Video Analysis: The Next Physics Laboratory?

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We summarize recent explorations within the USMA Department of Physics with the use of a commercial video analysis program, *LoggerPro*, to enhance the traditional mechanics lab and the interactive lecture curriculum in the calculus-based Newtonian Mechanics and Electricity and Magnetism courses at the United States Military Academy. We put forward several significant pedagogical advantages for using video analysis software. We hypothesize that these advantages include greater student-teacher interaction, enhanced visualization of mechanical phenomenon, and the ability to effortlessly analyze instructor demonstrations. When applied to the curriculum of a traditional laboratory program, these advantages should translate into an exportable, flexible, and independent platform. In effect becoming a cyber laboratory that can travel with the student, requiring only a laptop computer, a digital video camera, and a student's initiative to operate. By exporting the analysis of mechanical phenomena to the student's domain, we attempt to bridge the most important gap in science education: connecting the classroom to the dorm room, while encouraging student's to analyze everyday phenomena that might otherwise go unexplored. Applications are endless, and limited only by the instructor's (or the student's!) imagination. We highlight three applications as case studies of video analysis within our laboratory program. These case studies include a vertical loop in a popular roller coaster, a HMMWV (High Mobility Multi-Purpose Wheeled Vehicle) frontal crash test, and two charged hanging pith balls in electrostatic equilibrium. We summarize instructor and student survey data in an attempt to address the efficacy of video analysis as observed through the execution of these three case studies.

Introduction

The United States Military Academy Department of Physics teaches calculus-based Newtonian Mechanics to over 900 third-class cadets (cadets in their second year of study) each fall and teaches calculus-based Electricity and Magnetism to these cadets in the spring semester. Completion of both semesters of introductory physics is a graduation requirement. Cadets are grouped into classes of no more than 16 cadets per section and typically an instructor will teach four sections. Eight laboratory experiments are conducted each semester in support of the lecture curriculum.

Instructors have many tools available to exploit their small class size in an effort to create an interactive environment. Every classroom has a personal response systems, a full suite of Pasco demonstration equipment and sensors, a desktop and tablet computer, and a classroom video camera. Associated with each of the 18 core physics classrooms is a separate physics laboratory with five independent stations, each with a full suite of Pasco equipment and a desktop computer.

As new technologies filter into the hands of physics, engineering, and science teachers, we are faced with many questions. Are there valid reasons to use the technology to teach or is it solely for the sake of technology. Does the technology allow us to reach students we might not otherwise reach? Does the technology help our modern students to establish a link between "classroom physics" and "playground physics?" In retrospect, we attempt to answer these questions based on three case studies conducted during the Fall 2007 Introductory Newtonian Mechanics course and the Spring 2008 Electricity and Magnetism course.

Over a two-year period, the United States Military Academy Department of Physics has introduced PC-based video analysis as a means of enhancing both our interactive lecture curriculum and our introductory physics laboratory program. The impetus to implement video analysis focused on three key capabilities; the capability to analyze physical phenomena which are more familiar to cadets, the capability to create educational links between the classroom and the dorm room, and the capability to facilitate a more interactive classroom.

Method

In the Fall of 2006, video analysis was introduced as a capstone laboratory project for the Newtonian Mechanics course. Based on the feedback from this initial implementation, video analysis was used for two separate laboratories in the Fall 2007 Newtonian Mechanics course and one laboratory in the Spring 2008 Electricity and Magnetism course. The laboratories included the analysis of a popular roller coaster following a block of instruction on Newton's laws, the analysis of a frontal crash test following a block of instruction on linear momentum, and the analysis of two charged hanging pith in quasi-static equilibrium following a block of instruction on electrostatic force.

Assessment data were gathered starting in the Fall of 2007 from both instructors and cadets in an attempt to evaluate the efficacy of video analysis and to answer the above questions.

Case Study: Roller coaster loop.

A video of the Scream Machine roller coaster at Six Flags New Jersey was analyzed by cadets immediately following instruction in Newton's Laws.[1] Cadets analyzed the motion of the front cart of the roller coaster as the cart executes a loop. Project tasks included the determination of the location and the magnitudes of the maximum and minimum speeds, location and magnitude of the maximum total acceleration, as well as relating this maximum total acceleration to "g-forces." After determining that the front cart feels the greatest total acceleration at the 2 o'clock position, cadets are asked to analyze the forces on the cart at this location.

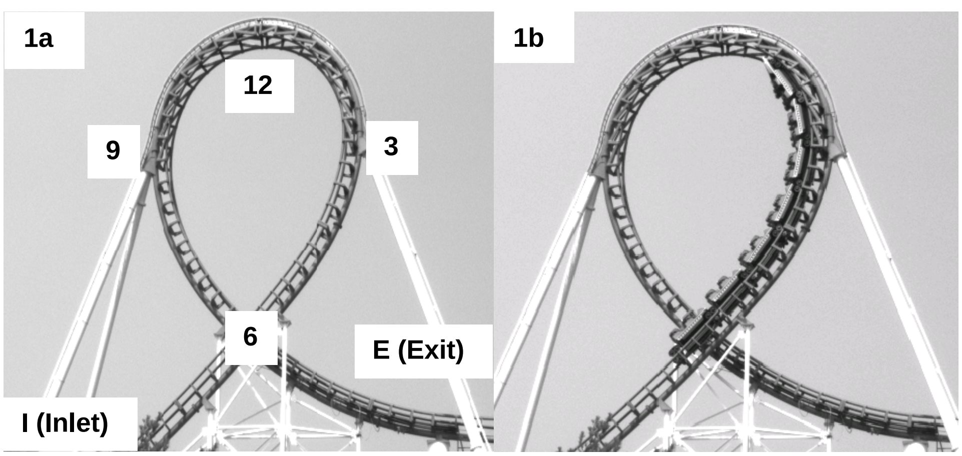

Figure 1a: Still picture of the coaster loop in *LoggerPro*. Figure 1b: Still photograph of the front cart in the 2 o'clock position.

The maximum speed occurs at the inlet to the loop, while the minimum speed occurs at the 9 o'clock position in the loop (see Figure 1b). This location is counter-intuitive, as many students might guess (incorrectly) that the minimum speed of the front cart would be at the 12 o'clock loop position. The 2 o'clock position, where we observe the maximum total acceleration, makes sense from a radial acceleration analysis by inspection: The car's speed is the greatest at the point where the radius of the curve is the smallest, thereby giving the greatest radial acceleration (see Figure 1a and Figure 1c). The maximum total acceleration, 3.8 *g*, is in accordance with many of today's roller coasters, where coaster engineers typically design for a maximum acceleration of 4 *g*.

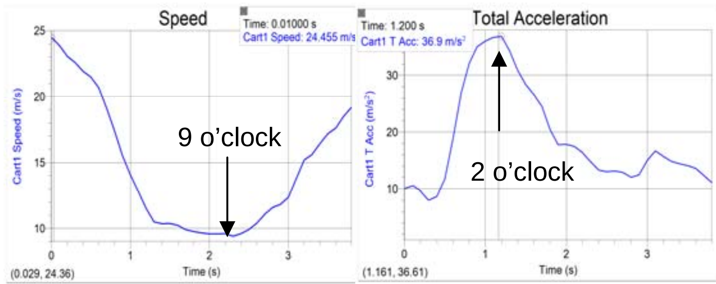

Figure 2a: Plot of Speed (m/s) vs. time (s) for the front cart. Figure 2b: Plot of Total Acceleration (m/s^2) vs. Time (s) for the front cart.

This analysis could easily be scaled to varying levels of difficulty and may also be suitable for engineering disciplines as well. Other physical phenomena which could be investigated from this case study include conservation of energy, non-conservative forces acting on the cart during its motion through the loop, and the motion of non-inertial reference frames.

A ubiquitous question that will capture the students' attention is to analyze where in the loop the rider feels "weightless." A common tool reinforced in many Newtonian Mechanics classes, the Free Body Diagram, can help elucidate this answer for confused students. Each of the forces in the Free Body Diagram can be solved for with a few assumptions (the weight of the cart, a reasonable coefficient of friction between the track and the coaster wheels) and some careful trigonometry. Of course, where the normal force is less than the component of all forces in the +y direction, the rider ceases to feel a force on his body from the coaster cart. At this point, the rider has the sensation of being "weightless." We found this exercise to be beyond the scope of our project expectations; however, this sort of analysis is a great opportunity for "extension learning."

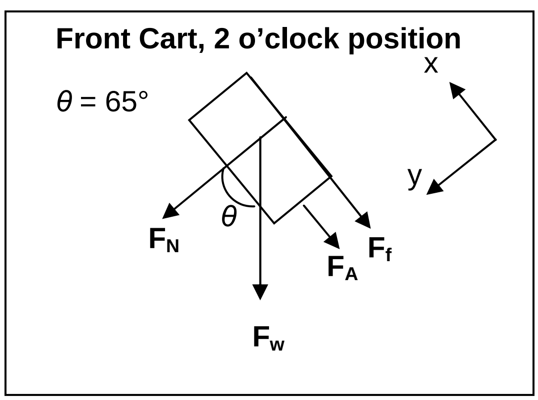

Figure 2a: Free Body Diagram of the Front Cart at its position of maximum total acceleration. F_N represents the normal force, F_W represents the weight force, F_A represents the applied force, and F_f represents the force of friction.

Noteworthy is an inspection of the much publicized idea that the rear cart provides the rider with the greatest thrill throughout the roller coaster ride, e.g., provides the greatest total acceleration. I sought to reinforce this general acceptance through a comparison of the accelerations of the front, middle, and rear carts through the motion of the loop. Surprisingly, video analysis proved otherwise for this specific loop: The front cart provides the greatest total acceleration, followed by the rear cart, followed by the middle cart. A follow-up conversation with the design engineer elucidated the physical phenomena:[2] The relative height of the inlet and exit of the loop determines which cart (front or rear) experiences the greatest total acceleration. If the loop is symmetrical, e.g., the loop inlet and loop exit are at the same height, then each cart feels an equal acceleration, albeit at opposite points on the loop. If the exit to the loop is higher than the inlet to the loop, the front cart feels the greatest total acceleration; while under the opposite geometry the rear cart feels the greatest total acceleration. Subsequent video analysis of two other loops from the Scream Machine roller coaster with different geometries confirmed this result. Nonetheless, in all three cases, the conservative rider should seek out the middle cart!

Case Study: High Mobility Multi-Purpose Wheeled Vehicle frontal crash test.

Two videos of a HMMWV frontal crash test were analyzed by cadets in order to reinforce the physical principle of linear momentum and impulse.[3] Cadets were provided a video of the right exterior side of the HMMWV and an interior video of the head of an anthropomorphic test dummy. Project tasks included an estimation of the kinetic energy absorbed by the frontal crash barrier during the crash test, a measurement of the HMMWVs "crush zone," and an estimation of the Head Injury Criterion[4] for the collision between the head of the anthropomorphic test dummy and the HMMWV steering wheel. By comparing their measured Head Injury Criterion's to the National Highway Transportation Safety Administration (NHTSA) head injury guidelines, they could determine if the HMMWV requires further safety features.

The NHTSA uses the Head Injury criterion as a one of several quantitative methods for classifying the safety of a car in a frontal crash. The NHTSA calculates the Head Injury Criterion (HIC) with the following model:

$$\text{HIC} = \left[t_2 - t_1\right]\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2}\frac{a(t)}{g}\,dt\right]^{2.5}$$

where t_2-t_1 is the collision time, $a(t)$ is the acceleration vs. time function for the anthropomorphic test dummy's head during the collision, g is the acceleration due to gravity, and 2.5 is an experimental parameter derived from cadaver testing.[5] The HIC is essentially a measure of the impulse on the driver during a very short time-duration collision. For a collision where the time duration is > 15 ms, the NHTSA considers a HIC < 700 a passing score, and a HIC > 700 a failing score.

By measuring the HMMWVs change in speed during the collision with the frontal barrier, cadets measure the amount of energy absorbed by the frame as ~.4 MJ of energy - 98% of the HMMWVs initial kinetic energy. Using data collected from the exterior video, we measured the length of the HMMWV after the crash as .40 m shorter than before the crash (see Figure 2b). This change in length as a result of the collision is defined as the "crush zone." The advantage of increasing the crush zone is to absorb more energy on the frame of the vehicle, transfer less energy and a lower average force to the occupants of the vehicle. We can probably assume that increasing the crush zone also increases the collision time, further reducing the average force felt by the occupants. However, increasing the crush zone could also be harmful if engine, transmission, or other mechanical components intrude into the crew compartment during the collision.

Using data collected from the interior video, we measured a HIC of (700 +/- 100) s as a result of the dummy-steering wheel collision. The time duration of the dummy-steering wheel collision was .007 s, or 7 ms (shaded purple region in Figure 3 below). The measured Head injury Criteria overlaps both the pass and the fail regime as interpreted by the NHTSA. Although this collision might not result in severe brain injury, we can assume that some form of head trauma would be suffered by the driver. Based on our analysis, we could recommend further safety testing in order to better estimate the Head Injury Criteria to lower the uncertainty of our measurement.

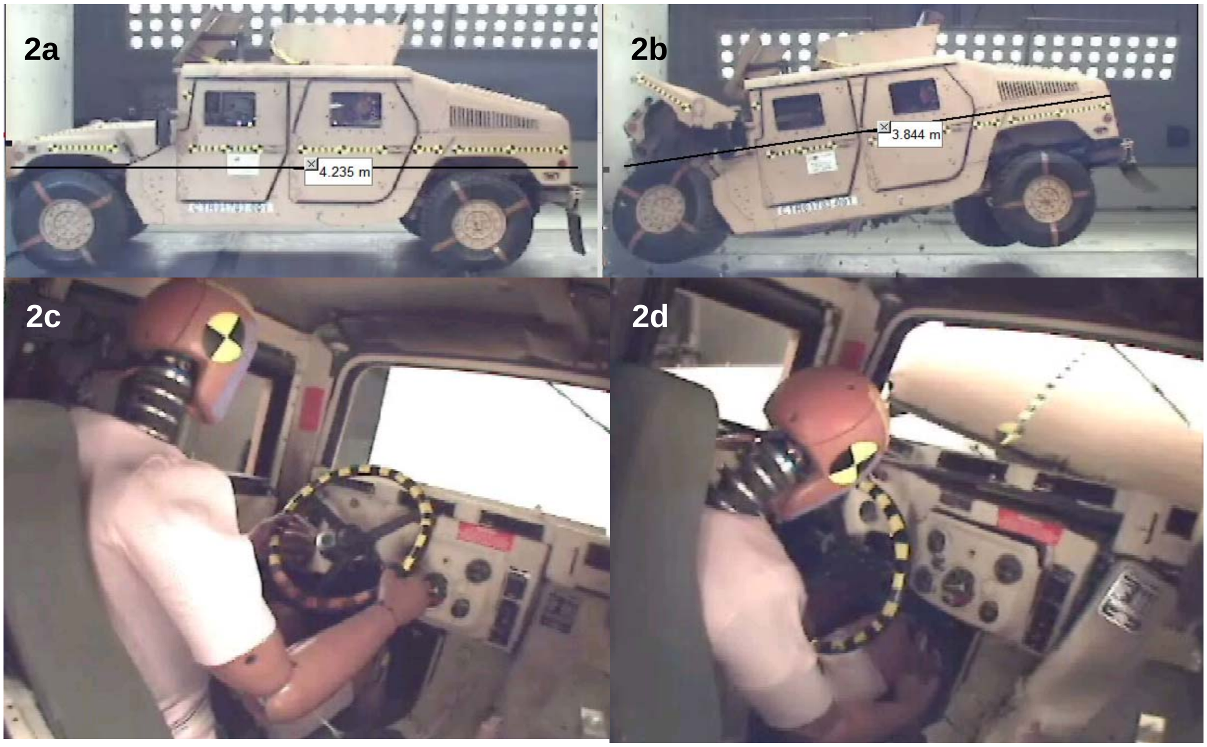

Figure 2a: Left exterior still photograph of the HMMWV before the frontal crash. Figure 2b: Left exterior still photograph of the HMMWV after the frontal crash test. Figure 2c: Interior still photograph of the anthropomorphic test dummy before the frontal crash test. Figure 2d: Interior still photograph of the anthropomorphic test dummy after the frontal crash test.

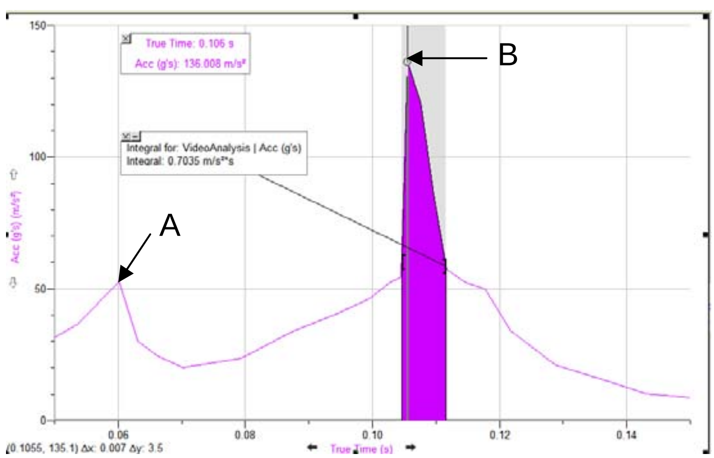

Figure 3: Plot of the acceleration (in *g*'s) vs. time for the motion of the anthropomorphic test dummy during the frontal crash test.[6]

During our video analysis, we observed a maximum head acceleration (Peak "B" in Figure 3 above) in excess of 130 *g*: ~25x the acceleration observed by the roller coaster rider! We can, however, survive these frontal crashes and extreme accelerations because the time duration is so small. Peak "A" appears to be the result of the acceleration caused by the locking mechanism inside the seat belt pretension system.

Case Study: Charged pith balls hanging in static equilibrium.

In the final case study the charge present on two hanging pith balls in quasi-static equilibrium was investigated. The cadets were tasked to analyze the video and determine the charge on the pith balls during a two-hour laboratory period. As a pre-laboratory exercise, the cadets were to complete the Newton's second law analysis of the charged pith ball system shown in Figure 4.

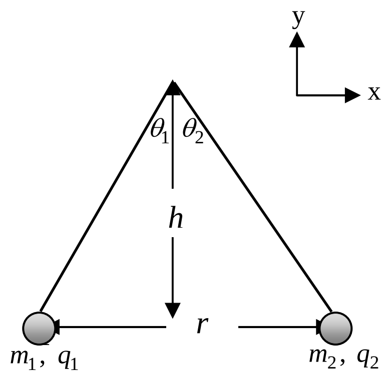

Figure 4: Setup with two charged pith balls.

Using Coulomb's law, and assuming the charge on each pith ball was the same, they determined the charge on each pith ball was:

$$q = \sqrt{\frac{mgr^3}{2kh}}$$

where *m* is the mass of the pith ball, *r* is the separation between the two pith balls, *k* is Coulomb's constant, and *h* is the vertical length of the string holding the pith balls. During the laboratory period this equation was used to determine what values had to be experimentally measured. The charged pith ball system was set up in the laboratory and it was demonstrated that actual measurements of the separation between the two pith balls was difficult due to discharging of the pith balls. The cadets were then provided a video (Figure 5) of the system and the diameter of a pith ball as reference value and tasked to measure *r* and *h*. Sample pith balls were provided and their mass was determined using a standard triple beam balance.

Figure 5: Still picture of charged pith balls in *LoggerPro*.

Based on their measured values and associated uncertainties, the cadets were able to experimentally determine the charge on each pith ball. Because the cadets were provided a video, the fact that the pith balls were not in static equilibrium was evident and allowed for additional questions to be posed. Overall, this case study is the simplest of the three addressed and was also the only one to be completed in a scheduled two-hour lab period vice an out-of-class lab project.

Results and Discussion

We, as educators, may never have an assessment tool that measures differential learning. Such a tool would, nonetheless, answer the question: “Do students actually *learn* more…” In the absence of such an assessment tool, we continue to rely on indirect assessment techniques. Therefore, students and instructors were asked specific questions in order to assess the value of video analysis.

Student survey results were mixed (N = 268, ~30% response rate, see Figure 6 below). When asked to consider whether video analysis helped them establish a link between classroom physics and real world applications, 53% of students agreed/strongly agreed, while only 25% of students disagreed/strongly disagreed. However, when asked if they would learn more from a video analysis laboratory, most students were neutral (31%). Students not neutral were much more likely to disagree/strongly disagree, 44% total. One factor in a student’s answer to this question might be the time investment involved with learning how to properly use the software. We routinely see students who want to invest little to no effort in learning how to use *any* lab equipment – we should expect the video analysis software to be no different. Students working in groups of three to four students exacerbate this problem, as some students simply volunteer to do other group related tasks, such as writing the report, instead of putting the effort into learning to navigate the software.

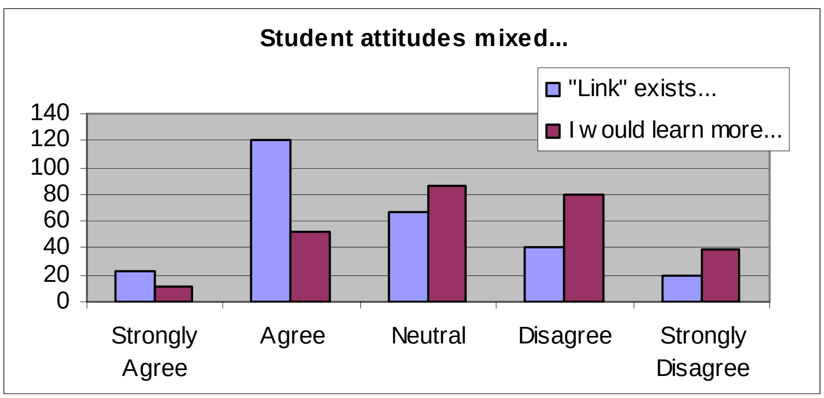

Figure 6: Summary of student assessment. Question 1 (in blue): Video analysis demonstrated the “link” between classroom physics and real world application. Question 2 (in red): I would learn more from a video analysis lab than a traditional lab experiment.

The data are encouraging that students felt a connection between the physics taught in class and the application of those physics to such complicated real world systems such as the roller coaster and the frontal crash test. Although our data do not support any claims based on a student’s choice of major, it seems logical that student’s choosing science and engineering majors would be more likely to see a learning gain from using video analysis. This is a direction for future study: Do non-science majors apply a lower value to the video analysis exercises than science and engineering majors?

Instructors were no less mixed than the students they teach (N = 14, response rate ~92%, see Figure 7 below). The query about classroom video analysis usage outside of the laboratory produced polarized results. 50% of instructors agreed that video analysis had the potential to be an integral part of their instruction, while 35% of instructors disagreed. Reassuring is the instructor belief that the overhead costs sunk into learning to use the software is worth its use, if even for just a few video analysis laboratories each semester.

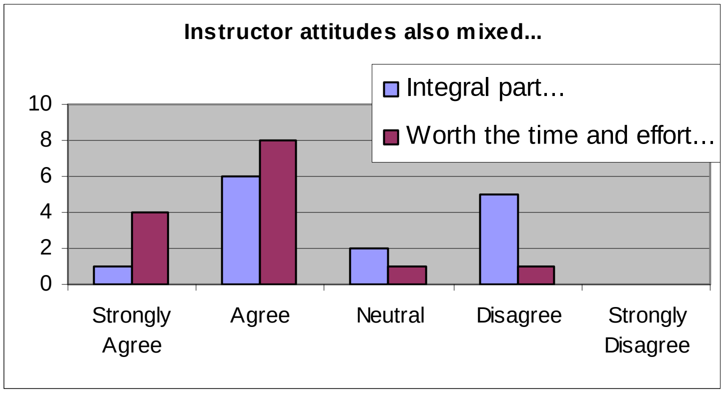

Figure 7: Summary of instructor assessment. Question 1 (in blue): Video analysis has the potential to become an integral part of how I demonstrate mechanical phenomena to my students. Question 2 (in red): The overhead costs (in terms of time and effort) are worthwhile for the execution of a limited number of video analysis lab exercises.

Conclusions

We have summarized our use of video analysis with three specific case studies as well as provide mixed assessment data supporting the use of video analysis. Clearly, video analysis is not a tool to supplant each traditional lab exercise. Video analysis exercises may be best implemented in judicious doses, and used especially for real world situations that are in some form familiar to students. However, we believe that when employed under these conditions, video analysis is not just a technological tool to be used for its own sake.

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[1]Mr. Chickola, L., Chief Corporate Engineer, Six Flags New Jersey Theme Park. Mr. Chickola provided the Scream Machine Roller Coaster video for our class project pro bono.
[2]Personal conversation with Mr. Chickola, on or about 15 September 2007. Mr. Chickola explained that the center of gravity of the cart system changes as the loop geometry changes; resulting in different peak accelerations for different carts based solely on the geometry of the loop.
[3]Mr. Chinni, J., Professional Engineer, Center for Advanced Product Evaluation. Mr. Chinni, with the express written permission of the US Army Tank and Automotive Command, provided the two HMMWV videos for our class project pro bono.
[4]National Highway Transportation Safety Administration, Federal Motor Vehicle Safety Standards 571.208 (2004). Ch. V, p. 519-520.
[5]Gadd, CW. (1966). Use of a Weighted Impulse Criterion for Estimating Injury Hazard. Proceedings of the Tenth Stapp Car Crash Conference, SAE Paper 660793.
[6] Although not published for copyright restrictions, the acceleration vs. time plot for the head measured by CAPE engineers is very similar to the data obtained using *LoggerPro*.