sample rate provides reliable data when the jerk is kept below 2.5 g/s as shown in Left Turn 1. If the testing is expected to exceed the 2.5 g/s jerk and 10% error is acceptable, then the external GPS antenna with a sample rate of 10 Hz or greater should be utilized.

Although there may be a reduction in accuracy when sampling data at a jerk of 2.5 g/s or greater, this is true primarily for evaluating peak g, and hence would not be problematic for some accident reconstruction analysis purposes. The jerk should be taken into consideration when analyzing the data, however for some reconstruction purposes the average acceleration is directly applicable to time-space analysis. If peak acceleration is the important measurement needed, then the jerk would need to be kept below 2.5 g/s and the testing would need to be sampled at 10 Hz and not 1 Hz.

Based on all the testing performed (distance, speed and acceleration), Harry's Lap Timer™ accurately reported data when compared to the VBOX at both 1 Hz and 10 Hz. Longitudinal and lateral accelerations were recorded accurately when the jerk was kept below 2.5 g/s for both the 1 Hz and 10 Hz; when exceeding 2.5 g/s of jerk, then the 10 Hz sampling was needed. Body roll of the vehicle and the location of the instruments should also be a consideration when evaluating the acceleration data.

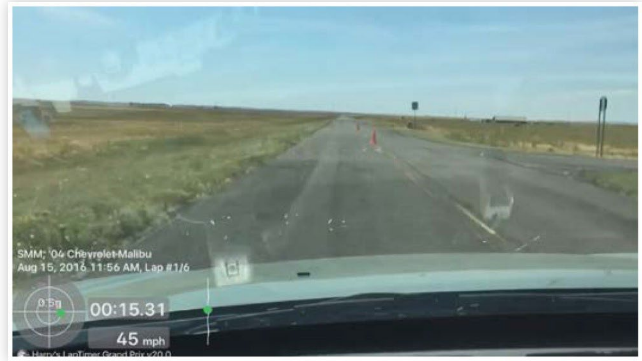
Video Sync

As part of the data collection, the phones were mounted to the windshield and oriented so the camera was facing forward. This setup allowed the use of Harry's Lap Timer's ™ video feature. The phones were mounted using a RAM™ system, which has a variety of mounting and orientation options that enable easy setup and adjustments for surfaces that are angled, such as the windshield. Figure 21 shows the two phones used in the testing mounted to the windshield, side by side.

The mounts provide two functions: the first is to orient the phone level and plumb to provide a base line for the accelerometer, and the second is to allow the phone's camera a level view from the interior of the vehicle.

After the phones were level and plumb, the testing was initiated. This orientation is important to not introduce an acceleration offset to the data. If the phone is out of level or plumb the accelerometer will record acceleration due to gravity in the longitudinal or horizontal direction. This can be checked by using the acceleration circle on the Harry's Lap Timer™ video before the test is started. The image on the phone shows the view out the front of the vehicle. As the vehicle performs the maneuver, the data is visually overlaid onto the video, providing real time feedback. Figure 22 shows a portion of the video from one of the tested runs.

FIGURE 22 - Video Image from Harry's Lap Timer™ overlaid with data



After the testing, the video can be downloaded without the data overlay, or viewed showing the synchronized speed, acceleration, and position of the vehicle during the testing. Harry's Lap Timer™ can also synchronize with other Bluetooth or WiFi capable video devices such as GoPro to allow a wider range of options.

Conclusions

Overall, we found that Harry's Lap Timer™ provided useful information on all testing maneuvers performed. The data can have its limitations, as outlined in this paper, but Harry's Lap Timer™ does record sufficiently accurate data to perform most accident reconstruction tasks. Speed data was found to correlate well when compared with the VBOX at 1 and 10 Hz for all testing maneuvers. The distance data, when calculated from the speed and time reported by Harry's Lap Timer™, was also found to have a good correlation when compared to the VBOX at both 1 and 10 Hz in all testing maneuvers. The calculated distance data was used to provide a direct comparison to the VBOX data because it matches the VBOX distance calculation method. Left and right turn lateral acceleration data (such as a vehicle taking a left turn across an intersection) also correlated well at both 1 and 10 Hz. A 1 Hz sample rate does not work well if the vehicle undergoes a more sudden change such as a abrupt swerve maneuver; in these situations a 10 Hz sampling rate, obtained by utilizing an external antenna, should be used. However even at 10 Hz, the peak accelerations are still missed and are underreported by as much as 20%, although this error can be at least partially attributed to the relative mounting locations of the phones and VBOX accelerometer, and to the smoothing performed by Harry's Lap Timer™.

Knowing the capabilities and limitations of Harry's Lap Timer™ in relation to different vehicle maneuvers, accident reconstructionists can determine when the 1 Hz sample rate or 10 Hz should be used during testing. The strong correlation of Harry's Lap Timer™ data to VBOX data, when utilizing steady-state or average accelerations, shows suitable functionality of mid-level smart phone data acquisition applications in the field of accident reconstruction.

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