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Determination of Road Load Coefficients with Smartphone Accelerometers

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Determination of road load coefficients with smartphone accelerometers

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Abstract – Due to the integrated sensors, smartphone owners carry not only handy communication tools but also fully-fledged data acquisition and measurement systems in miniature form in their pockets. The measured data can be transferred quickly and easily to laptops or desktop PCs, where they are then available for further processing. Consequently, smartphones can enrich physics and engineering education in many ways, as they enable low-threshold access to physical measurement methods.

In order to make use of this possibility, undergraduate student research projects with measuring tasks were initiated. One of them was the determination of the rolling and aerodynamic drag coefficients of model vehicles by using the accelerometers of their smartphones. The coastdown technique should be used, in which the vehicle is accelerated to a specified speed, shifted into neutral and allowed to decelerate freely. The time rate of change of its velocity is proportional to the total resistive force, which is assumed to consist of a speed-independent rolling resistance and an air resistance proportional to the square of the vehicle's speed.

A smartphone attached to the model vehicle provides the time-dependent acceleration data, which are usually noisy and need to be smoothed. The vehicle velocity, on the other hand, can be obtained from the acceleration data by numerical integration. By plotting the velocity square on the abscissa and the vehicle acceleration on the ordinate in a coordinate system for the coasting process, a straight line can be fitted. From the slope of this straight line, the aerodynamic drag coefficient can be derived, and its intersection with the ordinate provides information on the rolling resistance coefficient.

Three teams of three or four students each worked simultaneously and competitively on that project. They independently conducted experiments and developed computer programs for the visualization of the data and evaluation of the measurements. In this paper, the theoretical background, the approach to the problem and the outcome of the undergraduate student projects are presented and discussed.

Introduction

Smartphones have become ubiquitous in our society and are familiar tools for communication and leisure activity. This goes hand in hand with the fact that it is also a constant companion of our students and thus often perceived as disturbing or distracting by the lecturers in class. However, smartphones are also portable computers and, on top of that, have an arsenal of sensors and transmitters that can provide valuable data. Both can be used for more participatory teaching strategies and for exciting projects (see, e.g., [1-4], and for an evaluation [5]).

Today's smartphones typically include accelerometers, gyroscopes, proximity sensors, ambient light sensors, magnetometers, and GPS. Some high-end models may also include barometers, temperature sensors, and humidity sensors. In addition, most smartphones are equipped with sophisticated high-resolution cameras that can also be considered as sensors.

The accelerometers, gyroscopes, and magnetometers provide motion and orientation data, allowing the phone to automatically adjust its display or trigger certain actions when it is turned or moved. The accelerometers detect translational acceleration, while the gyroscope provides angular acceleration data relative to the body frame of the device. The six-degrees-of-freedom data provided by this combination characterizes the motion and orientation of the device without reference to an external coordinate frame. With the inclusion of the magnetometer data, however, the orientation of the smartphone with respect to the geographical frame of reference can be established. Finally, the GPS signal allows to determine the smartphone's location, which can be used for a variety of purposes such as maps, tracking, and location-based services.

A special feature of these physical data recorded by the internal sensors, however, is that they can be used beyond their actual purpose with the help of additional programs, so-called apps. This makes it possible to carry out both qualitative and quantitative experiments in a wide range of subject areas, especially in physics. Smartphones thus represent small, transportable measurement laboratories. The project presented in this paper focuses on the latter point, in which the sensors installed in smartphones are used to carry out quantitative experiments. The main advantages of the devices are to be exploited, which are reflected in their widespread use among our students and in their high mobility. In this project, which was inspired by [6], our second-semester engineering students were given the task of determining the drag coefficient (c_d value) of a car as well as the rolling resistance and the frictional force in the wheel hubs solely by means of the acceleration sensor in a smartphone.

For the purpose of such activities, a cross-curricular teaching framework has been created at our institution in which such multidisciplinary student research projects can be carried out [7]. The basis for this framework is the software development course in the second semester, in which our students learn a high-level programming language (C#). Computer programming is a suitable pivot for multidisciplinary project-based learning, because a large class of problems and tasks can be dealt with using numerical methods. All the student research projects have in common that the final results are stand-alone computer programs that can be installed and run on Windows operating systems. The following structure has been established over the years: Course instructors of various disciplines define multidisciplinary project tasks that involve computer programming, which should be challenging but solvable for second-semester students. The students form teams of three or four and choose their projects according to their interests and skills. Up to three groups are allowed to choose the same topic, and from then on work as competing teams on the best possible solution. The students are continuously supervised and supported by the associated course instructors during their project work, and at the end of the semester, all teams present their solutions to all participating groups and the faculty involved.

Three teams of students chose the vehicle drag coefficient project, which was also offered in this context, and developed individual solutions over the course of the semester. Their task consisted of several parts. First, they had to read up on the coastdown technique for the experimental determination of drag forces on the road. After that, they had to design experimental set-ups with which they could carry out such measurements with model cars by simple means. The only restriction was that smartphones had to be used for the measurements. Subsequently, they had to read out and process the collected data from the smartphone for the determination of the drag coefficients. And the ultimate goal was to design a computer program with which this evaluation and calculation can be carried out easily and user-friendly.

This paper is structured by first providing a brief outline of the coastdown method for the determination of vehicle drag. Secondly, the test procedure and the mathematical modeling are described. And finally, one of the student-developed computer programs for the visualization of the collected data and the computation of the drag coefficients is presented, the results are discussed, and a summary then closes the paper.

The coastdown testing method for drag determination

The coastdown method is a well-established technique widely used throughout the automotive industry for the experimental estimation of the drag forces that act on a vehicle when operating in its natural environment. The vehicle is accelerated up to a desired speed, shifted into neutral and allowed to decelerate freely. The time rate of change of vehicle speed is proportional to the total resistive force. This test procedure is simple and cost-effective compared to air resistance measurements in the wind tunnel and rolling resistance measurements on the dynamometer. The crux with this procedure is to find a route that is as straight and level as possible to keep the influences of incline and steering interventions as low as possible. In addition, the interference caused by ambient wind should be kept as low as possible [8].

The aerodynamic drag force depends, in general, on many factors including the density and velocity of the fluid (i.e., air in the case of a road vehicle) and the geometry of the body in the flow. The dimensionless Reynolds number of the fluid, which represents the ratio between inertial and viscous forces, plays a key role in determining the drag force. It is defined by

$$R = \frac{\rho l v_{\mathrm{r}}}{\mu}, \tag{1}$$

where ρ is the density of the fluid, μ its viscosity, l a characteristic length of the body in the fluid and v_{r} the relative velocity of the body. When the Reynolds number is large (in between the order of 10^3 to 10^6), the aerodynamic drag force F_{d} is assumed to be independent of the viscosity and proportional to the square of the relative velocity, i.e.,

$$F_{\mathrm{d}} \sim \rho A v_{\mathrm{r}}^2. \tag{2}$$

Since the dynamic pressure $\frac{1}{2}\rho v_{\mathrm{r}}^2$ plays a fundamental role in aerodynamic theory, the drag force is conventionally modelled by

$$F_{\mathrm{d}} = c_{\mathrm{d}} \frac{\rho A}{2} v_{\mathrm{r}}^2 , \tag{3}$$

where the constant c_{d} depends only on the shape and surface characteristics of the body.

The equation of motion for a vehicle coasting down freely in a straight horizontal line may thus be expressed as

$$m_{\mathrm{e}} \frac{\mathrm{d}v(t)}{\mathrm{d}t} = -\, c_{\mathrm{d}} \frac{\rho A_{\mathrm{f}}}{2} v_{\mathrm{r}}(t)^2 - F_{\mathrm{rm}}(v(t)) , \tag{4}$$

with $v(t)$ being the vehicle speed, $v_{\mathrm{r}}(t)$ the total airspeed relative to the vehicle, m_{e} the vehicle effective mass, i.e., the vehicle mass plus rotating component inertias, c_{d} the air drag coefficient, ρ the air density, and A_{f} the vehicle frontal area (see, e.g., [8, 9]).

The rolling and mechanical losses, termed F_{rm} in equation (4), are a combination of the tire losses and losses from the drive train and the wheel hubs. Rolling and mechanical resistance is in general a non-linear function of speed and, in addition, temperature dependent. For a simplified description of the rolling resistance a polynomial in $v(t)$ is commonly used. At lower speeds it increases approximately linearly with the vehicle velocity, over broader speed ranges higher order polynomials are indicated [10]. Due to the very limited speed range utilized in our investigation, only a non-speed-dependent rolling resistance $F_{\mathrm{rm}} = c_{\mathrm{rm}}\, m\, g$ was adopted in this work. F_{rm} is representing an average value within this speed range, with the coefficient of rolling and mechanical drag c_{rm}, the vehicle mass m, and the acceleration of gravity g.

Since the present study is based only on the vehicle's acceleration-time history $a(t)$ and no additional simultaneous measurement of the relative airspeed v_{r} is incorporated into the analysis, v_{r} in equation (4) is plainly replaced by the vehicle speed v. The rotating component inertias are often taken into account by means of a factor multiplied by the total mass or can be neglected in the case of model cars. Thus, the vehicle effective mass m_{e} is replaced by the vehicle mass m.

Introducing the new variables $k = (c_{\mathrm{d}}\, \rho\, A_{\mathrm{f}})/(2m)$ and $d = c_{\mathrm{rm}}\, g$, equation (4) can be formulated as

$$\frac{\mathrm{d}v(t)}{\mathrm{d}t} = -k\, v(t)^2 - d , \tag{5}$$

a nonlinear separable first order differential equation with constant coefficients, which can easily be solved. However, if one uses the variable $a(t)$ for the deceleration of the vehicle during the coastdown, which is the measured quantity in our experiments, equation (5) takes the form of a straight line if $v(t)^2$ is plotted on the abscissa ($x = v(t)^2$) and $a(t)$ on the ordinate ($y = a(t)$), i.e.,

$$a(t) = k\, v(t)^2 + d . \tag{6}$$

From this straight line equation, the coefficients k and d can be determined if the velocity-time $v(t)$ and acceleration-time $a(t)$ curves obtained in the coastdown experiments are known.

Since the smartphone sensor can only be used for the measurement of the acceleration-time history, but not for the speed of the vehicle, $v(t)$ must be obtained from the acceleration data by means of numerical integration.

The time-continuous acceleration data measured by the smartphone sensor must be discretized for further processing. This is done by the internal analog-to-digital converter of the smartphone that converts the voltage signals of the sensor at a fixed sampling rate (time step size Δt) into digital data. The acceleration data are then available in tabular form. Thus, all the necessary computations must be performed with the discretized table values a_n rather than with the time-continuous acceleration $a(t)$, where the subscript n corresponds to the sampling time $t_n = n\,\Delta t$.

For the numerical integration of the acceleration data various integration methods are available, such as the rectangular rule, the trapezoidal rule, and Simpson's formula. In the case of the trapezoidal rule, which is very familiar to our students, the algorithm for calculating the vehicle's velocity is

$$v_{n+1} = v_n + \frac{\Delta t}{2}\left(a_{n+1} + a_n\right), \tag{7}$$

where the initial velocity v_0 must be known. After integrating the acceleration data, the velocity and acceleration values are available for each time step and can now be combined into a pair of points, whereby the velocity is squared to obtain the functional relationship between $v(t)^2$ and $a(t)$ according to equation (6).

As a final step in determining the driving resistances, the coefficients k and d must be determined from equation (6). For this purpose, the acceleration data are plotted over the corresponding squared velocity data, and a least-squares fit is performed by using a first-degree polynomial.

Coastdown experiments with model cars

The three student teams opted for different test vehicles; the vehicle shown in this work is an open-wheel model racecar chassis (see Figures 1 and 2). To carry out the experiments, the smartphone was mounted vertically in front of the rear wing in such a way that the z-axis of the three-dimensional acceleration sensor points in the direction of travel. For the coasting process itself, a skater park that offers suitable acceleration routes was alienated (Figure 2).

The data acquisition thus takes place under realistic conditions and not, as is often the case in the classroom, under idealized laboratory conditions, which require negligible frictional forces and perturbations in data evaluation. If one wants to compare the data recorded in such a way with a theoretical model, however, even in simple mechanical experiments, one quickly reaches the limits of what is mathematically feasible for undergraduates – perturbations are always present in real-life experiments and can usually not be neglected in modeling. In order to compensate for external disturbances such as unevenness in the ground and wind gusts, the students had to carry out a series of measurements with subsequent averaging of the measured data.

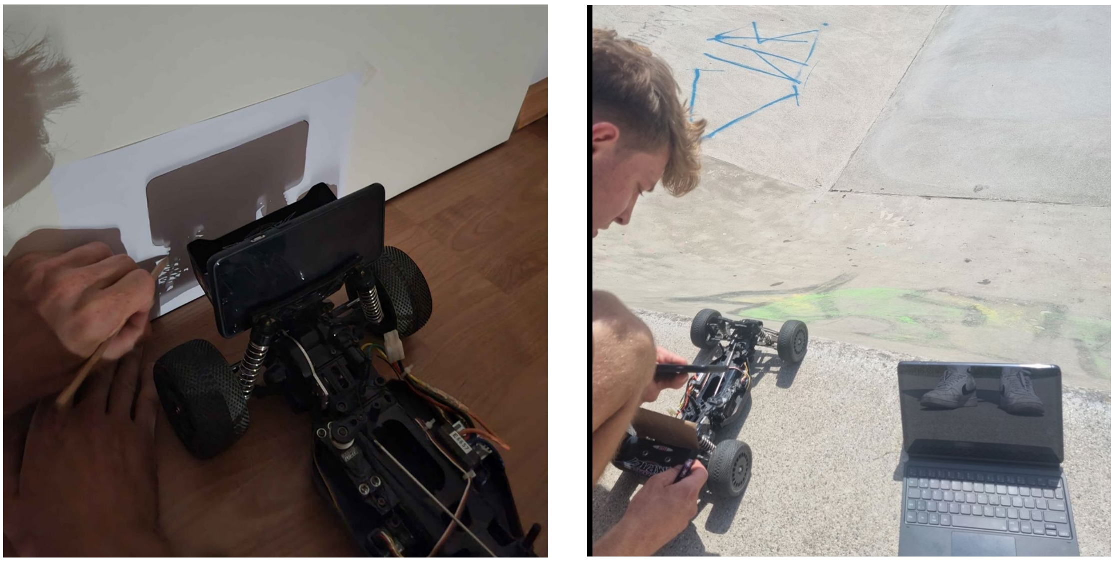


Figure 1: Determination of the frontal area and preparation of the test vehicle

Prior to the experiments the model car was weighed, and the effective area of the vehicle was determined by projection through a distant light source (Figure 1, left). Since the vehicle's speed is to be determined by integration, the car must be accelerated from a standing start (Figure 2, left). The acceleration measurement is started before the model car rolls down the ramp. Several apps are suitable for this purpose, like, e.g., *SPARKvue* [11], *Accelerometer Data Pro* [12], or *phyphox* [13].

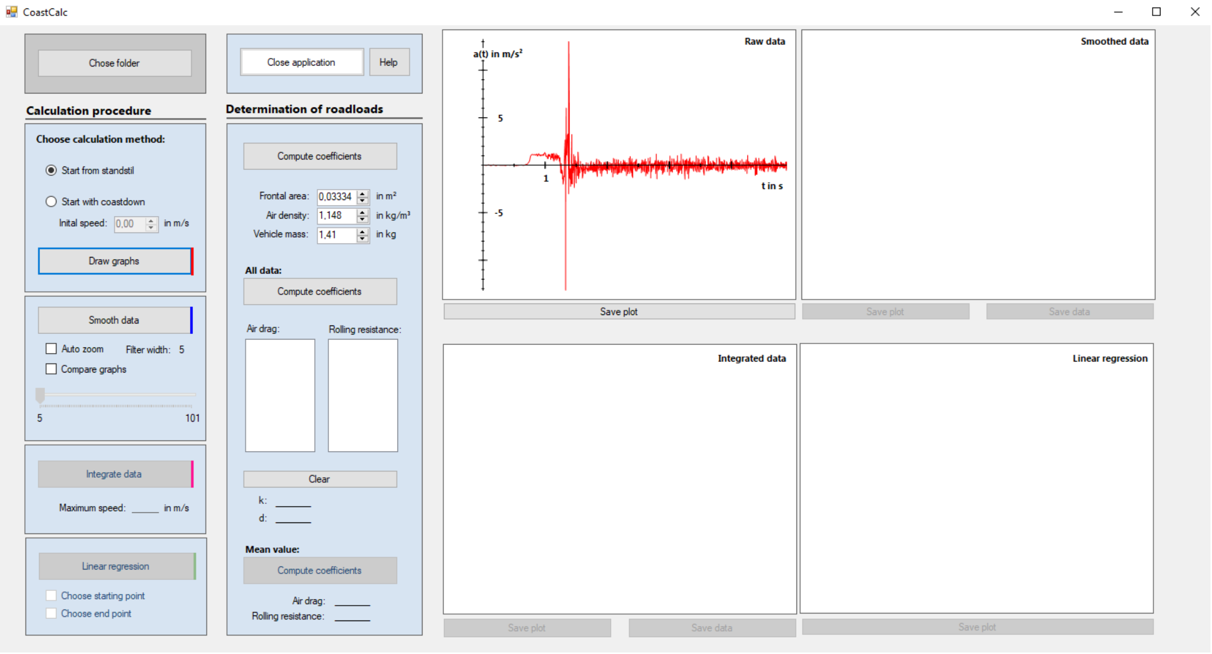
Figure 2: Skater Park as test track for the coastdown experiments

The app *phyphox* (physical phone experiments) was used for the coastdown experiments by all three student teams. *phyphox* has been developed at RWTH Aachen University and is available free of charge for Android and iOS operating systems [1, 4]. This app does not only serve as a data logger, but it also supports experimentation with some mathematical evaluation options and offers various suggestions for experiments. The spectrum of available mathematical methods ranges from simple addition to Fourier transformation, which can be displayed in real time during the data logging. For experiments in which the smartphone cannot be operated, the app offers remote access. This makes it possible to control the measurement via a second device with a web browser and to monitor the measurement process. In addition, this app also offers the possibility to integrate additional sensors that are not implemented in the smartphone via the Bluetooth Low Energy interface.

The student teams used different smartphone types, with sampling periods ranging from $\Delta t = 0.024$ s to $\Delta t = 0.05$ s. The measured data were temporarily stored on the smartphones and downloaded after the experiments.

Data evaluation with a student-written computer program

In order to cast the previously described procedure for determining the driving load coefficients into an algorithm, the students wrote a computer program with a graphical user interface (GUI) on which the user is guided step by step through the processing flow (see Figure (3)). The C# programming language was used for this purpose, an object-oriented, general-purpose language of the C family that enables the development of graphical user interfaces with comparatively little effort. Learning this programming language is mandatory for our students in the first year of study, as it is a valuable tool for the further course of their studies.



● Start from standstil

Inital speed: 0,00 in m/s

Filter width: 5

Frontal area: 0,03334 in m²

Air density: 1,148 in kg/m³

Vehicle mass: 1,41 in kg

Figure 3: Graphical User Interface of the student created computer program

As a first step, the program folder on which the acceleration data are stored can be defined in a pop-up menu by pressing the button in the upper left corner of the GUI. The data, which can be formatted as Excel or as CSV files is then automatically loaded into memory. By pressing the “Draw graphs” button, a graphical representation of the acceleration time history is displayed in the upper left diagram.

The two option buttons above are used to determine whether the acceleration data has been recorded at the start of the coasting phase, or from the beginning of the experiment, when the vehicle was still at rest. This is important because, without a speedometer, the starting speed of the coastdown is not known. Thus, it can only be determined by integrating the entire acceleration signal from the very beginning of the experiment, when the vehicle is still at rest, until the maximum speed is reached. However, if the initial speed at the start of the coasting phase is known by additional measuring equipment, it can be entered manually and thus only the deceleration curve during the coasting of the vehicle is necessary for the determination of the driving resistance coefficients.

Figure 4 shows the sampled acceleration raw data of a coastdown experiment with a model car. As can be seen, the data are extremely noisy, which can be explained by the road roughness, which is disproportionate compared to the size of the model car, and the unfavorable mass ratio between the measuring object and the measuring system.

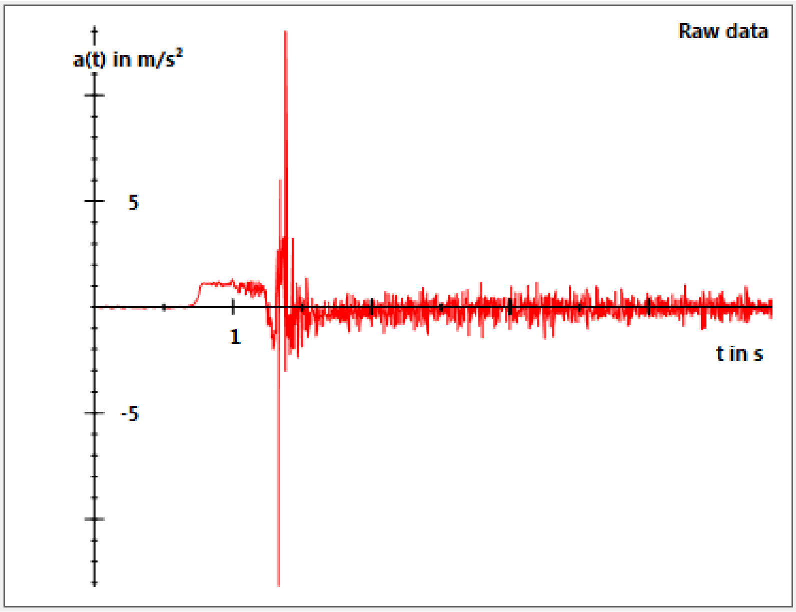


Figure 4: Acceleration raw data a_n

Hence, in order to be able to process the data further, they must be smoothed in an appropriate way. For this purpose, Savitzky-Golay filters [14] were used in this work. These filters use a variable window width and variable smoothing factors that affect the filtering effect. Thus, by adjusting the coefficients, the filter can act not only like a sliding average filter, but also like a low noise differentiation filter.

The construction of Savitzky-Golay filters is based on a least-squares fit to each window of data by a polynomial of some fixed degree. It acts on the vector of acceleration data **a** to produce a smoothed vector $\underline{\mathbf{a}}$. On a window of $N = 2M + 1$ samples $a_{n-M}, a_{n-M+1}, \ldots, a_{n+M}$,, the best fit by a polynomial of a specified even degree must then be calculated. The smoothed output value $\underline{a}_n$ is then taken at the center of the window.

If, for example, a polynomial of 2nd degree is fitted to a specified number of neighboring points for each sampled data point a_n, the smoothed values $\underline{a}_n$ are then represented by the polynomial

$$\underline{a}_n = c_0 + c_1 t_n + c_2 t_n^2 . \tag{8}$$

A filter window size of $N = 5$ leads to the following linear system of equations

$$\begin{pmatrix} 1 & t_{n-2} & t_{n-2}^2 \\ 1 & t_{n-1} & t_{n-1}^2 \\ 1 & t_n & t_n^2 \\ 1 & t_{n+1} & t_{n+1}^2 \\ 1 & t_{n+2} & t_{n+2}^2 \end{pmatrix} \begin{pmatrix} c_0 \\ c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} a_{n-2} \\ a_{n-1} \\ a_n \\ a_{n+1} \\ a_{n+2} \end{pmatrix}, \tag{9}$$

abbreviated in matrix notation as $\mathbf{Mc} = \mathbf{a}$, with $\mathbf{M}$ being the Vandermonde matrix, $\mathbf{c}$ the coefficient vector and $\mathbf{a}$ the vector of the acceleration raw data.

The filter coefficients c_i (c_0, c_1, and c_2 in equations (8) and (9)) can be determined by applying the Moore-Penrose pseudoinverse $\mathbf{M}^\dagger$ of the Vandermonde matrix $\mathbf{M}$ to the overdetermined linear system (9), which results in

$$\mathbf{c} = \left(\mathbf{M}^\mathrm{T}\mathbf{M}\right)^{-1} \mathbf{M}^\mathrm{T}\mathbf{a} = \mathbf{M}^\dagger \mathbf{a}. \tag{10}$$

The students have implemented a $p = 2$ polynomial Savitzky-Golay filter for a constant time step size Δt that is activated by pressing the “Smooth data” button. This filter has a variable window size N, ranging from 5 to 101, which can be selected in the program quite comfortably with a slider bar. In addition, two checkboxes are provided. The first enables automatic scaling of the smoothed data, which is displayed in the upper right diagram of the GUI, and the second overlays the smoothed acceleration data onto the raw data (see Figure 5).

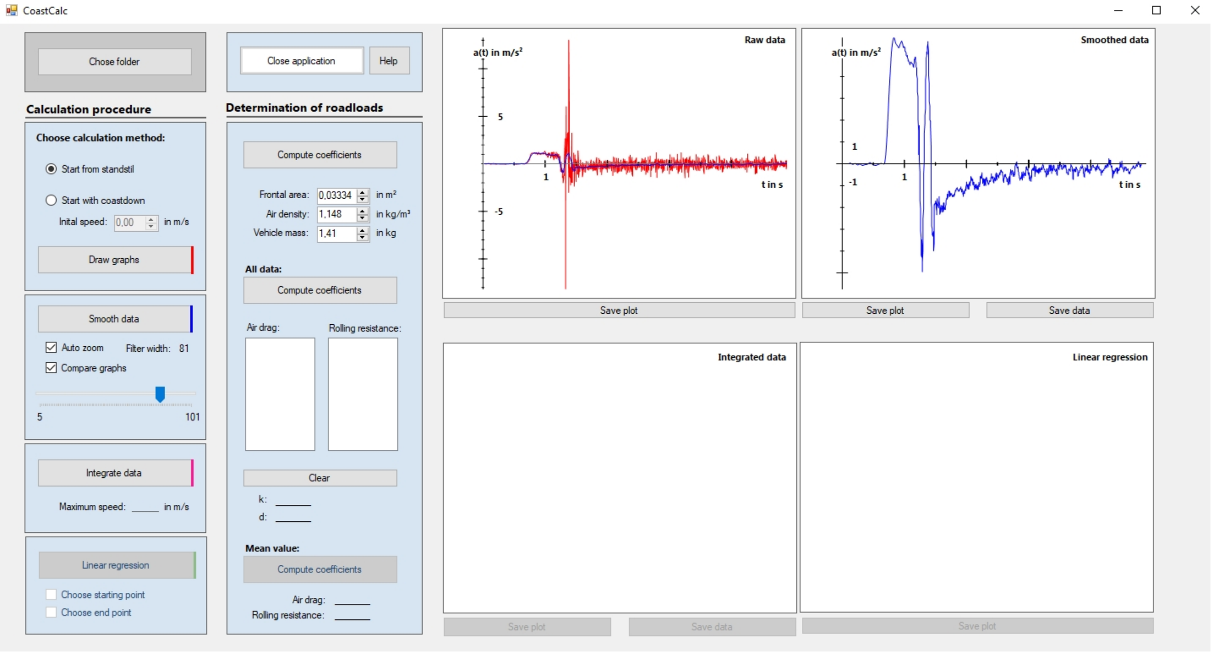
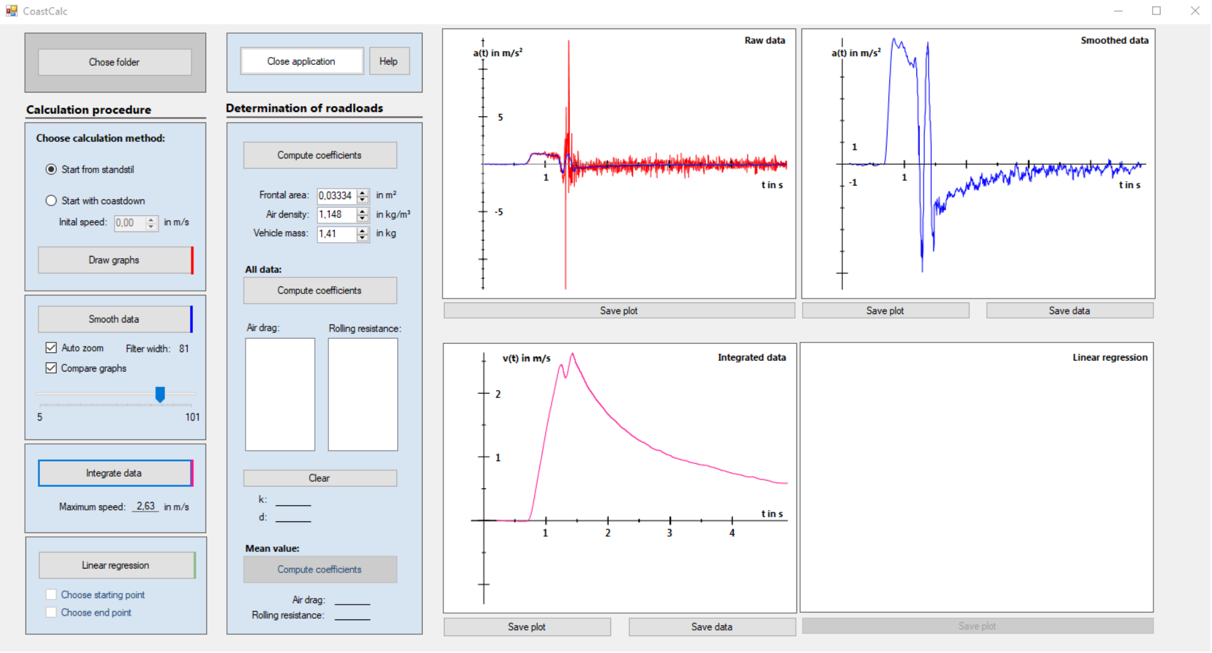

Choose calculation method:
● Start from standstil
○ Start with coastdown
Inital speed: 0,00 in m/s
☑ Auto zoom
☑ Compare graphs
Filter width: 81
☐ Choose starting point
☐ Choose end point
Frontal area: 0,03334 in m²
Air density: 1,148 in kg/m³
Vehicle mass: 1,41 in kg
Maximum speed: _____ in m/s
k: _____
d: _____
Air drag: _____
Rolling resistance: _____

Figure 5: Smoothed acceleration data $\underline{a}_n$ superimposed on raw data a_n

By pressing the “Integrate data” push button, a numerical integration of the smoothed acceleration data is carried out, and the resulting velocity curve is displayed in the lower left diagram. The dent at the peak of the speed profile is explained by a jerk occurring at the transition from the acceleration ramp to the horizontal coasting section (Figure 6).

Both the smoothed acceleration curve and the calculated velocity curve can be saved as CSV files or as images externally by clicking on the push buttons arranged below the diagrams.



Choose calculation method:
● Start from standstil
○ Start with coastdown
Inital speed: 0,00 in m/s

☑ Auto zoom Filter width: 81
☑ Compare graphs
5 101

Maximum speed: 2,63 in m/s

☐ Choose starting point
☐ Choose end point

Frontal area: 0,03334 in m²
Air density: 1,148 in kg/m³
Vehicle mass: 1,41 in kg

All data:
Air drag:
Rolling resistance:
k:
d:

Mean value:
Air drag:
Rolling resistance:

Figure 6: Added speed-time history, derived by numerical integration

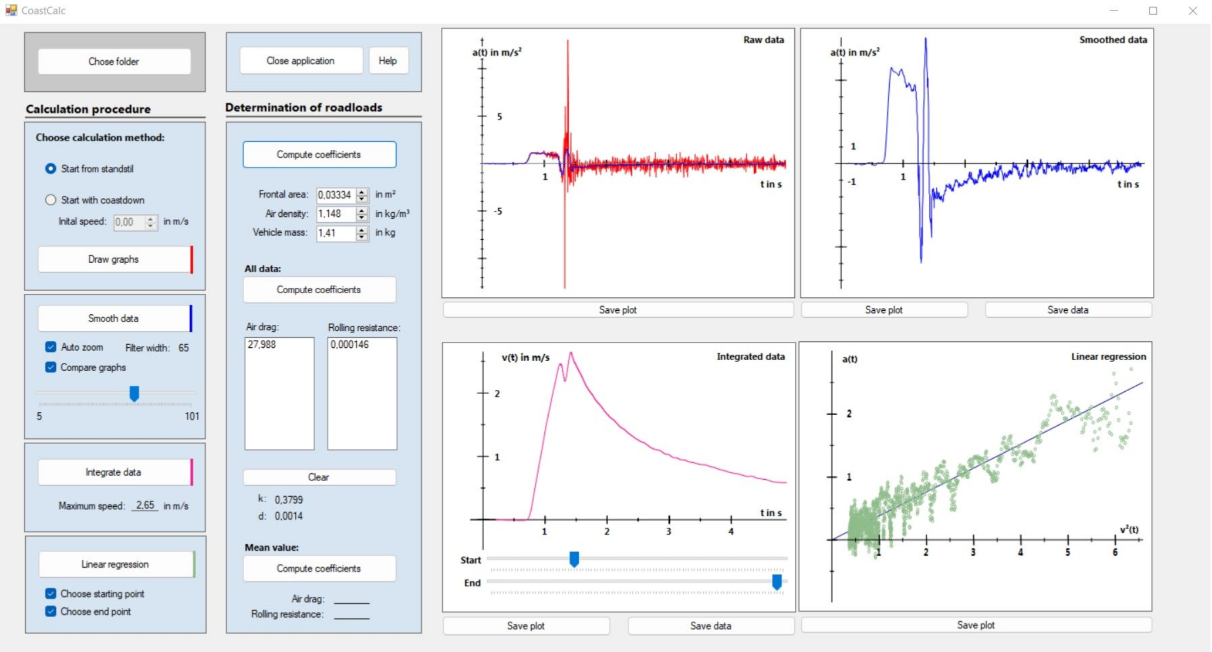
The lowest push button in the left control panel of the program starts the calculation of the linear regression between the smoothed acceleration data and the square of the associated vehicle speed data. By clicking on the two checkboxes below, two sliders are displayed beneath the speed time history, which allow the definition of a left and a right limit for the coastdown period that should only be considered in the regression calculation. In this way, the vehicle's acceleration phase up to the maximum speed can be eliminated from the velocity and acceleration data. The selected data cloud and the associated regression line are shown in the lower right graph (Figure 7).

For the calculation of the driving resistance from the slope and the ordinate intersection of the regression line, additional data must be entered in the middle control panel of the program, namely the vehicle mass, the frontal area of the vehicle and the air density. After pressing the "Compute coefficients" push button, the drag and the rolling resistance coefficient are displayed.

Due to various environmental influences on the measurement like varying road roughness or wind gusts, several coastdowns should be carried out and the data obtained averaged. The program allows the reading of several test files from the same test folder and calculates the mean values of the driving resistance coefficients.

As can be seen from Figure 7, the road load coefficients seem to be calculated incorrectly by about an order of magnitude. The air resistance seems to have been determined clearly too high and the rolling resistance clearly too low, at least if the coefficients of real passenger cars are taken for comparison. The sum of the resulting drag forces, however, coincides with the deceleration curve of the coastdown.

An initial search for causes did not provide an explanation for these values, as the other student teams also obtained comparable results. The Reynolds number was in the range of $2 \cdot 10^4 - 5 \cdot 10^4$ and thus relatively low, but still in the range where the air resistance may be assumed proportional to the square of the flow velocity.



Choose calculation method:
● Start from standstil
○ Start with coastdown
Inital speed: 0,00 in m/s

☑ Auto zoom Filter width: 65
☑ Compare graphs

Maximum speed: 2,65 in m/s

☑ Choose starting point
☑ Choose end point

Frontal area: 0,03334 in m²
Air density: 1,148 in kg/m³
Vehicle mass: 1,41 in kg

All data:

Air drag:	Rolling resistance:
27,988	0,000146

k: 0,3799
d: 0,0014

Mean value:
Air drag: ______
Rolling resistance: ______

Figure 7: Added linear regression of the acceleration-over-velocity-square point cloud

An estimation of the variable uncertainty in the linear least squares fit can be derived from the variance of the data by

$$\sigma \simeq \sqrt{\sum_{i=1}^{N} \frac{\left(a_i - \left(k v_i^2 + d\right)\right)^2}{N-2}}\,, \tag{11}$$

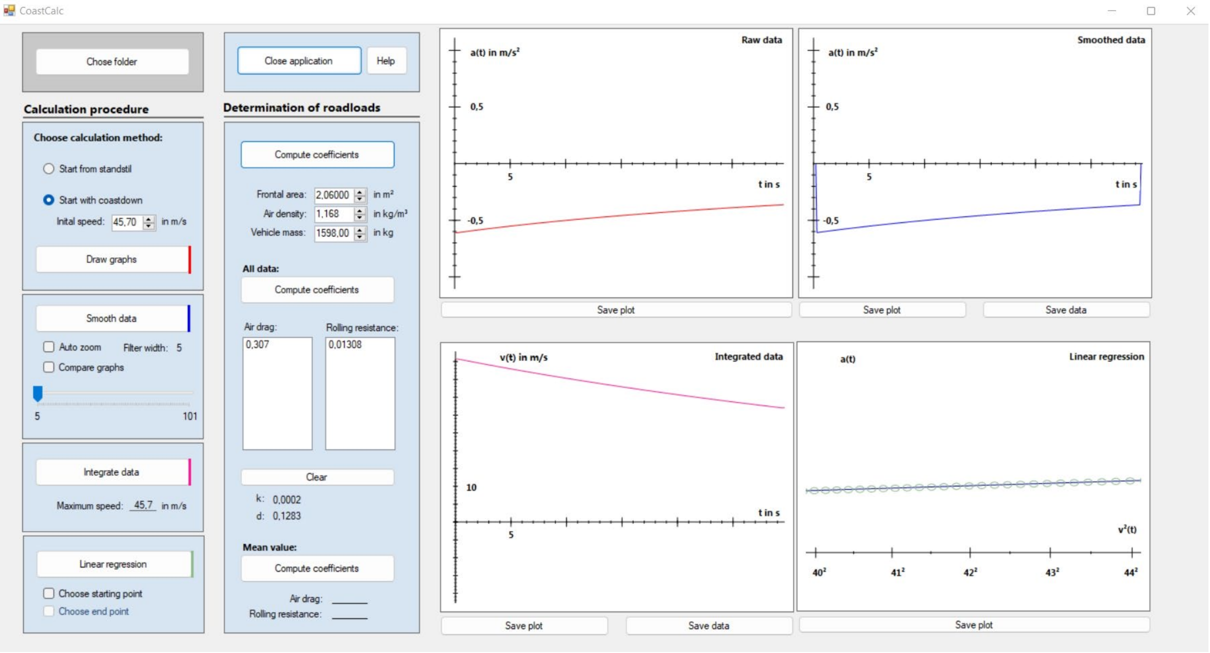
which gave $\sigma = 0.356$ in the case of the fit illustrated in Figure 7. This value is relatively large but does not explain deviations of this order of magnitude.

In order to check the correct functioning of the program, acceleration data from a coastdown test with a real passenger car were used. The test was conducted with a BMW 3 series car on the BMW Testing Ground in Aschheim. The vehicle was accelerated up to a speed of about 180 kph, momentarily allowed to settle and then shifted to neutral to decelerate freely. The recording was triggered at a start test speed of slightly about 160 kph (~100 mph) and stopped when the vehicle velocity fell below 120 kph (for details, see [15]). This speed range symmetrically encloses the European Aerodynamic Data Exchange Group (EADE) standard wind tunnel test speed of 140 kph. This high speed range ensures that air resistance dominates over rolling resistance, which is usually the case from above 80 kph. The Reynolds number of the flow during this coastdown was in the range of $10^6 - 10^7$.

Although both the acceleration data and the velocity data were available from these experiments, the latter was omitted, and the program was fed only with the acceleration data. In this way, the integration algorithm could also be checked for accuracy. Figure 8 shows the result of the computation.

Due to the fact that the vehicle weighs over 1.6 tons and the coastdown test was carried out under controlled conditions on a suitable test track at a high speed level, the acceleration curve is much smoother than in the case of the model car. Since the acceleration data were only recorded after the vehicle was disengaged and in coasting mode, the initial speed

(45.7 m/s) had to be entered as additional information, which is controlled by the option buttons in the “Chose calculation method” field in the program.



CoastCalc

Calculation procedure

Choose calculation method:

○ Start from standstil

● Start with coastdown

Inital speed: 45,70 in m/s

☐ Auto zoom Filter width: 5

☐ Compare graphs

Maximum speed: 45,7 in m/s

☐ Choose starting point

☐ Choose end point

Determination of roadloads

Frontal area: 2,06000 in m²

Air density: 1,168 in kg/m³

Vehicle mass: 1598,00 in kg

All data:

Air drag: 0,307

Rolling resistance: 0,01308

k: 0,0002

d: 0,1283

Mean value:

Air drag: ______

Rolling resistance: ______

Figure 8: Results of a coastdown experiment with a real passenger car on a test track

The smoothness of all graphs led to an extraordinarily low fluctuation in the acceleration-over-velocity-square point cloud and to a vanishingly small variance ($\sigma \approx 0.0003$). The program provided the same air drag and rolling resistance coefficients as in [15], which confirmed the correctness of the algorithms used in the program. The c_d value of this vehicle has also been confirmed in wind tunnel tests. The computer programs designed by the student teams thus provide basically correct results. The deviations from the expected values in the case of the model cars raise the question of the scalability of the test procedure, both in terms of the size difference of the vehicles, and the speed range in which the coastdown tests are carried out. Further investigations on these questions are planned.

The impact on students’ learning

The description of the student projects shall be completed by some thoughts on the impact of our team-oriented project-based learning environment on the learning success of our students.

This learning format exists since about two decades [7], but it is only in recent years that we have been increasingly confronted with inquiries about the student learning outcomes. This is probably due to the shift away from the broad and general aims of earlier liberal education programs, towards the more focused, explicit training objectives and tightly framed, precisely-worded learning outcomes that are found in competency standards [16]. However, universities have an obligation to prepare students for the world of work, not only to transmit prescribed academic or technical content [17]. Since we have gained the impression that learning outcomes have squeezed broader-based skills and capabilities to the margins of the course curricula, we have chosen a more holistic approach to our cross-course projects to bring such skills back into focus.

Our institute’s faculty tries to invent every year new project topics in order to give the students the certainty of working on a new problem that has not yet been solved by students in previous classes. This leads to a wide variety of project topics, which thus has different effects on the lessons learned and experience gained by our students. However, all projects have in common that the team orientation promotes the development of certain generic skills strongly required by industry, like the ability to work in teams, to keep records and to meet deadlines (see, e.g. [18]).

Despite the common framework, each project topic sets different priorities with regard to the analysis of the task, the development of the necessary knowledge and skills, and the implementation into algorithms and computer programs. According to the students involved in the project described here, they were particularly attracted to this topic by its interdisciplinarity and the close relationship to automotive engineering. When asked about the specifics of their project and its impact on their knowledge gain, they emphasized the interaction between experimenting, collecting and processing the data, and programming the algorithms necessary for the computations. They were able to gain a playful insight into the design of an experiment, and at the same time could gradually improve their programming skills.

The evaluation of the performance of the individual students at the end of the project is carried out on the one hand by assessing the functionality of the computer programs created and the evaluation of the project reports, and on the other hand by a self-evaluation of the students within the team. This assessment is then reflected in the overall grade of the software development course. An assessment of the learning outcomes in the context of a comparative study, however, proves difficult; on the one hand because the student sample per project topic is too small, and on the other hand because there are no reference groups that do not participate in these projects. Nevertheless, anecdotal evidence suggests a corresponding benefit of the learning format in general, as it prepares our students for more extensive project work in higher semesters, which similarly takes place in a competitive framework. One of these lighthouse projects is the annual participation in the international Formula SAE [19] or Formula Student [20] competitions, in which our student teams continuously achieve top ranks [21].

Summary and Conclusions

Smartphones represent a fully-fledged measurement system and thus enable low-threshold access to physical measurement methods and quantitative analyses. The advantages of smartphones are based in particular on the widespread use of the devices, the great familiarity among the students in dealing with this technology, the intuitive usability, and the high mobility. This makes it possible to outsource or deepen experimental content in the form of home experiments.

In this paper we have presented a multidisciplinary (physics, mathematics, computer programming) undergraduate student research project in which smartphone acceleration sensors were used to determine the driving resistance during coastdown tests with model cars. The work on this project took place within the framework of a team-oriented project-based learning environment, which is anchored in the computer programming course in the second semester of study. Three teams of three students each dealt with this topic, with most of the work taking place outside the university. The students prepared model cars for the coastdown tests and built suitable acceleration ramps or used naturally occurring gradients followed by horizontal coasting sections. In addition, they selected suitable smartphone apps and used them to read out the data obtained by the acceleration sensors for further processing. Their main task, however, was to write user-friendly computer programs in C# that compute the driving load coefficients from the acceleration data obtained during the experiments. All three teams managed to develop programs that are able to smooth out the acceleration data, integrate them for the acquisition of the velocity curves, and fit the desired coefficients. Proof of this was provided by the evaluation of coastdown test data of a real passenger car in a high-speed range. However, the coefficients obtained in the model car experiments remained at least one order of magnitude away from the expected values. The reasons for this are manifold, on the one hand there is an unfavorable mass ratio between the measuring object and the measuring system, on the other hand the speed range of the model cars is much too low to achieve a predominance of air resistance over the rolling resistance. As a consequence, the students gained valuable experience with regard to the influence of disturbances on measurable effects, the scalability of effects and the limitations of model assumptions.

The outcome of this project arouses interest in further investigations, such as a series of measurements with model cars with different scale factors and in higher speed ranges, experiments with more streamlined models, or coastdown tests with bicycles, go-karts or even with Baja SAE or Formula SAE cars. A possible follow-up project is the measurement of the air resistance of the model cars used in the on-road experiments in the institute's own model wind tunnel for comparison.

In any case, the project has aroused enthusiasm among all those involved for the possibilities offered by smartphones with their integrated sensors. They enable a simple and joyful experimental exploitation of everyday contexts.

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