September Project Update: Development and Validation of an Aerodynamic-Load Measurement System for Formula SAE

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The objective of the project is to prove the feasibility of developing a system to quantitatively measure the aerodynamic center of a Formula SAE vehicle during dynamic, on-track loading. A first version of a theoretical dynamics model has been constructed for measuring the center of pressure. A preliminary noise sensitivity study found that at low downforce the error in ground-plane intersection is very large. The project includes independent validation; accuracy, repeatability, and uncertainty studies; and a test attempting to distinguish between two wing settings.

I. Nomenclature

$a_{G,x}, a_{G,z}$	=	acceleration of the vehicle center of gravity in the x and z directions, m/s^2
α_y	=	vehicle pitch angular acceleration, rad/s^2
$\mathbf{b}$	=	calibration offset vector
$\mathbf{C}$	=	calibration matrix
c_{ij}	=	element of the calibration matrix
D, D_0	=	aerodynamic drag and calibrated baseline drag, N
g	=	gravitational acceleration, m/s^2
h_G	=	height of the center of gravity above the ground plane, m
$I_{G,yy}^{\text{locked}}$	=	locked vehicle pitch moment of inertia, kg m^2
I_w, I_e	=	wheel and engine rotating inertias, kg m^2
k	=	drag-polar coefficient
K	=	force-level drag-polar coefficient, N^{-1}
L	=	aerodynamic downforce, N
m	=	vehicle mass, kg
$M_{A,G}$	=	aerodynamic pitching moment about the center of gravity, N m
N_F, N_R	=	front and rear tire-road normal forces, N
q_∞	=	freestream dynamic pressure, Pa
S_{ref}	=	aerodynamic reference area, m^2
$\mathbf{s}$	=	vector of sensor-derived input channels
s_x, s_z, s_{M_y}	=	sensor-derived x-force, z-force, and y-moment channels
$x_{F/G}, x_{R/G}$	=	front and rear contact-point positions relative to the center of gravity, m
$x_{G/O}, x_{\text{ground}/O}$	=	center-of-gravity and line-intersection positions relative to datum O, m
$\dot{\Omega}_i, \dot{\Omega}_e$	=	signed wheel and engine spin accelerations, rad/s^2

II. Problem Statement

Definition: Design, calibration, and experimental validation of an FSAE aerodynamic-load measurement system.[1]
Research question: How accurately can an instrumented FSAE vehicle measure the downforce, drag, and center of pressure location under combined loading, and can the aerodynamic effects of two wing settings be reliably distinguished?

MSU's FSAE team does not currently have a system for measuring the real-world aerodynamic effects of the vehicle's aerodynamic package. Having such a system is very important for understanding the discrepancies between theoretical and computational predictions and real-world physics.

A. Objective and Initial Scope

The objective of the project is to prove the feasibility of developing a system to quantitatively measure the aerodynamic center of a Formula SAE vehicle during dynamic, on-track loading. Measurements from such a system serve as a comparison to predicted aerodynamic loads from computational fluid dynamics (CFD) simulations. This comparison provides the MSU FSAE team with a characterization of an error range between prediction and reality,

providing an established error margin to design within. Such a system also provides valuable data for future on-track vehicle-dynamics studies.

The system takes input from calibrated sensors along the x-z plane, where the x, y, and z axes follow the standard aircraft convention. This two-dimensional assumption is made to simplify the system, as the side-slip angle of the team's vehicle is less than 5 degrees under nominal conditions. The measured aerodynamic center of the vehicle will be represented by a line of action defining all locations where the resultant aerodynamic load can act to produce the loads measured by the sensors. This line of action can then be paired with a reference such as the ground plane to produce a center-of-pressure location along the x direction, providing the team with a tangible point to compare with CFD predictions.

The project includes independent validation; accuracy, repeatability, and uncertainty studies; and a test attempting to distinguish between two wing settings. The final resulting system will be showcased with a video of the vehicle during testing overlaid with a time-synced visual representation of the measured aerodynamic center of the vehicle.

III. Objectives

1) Establish measurement requirements and practical constraints for evaluating aerodynamic loads on an FSAE wing. (20% complete)
2) Develop an aerodynamic-load measurement system suitable for the selected loading conditions and intended testing environment. (20% complete)
3) Calibrate and independently validate the measurement system to characterize its accuracy, repeatability, and measurement uncertainty. (0% complete)
4) Evaluate the system's usefulness for FSAE aerodynamic validation, including its ability to locate center of pressure and identify changes in aerodynamic loading and its limitations in practical use. (0% complete)
5) Develop a foundational, robust, and adaptable aerodynamic-load measurement system suitable for future testing and engineering applications beyond the immediate FSAE use case, with an emphasis on modularity, maintainability, and scalability. (5% complete)

IV. Research Plan for September

Planned project work from the website Gantt chart is listed in Table 1. The website's displayed progress was last updated September 5, so the table gives planned dates rather than a September 30 status.

Table 1 Project work scheduled for September in the team Gantt chart.[2]

Planned task	Planned dates
Project definition and advisor alignment	Aug. 19–Sept. 4
Requirements and constraints	Sept. 4–17
Literature review and background	Sept. 4–28
Sensor and instrumentation trade study	Sept. 16–Oct. 4
Mount design and fabrication	Sept. 26–Oct. 15
Data acquisition and software development	Sept. 26–Oct. 11
Calibration and uncertainty	Sept. 30–Nov. 23

V. Tasks Accomplished

A. Project Setup and Advisor Alignment

Table 2 Completed setup work recorded on the project website through September 5.[2]

Date	Recorded work
Aug. 28	Two-person team formed; Dr. Narsipur and Dr. Khare agreed to advise.
Sept. 4	Statement of Work signed; proposal presentation delivered; project website published.
Sept. 5	Advisor meeting revised the scope and reporting cadence; system function formulation drafted.

B. Theoretical Dynamics Model

A first version of a theoretical dynamics model has been constructed for measuring the center of pressure. The model receives normal force on the tires, acceleration in the x and z directions, pitching rate, wheel rates, engine RPM, and a changing center-of-gravity location. Lift is calculated from the normal forces on the tires, weight of the vehicle, and the force due to acceleration in the z direction, as shown in Eq. (1).

$$L = N_F + N_R - mg + ma_{G,z}. \tag{1}$$

Drag is calculated using a drag polar calibrated to the aerodynamic characteristics of the vehicle, represented by Eq. (2), where $K = k/(q_\infty S_{\text{ref}})$.

$$D = D_0 + KL^2, \qquad K = \frac{k}{q_\infty S_{\text{ref}}}. \tag{2}$$

Summing all moments about the center of gravity and accounting for the dynamic moment, normal moment, and thrust moment results in the aerodynamic moment acting about the center of gravity. The dynamic moment represents the pitching rate, wheel rates, and engine RPM; the normal moment accounts for the moments from the normal forces on the tires; and the moment due to thrust is accounted for, all in Eq. (3).

$$\begin{aligned} M_{A,G} = I^{\text{locked}}_{G,yy}\alpha_y + I_w \sum_{i\in\{FL,FR,RL,RR\}} \dot{\Omega}_i + I_e\dot{\Omega}_e \\ - x_{F/G}N_F - x_{R/G}N_R - h_G(ma_{G,x} + D). \end{aligned} \tag{3}$$

The center of pressure represented by the intersection of the aerodynamic line of action and the ground plane is found via Eq. (4).

$$x_{\text{ground}/O} = x_{G/O} - \frac{M_{A,G} + Dh_G}{L}, \qquad L \neq 0. \tag{4}$$

A study was run on the model to determine how sensitive it is to noise from the sensors and how edge cases and assumption violations affect the results.

C. Preliminary Findings

The noise sensitivity study run on the model used a MATLAB script that ran 1,500 trials for each case, adding zero-mean Gaussian perturbations to the inputs. The assumed standard deviations are for illustrative purposes only and are not based on sensor specifications. The errors in Table 3 are the 95th percentile of the absolute error between the model estimate and reference value. “Reportable” means that the ground intersection passed according to the script’s illustrative force thresholds. “Raw ground-position error” includes reportable and non-reportable model estimates. Tables 3–5 show the sensitivity, assumption violations, and boundary tests. From these results, the biggest concern for the model is that at low downforce the error in ground-plane intersection is very large. This is concerning, as many of the vehicle’s important dynamics situations are during slower, lower-downforce turns.

Table 3 Mathematical-model noise sensitivity. Each case used 1,500 synthetic trials with illustrative input noise. Errors are 95th-percentile absolute errors.

Case	Reference downforce (N)	Downforce error (N)	Drag error (N)	Pitch moment error (N m)	Ground intersection reportable	Raw ground-position error (m)
Steady baseline	180	10.64	12.35	10.66	100.0%	0.06
Low downforce	4	10.88	3.07	9.99	0.1%	33.28

Table 4 Intentional assumption violations. Bias is the model estimate minus the synthetic reference.

Violation	Drag bias	Pitch-moment bias	Ground-position bias	Finding
30 N drag omitted from the calibrated relation	−30.0 N	+8.4 N m	≈ 0 m	The position errors cancel, but the inferred force direction is wrong.
12 N m pitch couple omitted	0 N	+12.0 N m	−0.0545 m	The omitted couple is incorrectly attributed to aerodynamics.

Table 5 Boundary behavior of the mathematical model.

Condition	Model response
Low downforce ($L = 4$ N)	Force and moment remain available; ground intersection is withheld by the illustrative 20 N downforce cutoff.
Zero resultant aerodynamic force	No force direction, line of action, or ground intersection is reported.
Zero downforce with nonzero drag	The horizontal force line is defined, but it has no unique ground intersection.

D. Problems Encountered

Currently, the biggest hurdle will be choosing and validating a model for measuring our aerodynamic center. Another approach suggested to us by Dr. Khare is using a 3×3 calibration matrix to map sensor input from the x direction, z direction, and moment about the y axis directly to lift, drag, and pitching moment. An example of this mapping is shown in Eq. (5); the coefficients and offsets would be determined by calibration rather than assumed. Similar multi-component balance calibration methods have been used in aerospace testing [3].

$$\begin{bmatrix} L \\ D \\ M_{A,G} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} s_x \\ s_z \\ s_{M_y} \end{bmatrix} + \begin{bmatrix} b_L \\ b_D \\ b_M \end{bmatrix}. \tag{5}$$

However, a cost estimate and fidelity and feasibility analysis will need to be done between the two methods of measuring, and more research into the calibration-matrix method will need to be conducted as well. For validating the theoretical dynamics model, running the car in an enclosed space with still air and a known speed could provide a controlled condition for cross-checking the model's estimated results, though independent load measurements and more planning would be needed before this validation method is decided on.

The next big challenge will be sensor calibration. A proposed idea by Dr. Khare is to set the car up on stands and use rope, pulleys, and weights to simulate lift, drag, pitching moment, and other loads on the car. This can also be combined with setting weights on the car while it sits on scales under all four wheels. Knowing the applied loads during each condition, the sensors can be properly calibrated.

E. Overall Timeline

- **Project definition and advisor alignment** was scheduled and completed for August/September on time.
- **Requirements and constraints** were scheduled to be done for September and were started but not completed as a model must be selected before considering the constraints.
- **Literature review and background** were started, but more thought found that more research must be done into our model options, and so it did not get done this month.
- **Sensor instrumentation trade study** was never started, and was planned to mostly take place in the beginning of October; this was delayed due to back up on the plans above.

VI. Research Plan for October

Our model research and refinement will continue along with an analysis and comparison of the two mentioned methods. Physical design of the system on the vehicle will start soon, and work on a full-car CFD simulation of the FSAE vehicle for comparison to the system has begun already, with meshing refinement currently being worked on. A meeting is needed with our advisors to discuss the CFD simulation, meshing, and validation of the dynamics model. Once more research into the calibration-matrix method has been done, a meeting with Dr. Khare on how to continue with the chosen model will be in order.

Table 6 Project work extending into October in the team Gantt chart.[2]

Planned task	Planned completion
Literature review and background	Oct. 5
Requirements and constraints	Oct. 5
Sensor and instrumentation trade study	Oct. 5
Data acquisition and software development	Oct. 12
Mount design and fabrication	Oct. 15
Calibration and uncertainty	Nov. 23

Table 6 shows what carries over from the September plan and what new things will be started in October. All dates shown are updated based on the project's current standing. The model will be decided on and finalized by Oct. 5, and work on the CFD meshing will continue.

Faculty Review and Signatures

The students named above have discussed their monthly progress with us.

Dr. Shreyas Narsipur, faculty reviewer	Date
Dr. Vivek Khare, faculty reviewer	Date

Acknowledgments

AI assistance was used to format this report in LaTeX and typeset the equations and tables.

References

[1] Stout, D., and Medina Gutierrez, C., "Development and Validation of an Aerodynamic-Load Measurement System for Formula SAE and Broader Vehicle Dynamics Applications: Statement of Work," , 2026. Mississippi State University, September 2026.

[2] Stout, D., and Medina Gutierrez, C., "FSAE Aero-Load Measurement: Project Timeline," Project website, last updated September 5, 2026, 2026. URL `https://capstone-project-carlos-medina-gutierrez-and.david-stout.com/`.

[3] Ulbrich, N., and Reed, M., "Calibration and Data Analysis Recommendations for Three-Component Moment Balances," Tech. Rep. ARC-E-DAA-TN66180, NASA Ames Research Center, Moffett Field, California, Jun. 2019.