

**Vehicle Dynamics  
at  
General Motors Corporation  
1952-1980**

**Presented at the**  
**SAE Automotive Dynamics and Stability Conference**

**Troy, Michigan**

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**by**  
**R. Thomas Bundorf**  
**General Motors Corporation – (Retired)**

Good morning. I am very honored to be here, and I want to thank Rajiv Gupta and Tom Gillespie for inviting me to represent the many people in GM who worked in the field of vehicle dynamics.

I also thank Joe Bidwell, Ron Leffert and Dick Rasmussen for refreshing my memory and filling in many of the gaps in my knowledge.



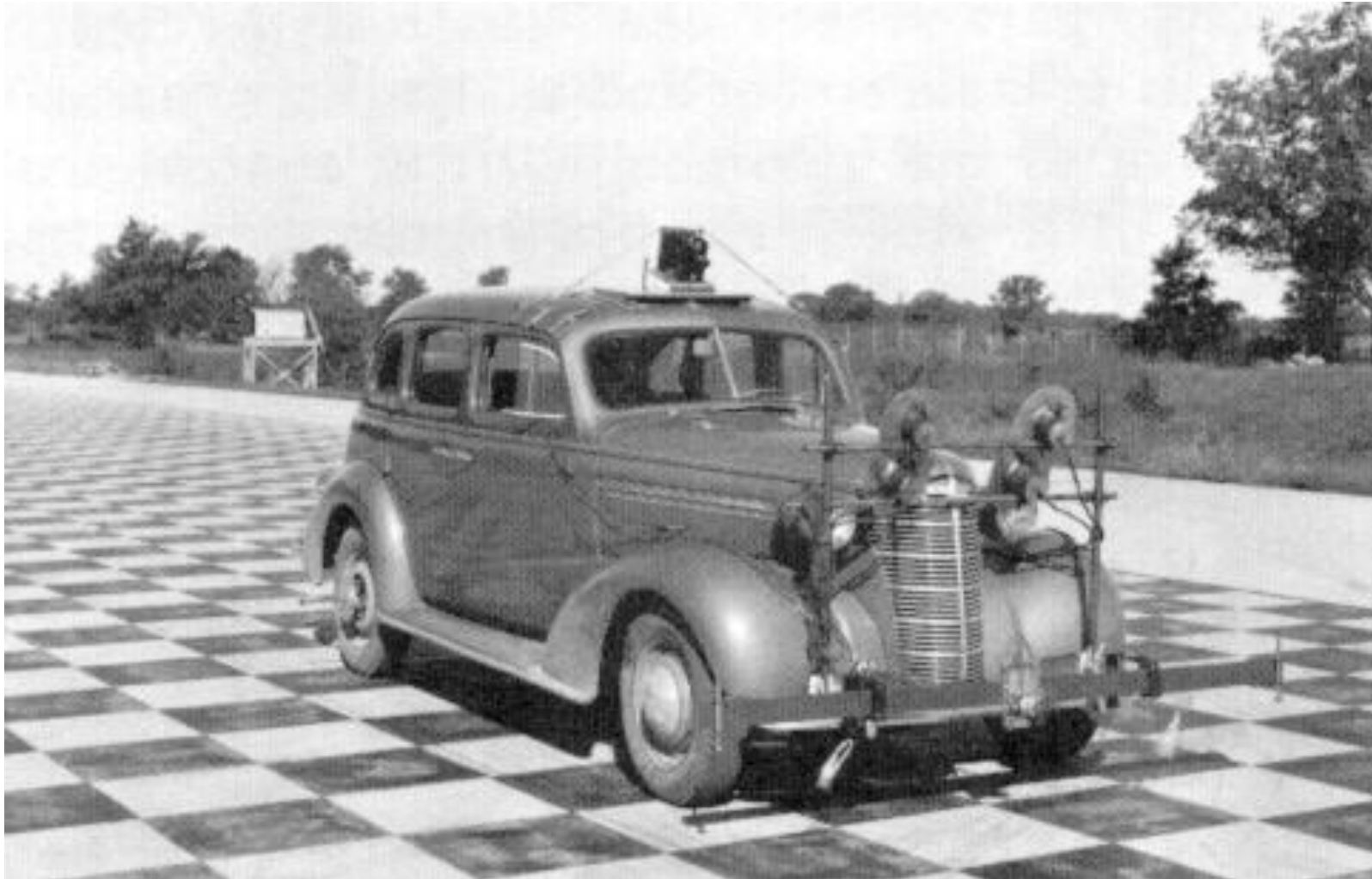
I will cover the period between 1952 and 1980, when the equations of motion developed by the Cornell Aeronautical Laboratories were being put to their ultimate use in the design process. I will mention many people this morning and I am afraid I will miss some. To those I miss, I sincerely apologize. There were so many who did so much.

And I may also confuse the chronological order of events at times, but this is to avoid changing subjects too often.

In the 1940's, Maurice Olley, Bob Schilling and others were interested in vehicle transient response and dynamic analysis. This is Maurice Olley, whose remarkable accomplishments are well known.



In fact, as early as 1941, Ken Stonex measured the dynamic response of an automobile by taking motion pictures of a checkerboard road and a steering wheel protractor using a vehicle mounted camera. The motion variables were analyzed from the film, optically, frame-by-frame, a remarkably tedious process.



Also, in the early 1950's, Bob Schilling wrote a set of differential equations to describe dynamic response and subsequently presented them to the Detroit Industrial Mathematics Society. As you can see, they are very similar to the CAL set, although the accelerations are not in moving axis format. This work by Schilling and that by Stonex shows that they were well familiar with the dynamic analysis problem and knew its difficulty.

From Figure 4 we can then write three equations of equilibrium.

Lateral forces:

$$m\lambda - c_1(\alpha_1 - r_1\theta) - c_2(\alpha_2 - r_2\theta) = 0 \quad (1)$$

Moments about yaw axis:

$$I_y\ddot{\theta} - c_1a(\alpha_1 - r_1\theta) + c_2b(\alpha_2 - r_2\theta) = 0 \quad (2)$$

Moments about roll axis:

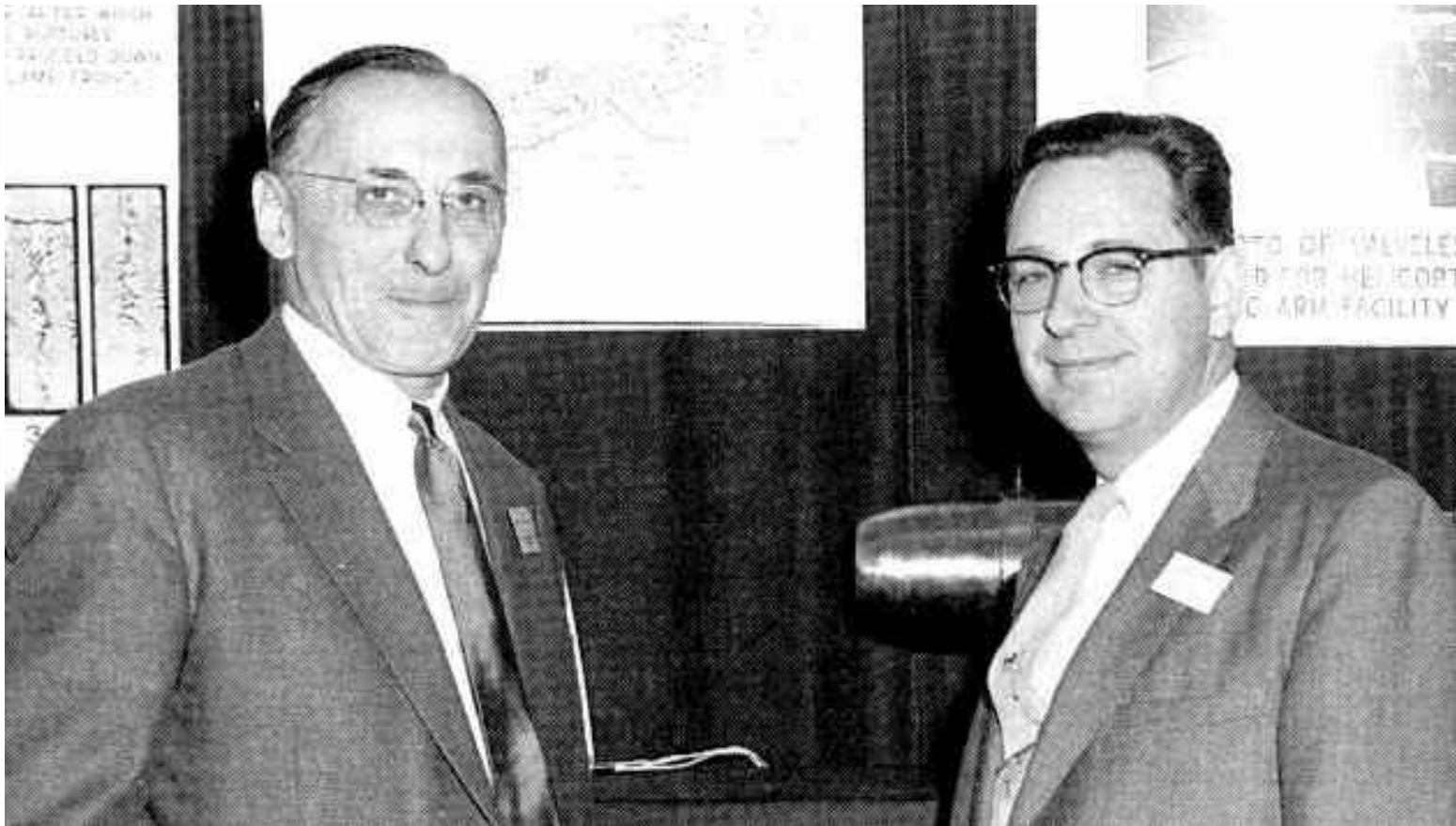
$$I_x\ddot{\theta} + f\dot{\theta} + K\theta - m h \lambda = 0 \quad (3)$$

Then, in 1952, Bill Milliken visited Maurice Olley, Bob Schilling, Ken Stonex, von Polhemus and Tom Carmichael at the GM Proving Ground. There he told them of how they had written the equations of motion for the airplane.

And although our GM people had made remarkable progress in understanding handling, they also had the wisdom that day to see how to progress even faster. They suggested that the Cornell Aeronautical Laboratories should do the equations of motion for the automobile for GM, and GM paid the better part of one million dollars for this work and other allied projects.



The work was monitored from the GM Research Laboratories under Bob Schilling, with Bob Kohr having the responsibility for following the work. Then, in 1955, when Joe Bidwell was made head of the Engineering Mechanics Department, he was charged with developing this emerging technology into the vehicle design process. That is Bob Schilling on the left and Joe Bidwell on the right. I came into GM at that time and worked under Schilling and then under Bidwell.



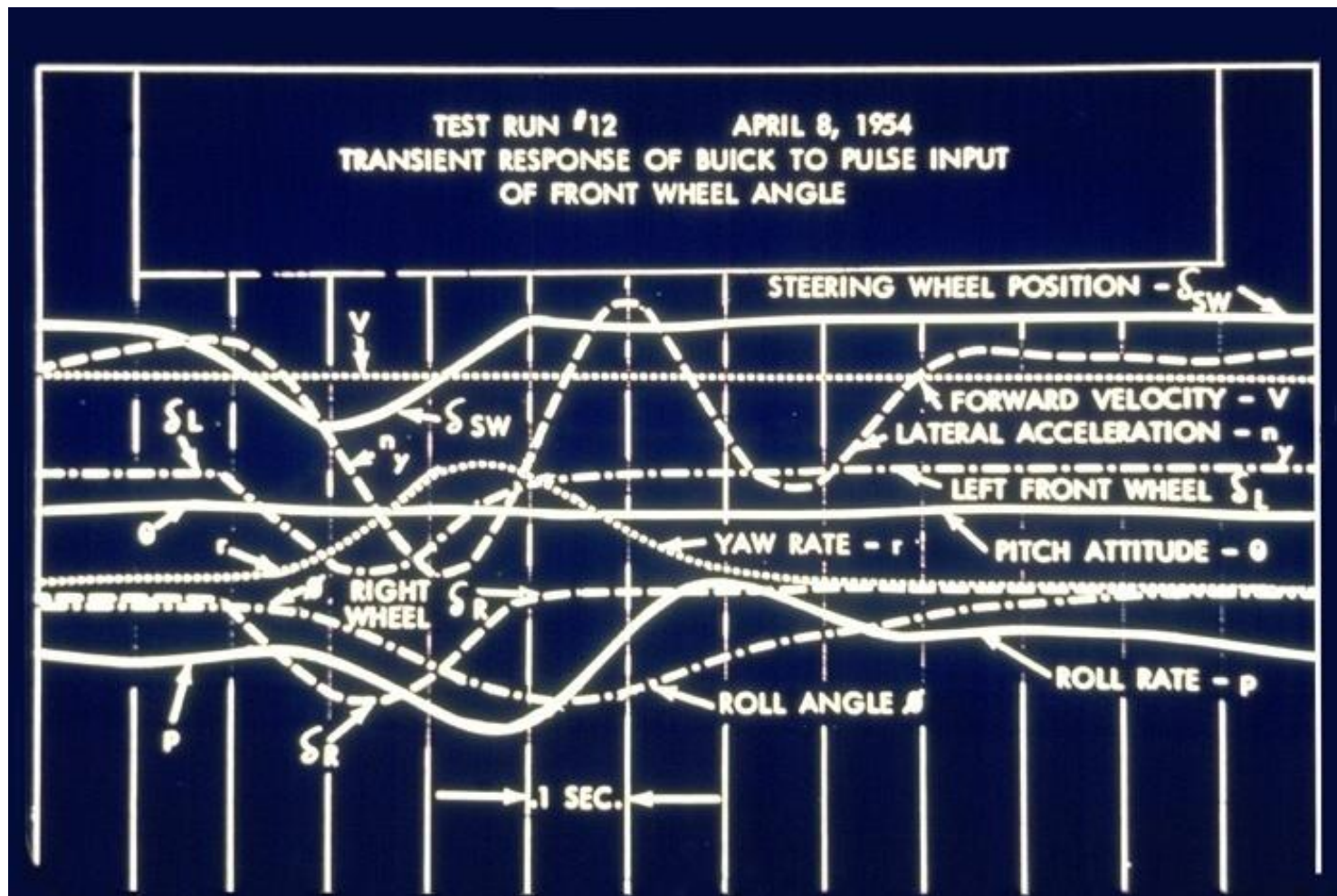
This is an informal photo that includes many members of the staff. A lot of the people I will mention this morning are in it. This department would spend the next ten years on vehicle dynamics with a mixture of analytical work and experimental testing.



The experimental work was used to confirm the equations and our understanding of vehicle dynamics, and in those cases where it did not, we had to go back and reanalyze. There was an incredible amount of work to be done.

I remember observing the differences in the handling properties of station wagons and sporty cars. The question was, “Why are they different, what parameters are responsible, and how do they interact?” Even with a good knowledge of all of the great work that had already been done, it seemed like a new area for development, and it was very exciting for me and the others working on this program. While we may not have been fully aware of it, we were on the threshold of having what Olley and Schilling needed, which were good measurement techniques, good equations, and computers to solve them.

The state of art at that time in GM was about as good as it could be without having computers. Steady state response was pretty well understood, but transient response was not. Data acquisition was by oscillograph, and analysis was very time consuming. CAL had used frequency response analysis to confirm their equations, which made their analysis even more difficult.



For use in ride projects, there was a test method for measurement of pitch inertia and cg height by use of a swing. Yaw inertia could be measured by multifilar pendulum, but was not commonly done.





Roll steer and roll rate distribution were measured by a device that transferred water from tanks mounted on a transverse beam fixed on the vehicle. This caused the vehicle to roll, and as it rolled, wheel weight and wheel steer information were recorded.

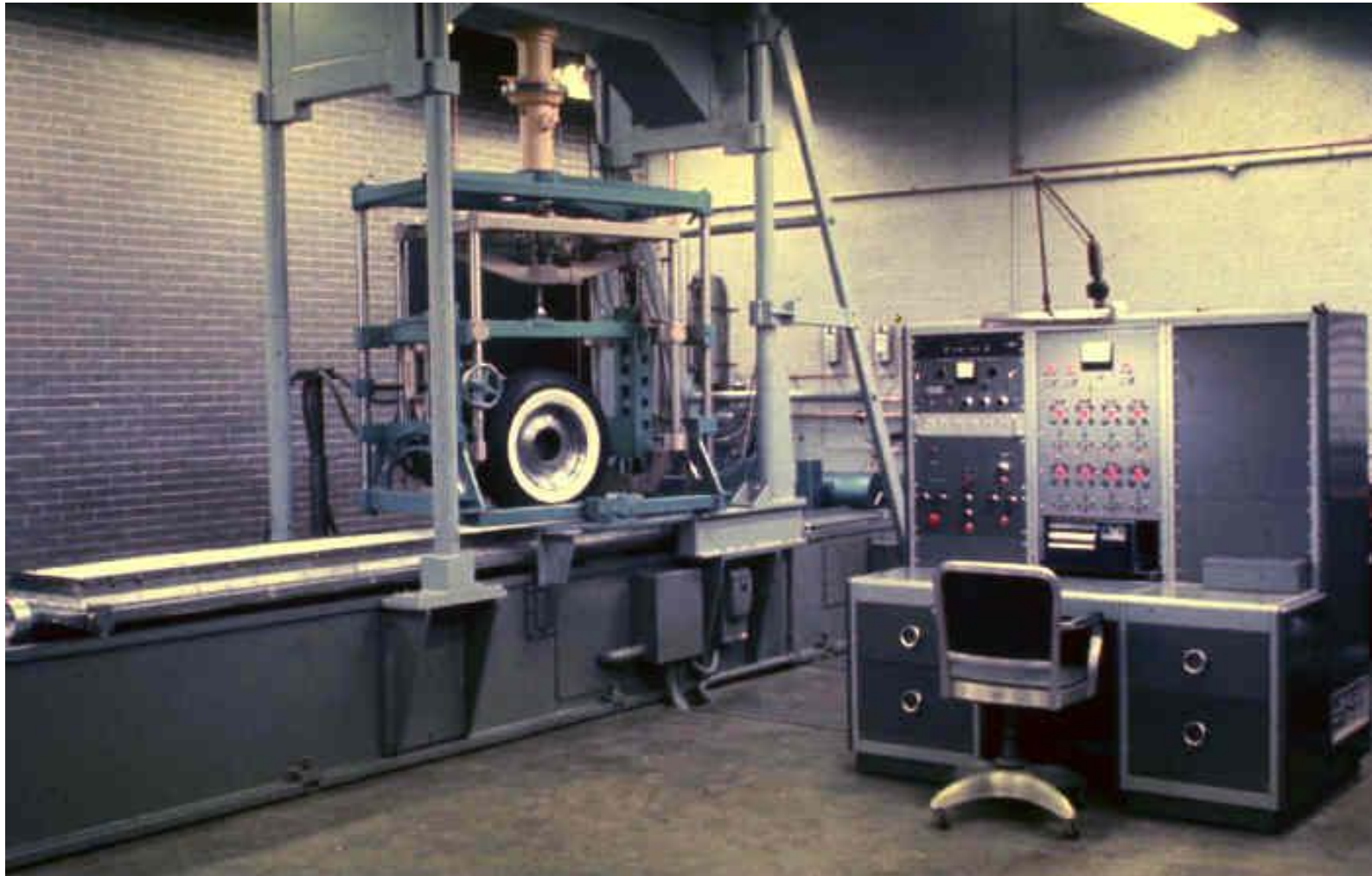


But there was no test for deflection steer. Schilling had certainly been aware of the deflection steer influence, and Olley too, but no test had been developed.

We recognized the need for one rather quickly and I recall going to the Proving Ground and working with their Experimental Engineering Department to devise a test for this purpose.

We had excellent support from the Proving Ground in all of our work, despite our being 40 miles away.

A good understanding of basic tire properties existed, but there was a need for a test machine at GM. Bob Van House designed GM's first tire test machine, with Tony Cortese the principal test engineer.





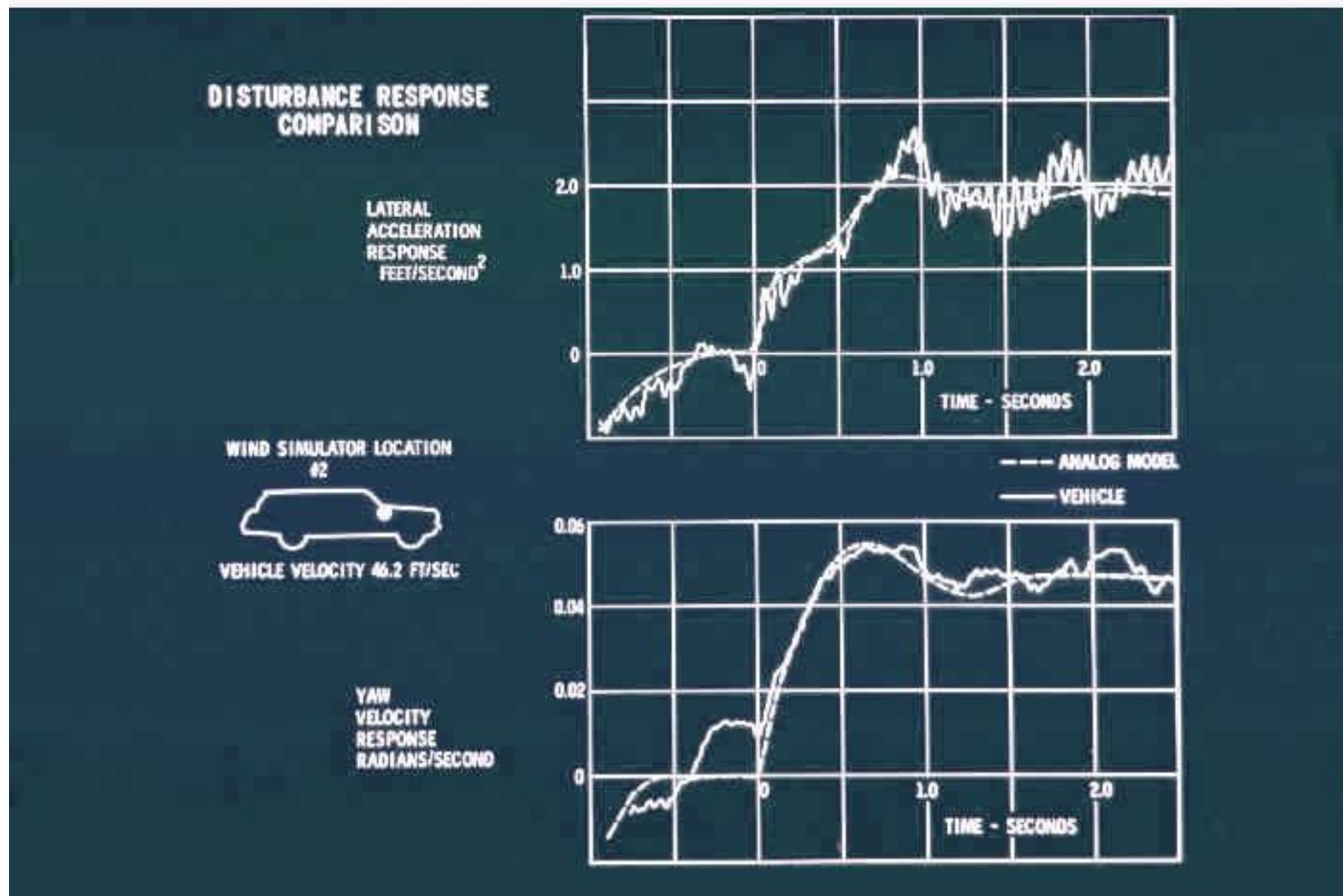
Don Nordeen was very much involved in this effort and devised the splined bicubic method for fitting the data into carpet plots. He also developed the method of transforming these data into 3 simple functions for nonlinear simulation in the computer.

(As time went by better and faster tire test machines were built at GM to supply the data for simulation. And in later years a complete Tire Lab was formed at the Milford Proving Ground; and its interaction with the tire industry is a story that deserves its own presentation. Ken Peterson and Fraser Smithson were key people in this effort.)

We quickly began to use the equations. I believe the first analog computer we used was made by Beckman but it was soon replaced with a larger one made by Electronic Associates. Bob Kohr installed the equations on it and I used it to simulate wind gust response. Allison Division built a rocket that could be strapped on the side of a car, and we qualified the equations for that purpose. We also learned something about the desirability of more rearward centers of aerodynamic pressure.



These are the vehicle and computer responses that show the correlation we achieved.



We also helped build the Firebird III. This was a gas turbine powered, fully operational show vehicle for the GM Motorama. It had many unusual features, among them stick steering with acceleration and braking control. Forward motion to accelerate, left and right to steer and back to brake. Roy Cataldo did the servo design. Roy also led our project on automatically guided vehicles, using a cable buried in the road.

That is a very young Tom Bundorf standing by the car. My job was the design of its compact 3000 psi air over oil suspension system.



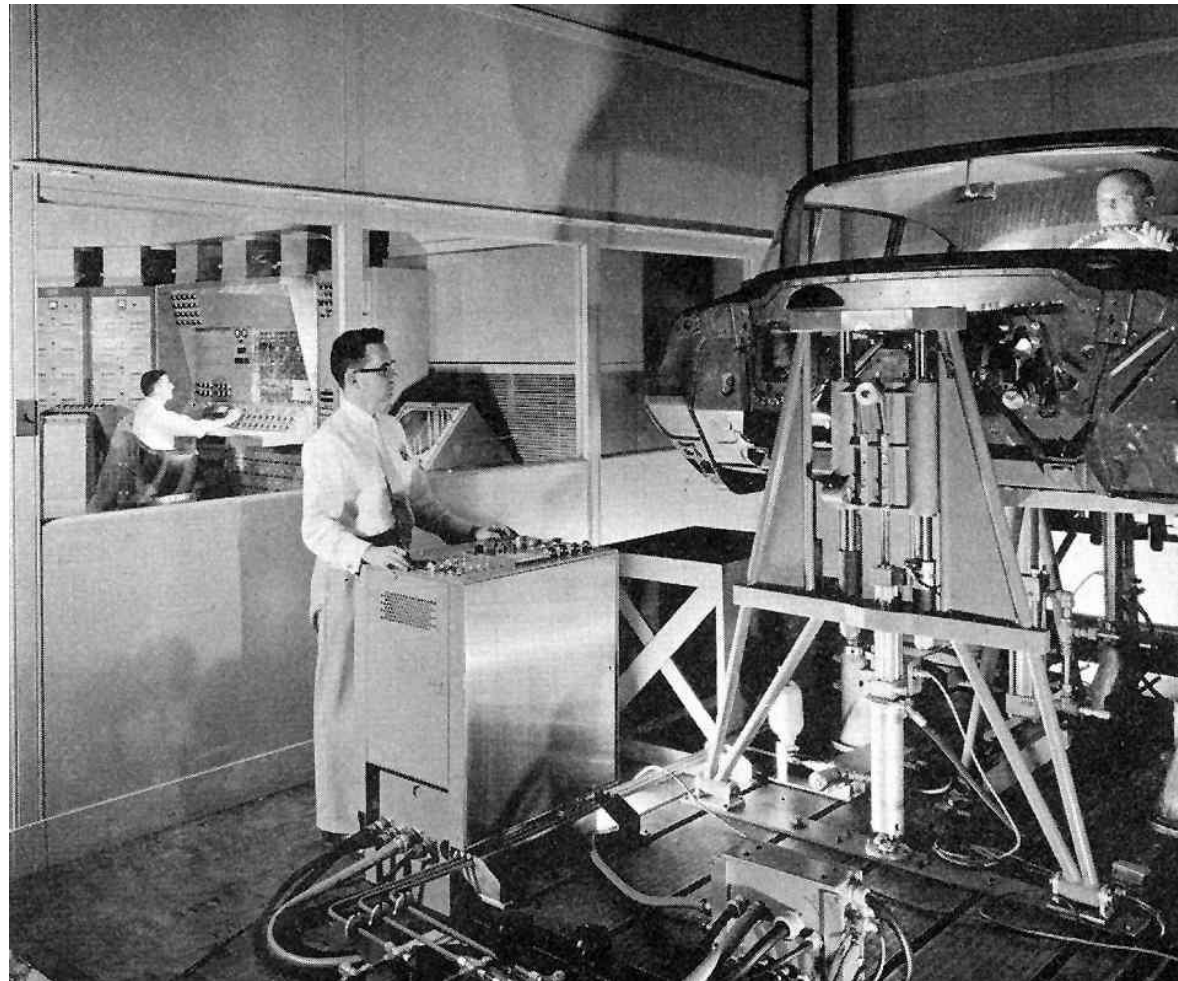


This is the car running at twilight with Emmet Conklin of the Gas Turbine group driving and Joe Bidwell at his side.



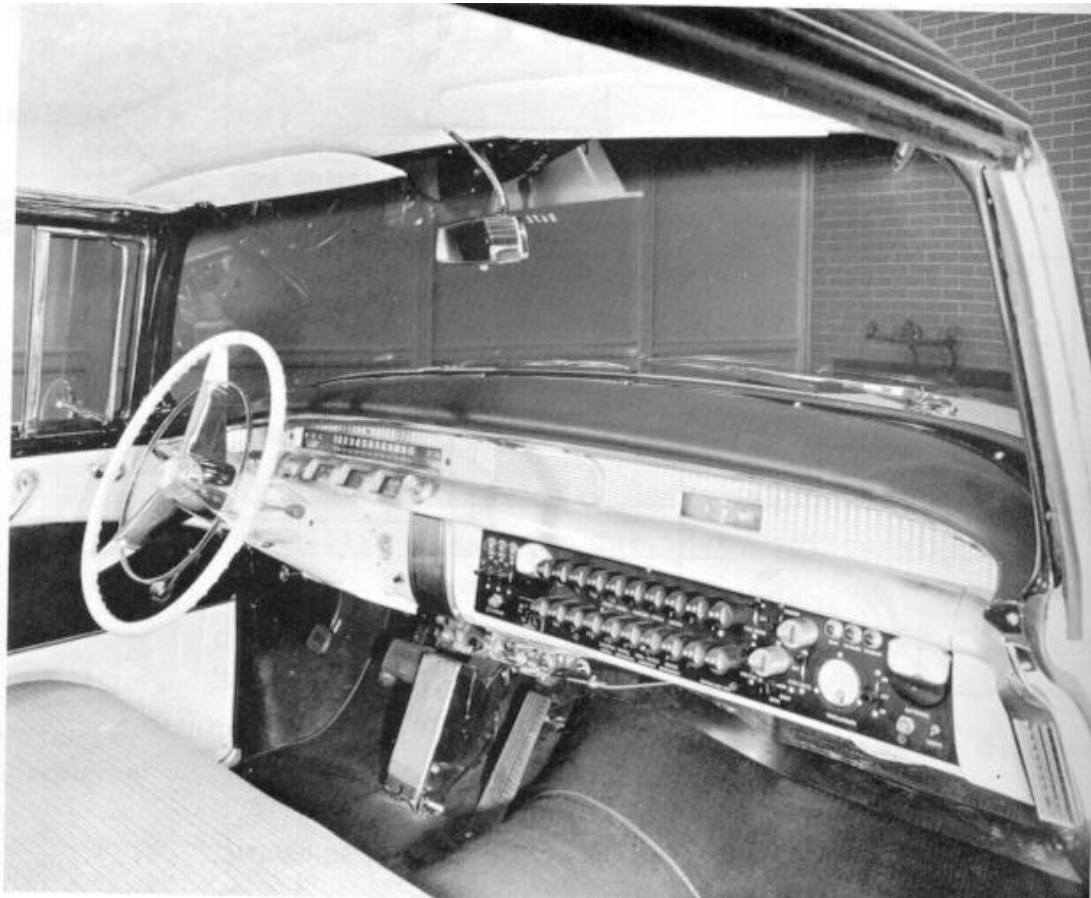
Another area of work aside from directional control was that of ride quality. A ride simulator was built which reproduced vehicle motion in the laboratory from known road profiles. It allowed the rider within the simulator body to evaluate simulated suspension designs.

Bob Kohr is at the console.



We brought in psychologists. Paul Olson was among the first and Bob Bierley and Rudy Mortimer also contributed. In addition to handling work, there was work on braking and other aspects of driving.

One of Paul Olson's projects was a study of how well drivers could control differing response characteristics. He used this variable stability vehicle that had been built by CAL for GM. It was set up in three configurations of transient response.





A serpentine driving course that required rapid and continuous steering was used. (This is that course with a different test vehicle). It was determined the drivers could adapt quickly to any of the three configurations, but that the fastest transient response was best.





This was one of the earliest, if not the first human factors test of this type, and it helped us to a better understanding of how response qualities were perceived by drivers.

This work was just the beginning of such human factors evaluations, and I must also mention that in later years Brian Repa did excellent work at the Research Laboratories using driving simulators.

We were able to do the foregoing testing on four lane straightaways, but needed more room for transient response testing to steady state at high g's. At Joe Bidwell's request, the Milford Proving Ground paved an area beside the East-West Straightaway so that we could have sufficient maneuver room. While this area did not get officially named, it was commonly called Bidwell's Bulge. I recall running power on and power off turning tests on front wheel drive vehicles when they were first designed in GM.

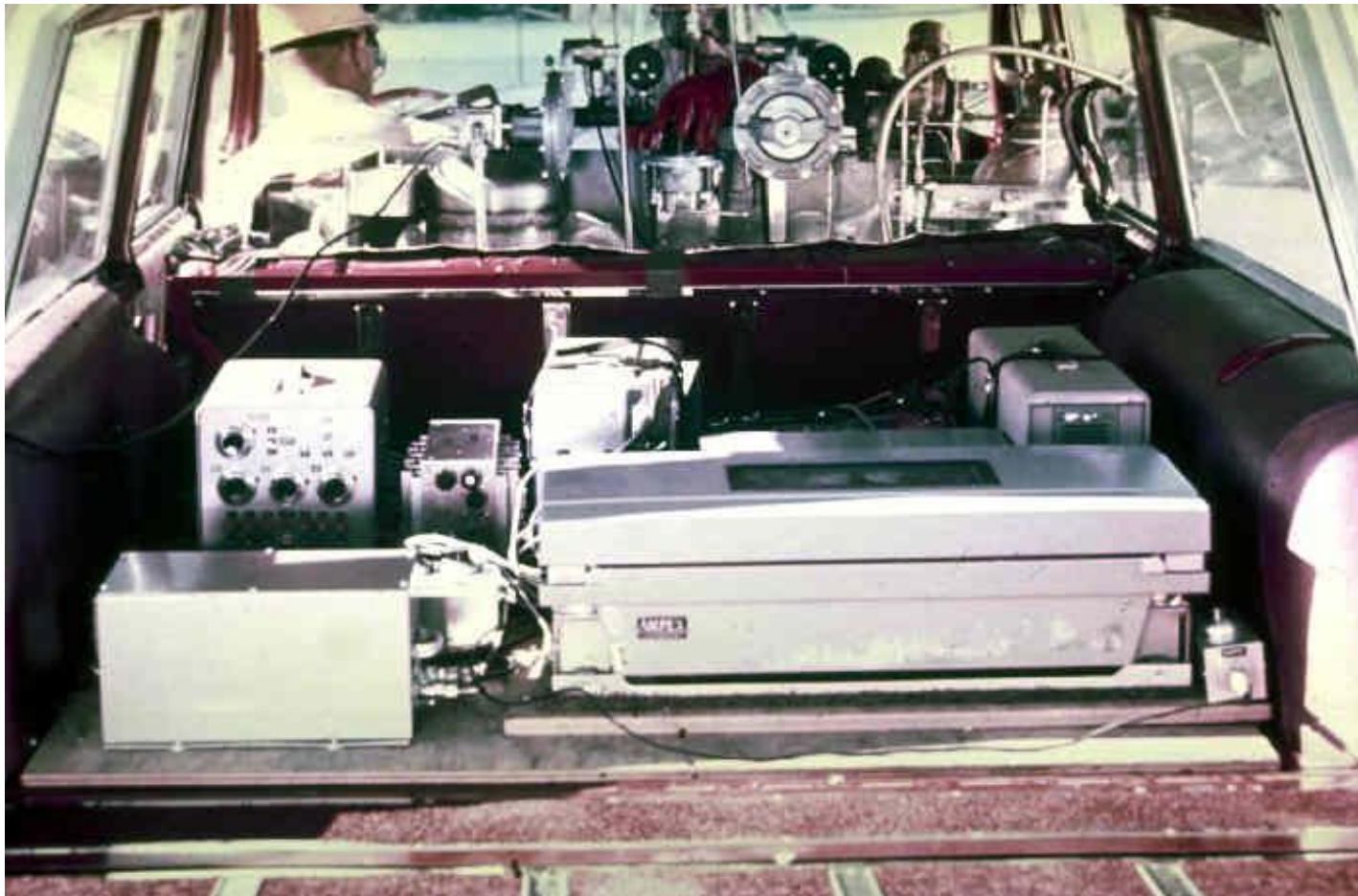


Later on, the Vehicle Dynamics Test Area was built, 67 acres of 6 inch asphalt. This also got a special name, Black Lake, because when it was wet the migrating geese thought it was water and landed pretty hard.



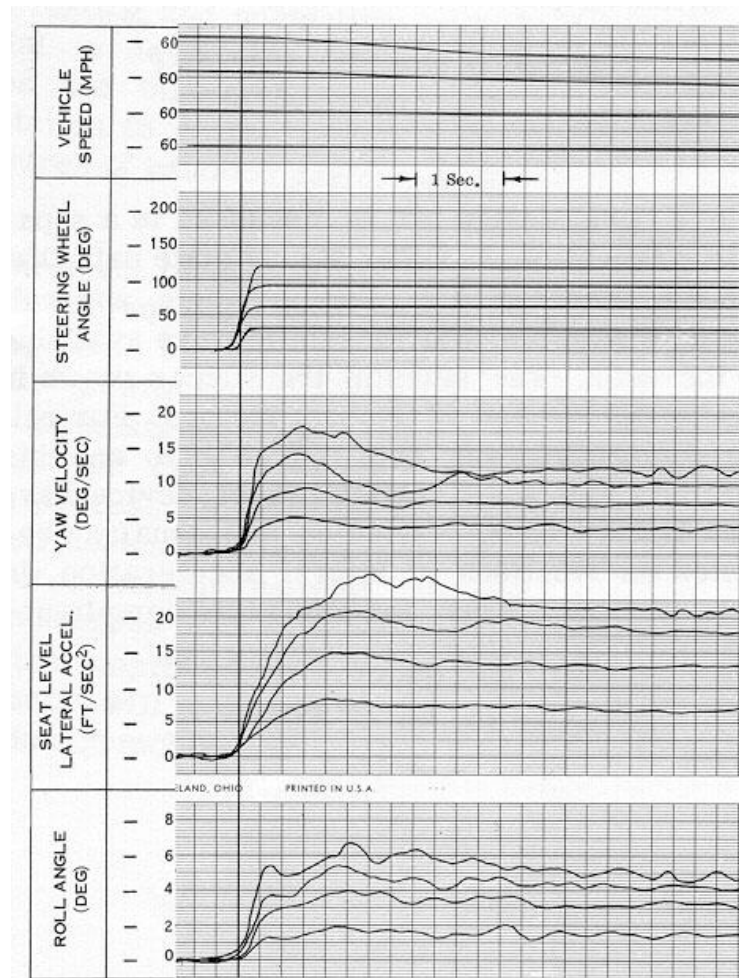


Very early in our research the Milford Proving Ground measured the response characteristics of a wide range of production vehicles. This was our first look at the variety of response characteristics that existed in typical vehicles. While the data were excellent, the tests took a long time to execute, and we needed to speed the process greatly. Early test setups were very bulky, using on board tape decks.



After a number of years of work we were in much better shape for testing. We progressed to telemetered data to a central ground station. There were many people involved in facilities and instrumentation development, engineers such as Dick Hoffman and Dick Moore, and skilled technicians such as Irv Hill and Al Gall.

We were beginning to understand transient response. We plotted the responses on strip charts and analyzed for response times and gains, with attention mainly to yaw velocity and lateral acceleration. We liked using transient response better than frequency response. It was easy to do; we could assess the nonlinear behavior; and the transient responses seemed closely related to what we could see and feel as we drove the cars.



We began to see that the usage of words like “oversteer” and descriptive phrases like “rear swing out” were related to long response times, and the delayed sense of lateral acceleration being felt on our bodies. We quickly saw the need for an accurate terminology and first agreed on a set of terms within GM, then took it to SAE.

Joe Bidwell convinced the Ride Comfort Committee to enlarge its charter to include handling and become the Vehicle Dynamics Committee. This committee took the terminology and a number of the test procedures we used, and enlarged and improved them. They have since taken to international standards through the ISO.

In 1965, the work at the Research Laboratories ended and was continued at Engineering Staff, and soon after, also at the Milford Proving Ground. The Vehicle Dynamics Lab at the MPG, under Don Nordeen, became the focal point.

The research phase was over and application to the production vehicle was emphasized.



Additional test equipment had been and was being built. An accurate CG height measurement system was in place. The technician is Charlie Stone.



Roll inertia was measured by use of an inverted pendulum. Rick Hill was creator of the inertia test devices. Dave Bubolz is standing by the machine.





Deflection steer was being measured as a routine. Bill Kristofetz was a very dedicated engineer on these projects, and Dick Henry was a designer.



Then a new sophisticated unified test machine was built at Chevrolet, and parameter testing advanced further still. Lloyd Nedley was a key person in this work.





At this point I want to emphasize that at the same time this work was done there was also ongoing a great amount of work at Chevrolet under Frank Winchell.

The work involved vehicle handling at high lateral acceleration. They created many special test vehicles, as well as tire and vehicle test equipment, to better understand limit handling properties of vehicles.

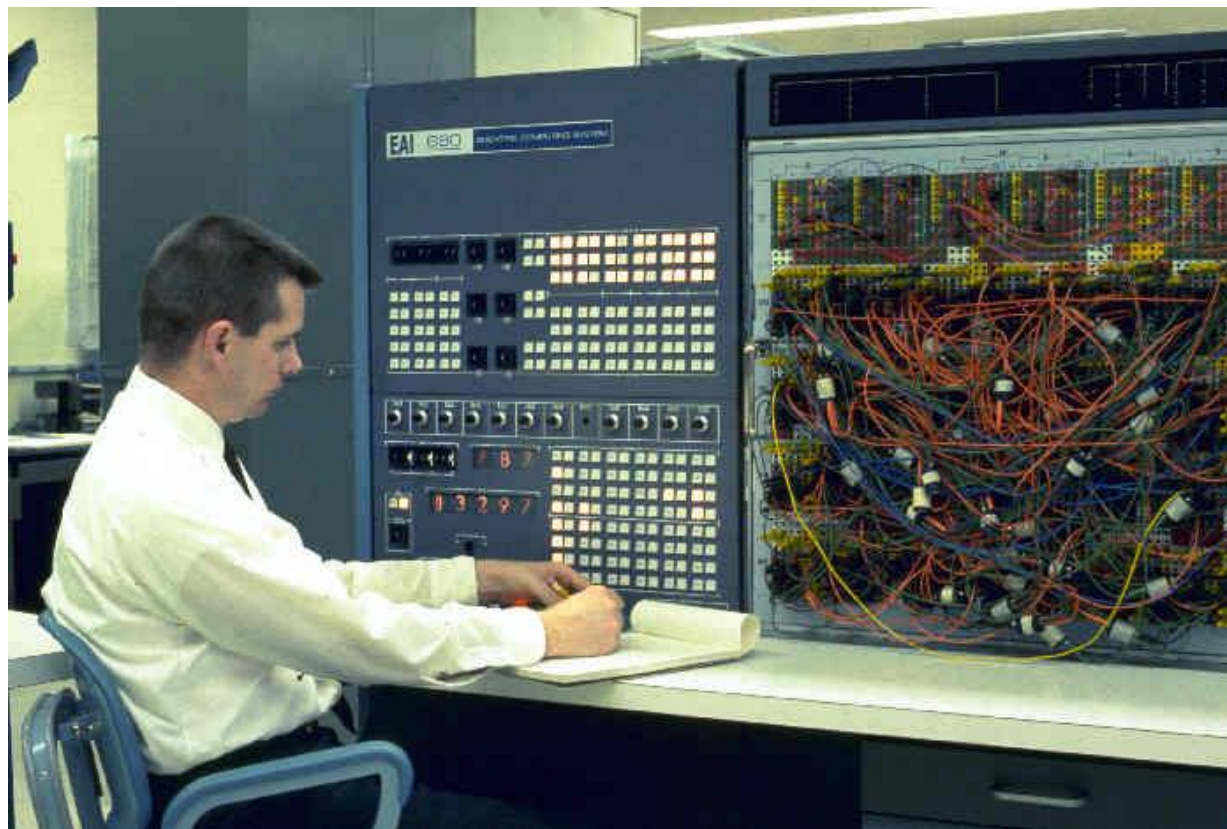
Frank Winchell had an insatiable desire for a full understanding of vehicle handling. He really wanted to know everything, but he also wanted to communicate it to others and developed many good educational presentations. He said, as he wrote in Bill and Doug Milliken's book, *Race Car Vehicle Dynamics*, (and I heard him say it myself), that "he didn't know sic'um" about handling when he started, but I assure you he did know an awful lot when he finished.

I cannot begin to cover this work in any adequate way, but you can read about much of it in his contribution to Bill and Doug Milliken's book on Race Car Vehicle Dynamics. He and others supported the proposal by Milliken for the Moment Method which described limit handling properties of tires and suspensions.

In addition, a large computer model of nonlinear directional control was sponsored and implemented. All of this work at Chevrolet was quite valuable and deserving of historical attention.

Now I continue with the work at the Milford Proving Ground. The analog computer had been replaced by the hybrid computer rather quickly, because of the need to resolve nonlinear tire behavior. This is Ron Leffert operating it. Dick Valentine was an expert in simulation and was our key person in this effort.

I should mention that analog and hybrid computers were fast machines. The small analogs could also serve as closed loop system controllers in vehicles like the variable stability vehicles. When digital computers became faster, they were quickly employed and the equations were put on a time sharing computer for everyone's use.



We were also working closely with the suspension designers and were doing increasing amounts of dynamic response testing in the development process.

New and better simulation programs were being developed and there was an improved understanding of how all the suspension parameters interacted to affect transient and steady state response.



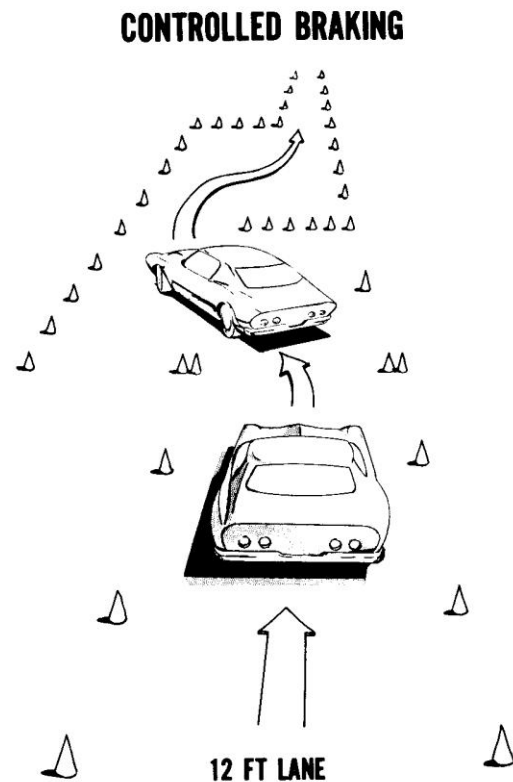
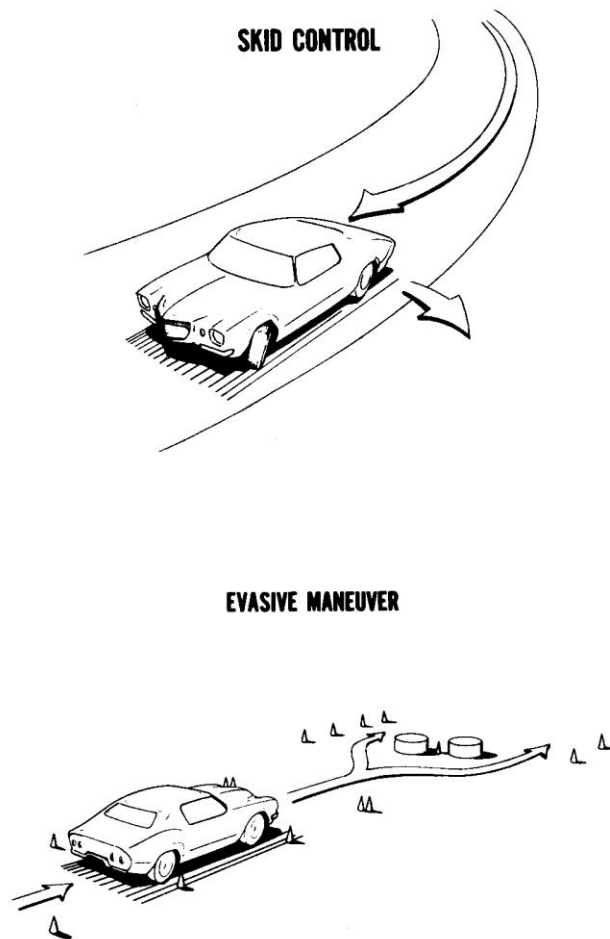
The effort to understand the driver and vehicle interaction also continued. Task Performance Testing, started earlier by Dick Denzer, was also conducted at the MPG, much of it done under Pete Riede. The task performance tests, such the evasive performance maneuver, shown here, used expert drivers. This was a method of quantitatively evaluating handling performance in accident avoidance situations.



There was also a “Man Off the Street” program sponsored by GM and run at Calspan, although this picture is of a similar task at the MPG. This program involved many volunteer drivers and many linked tasks, using two vehicles, one standard and one configured for increased controllability. The data showed that drivers were very adaptable, and could recognize and utilize some of the increased controllability by more aggressive driving. It also showed that driver training for extreme conditions was desirable.



A program for driver training was developed at the MPG by Fraser Smithson and later managed by Doc Whitworth. It has become widely used by the police and high schools. It was first used to train our Proving Ground drivers. These are some of the training maneuvers.

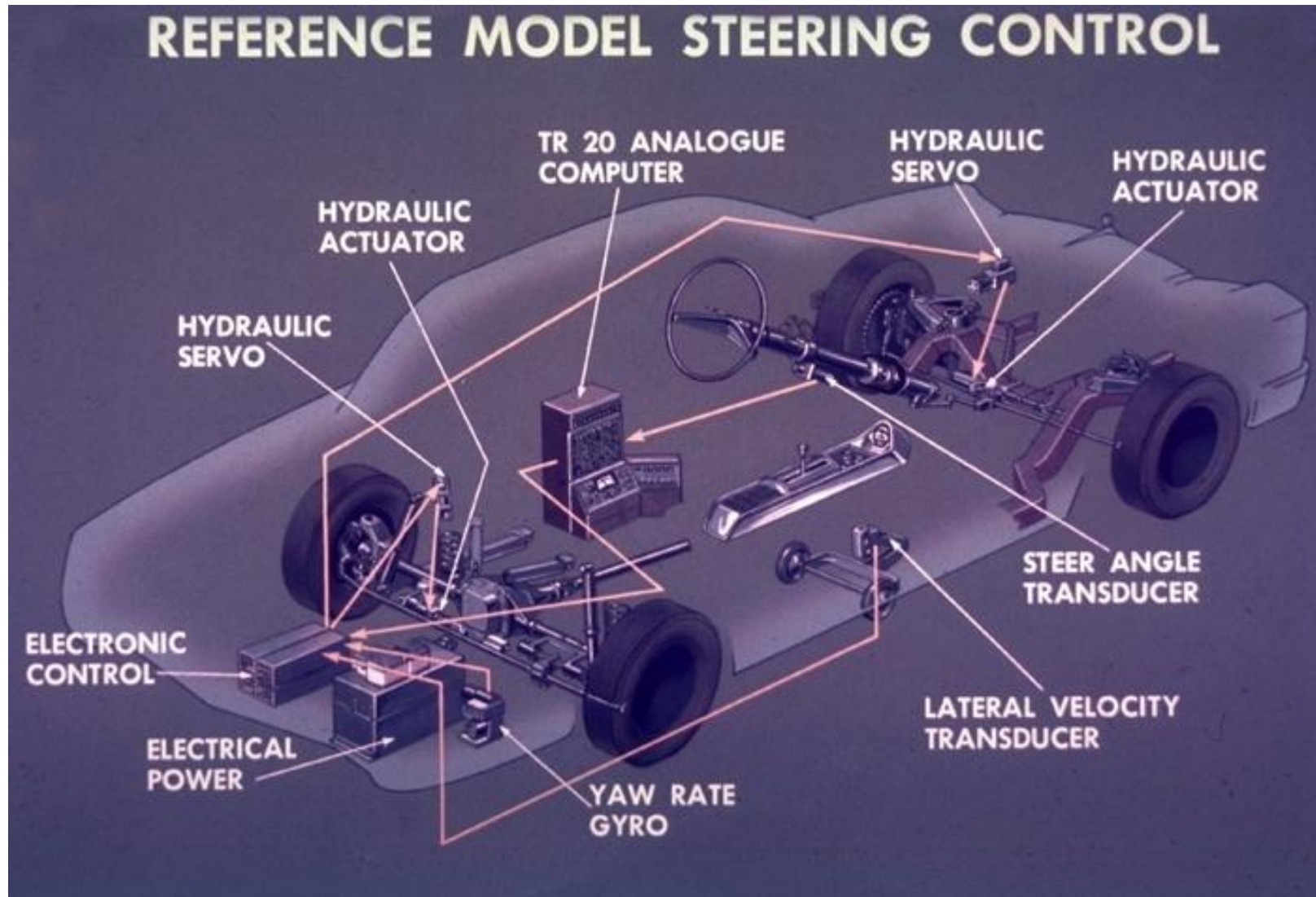


Another very interesting program was the Variable Response Vehicle, which had both front and rear wheel steering capability. Keith McKenna was the key engineer. It could be steered with a conventional steering wheel or with a stick.



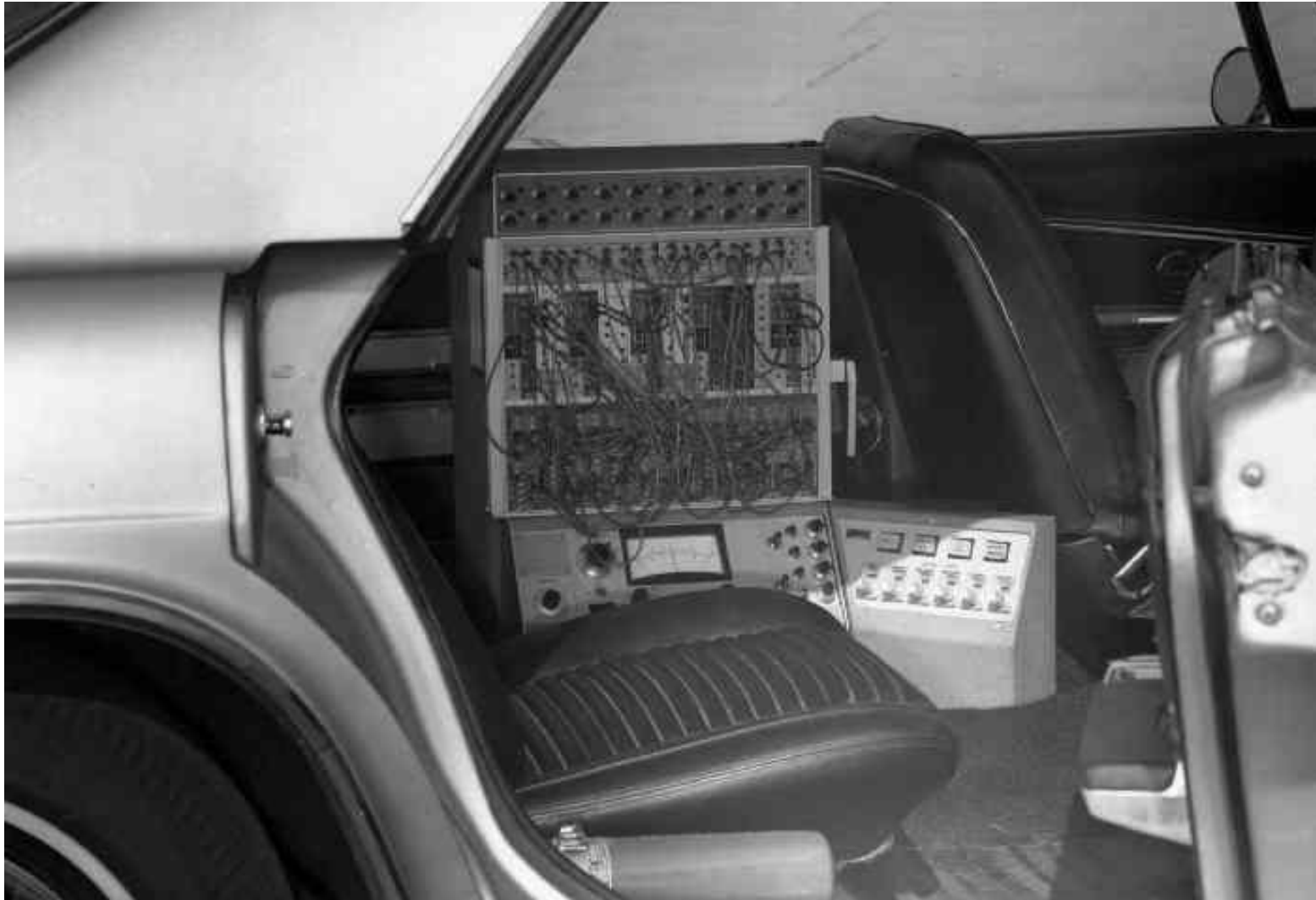


There was a mode of use in which the analog computer could be set to represent various types of cars. The steering wheel would send steering signals to the computer and the computer would drive the car.

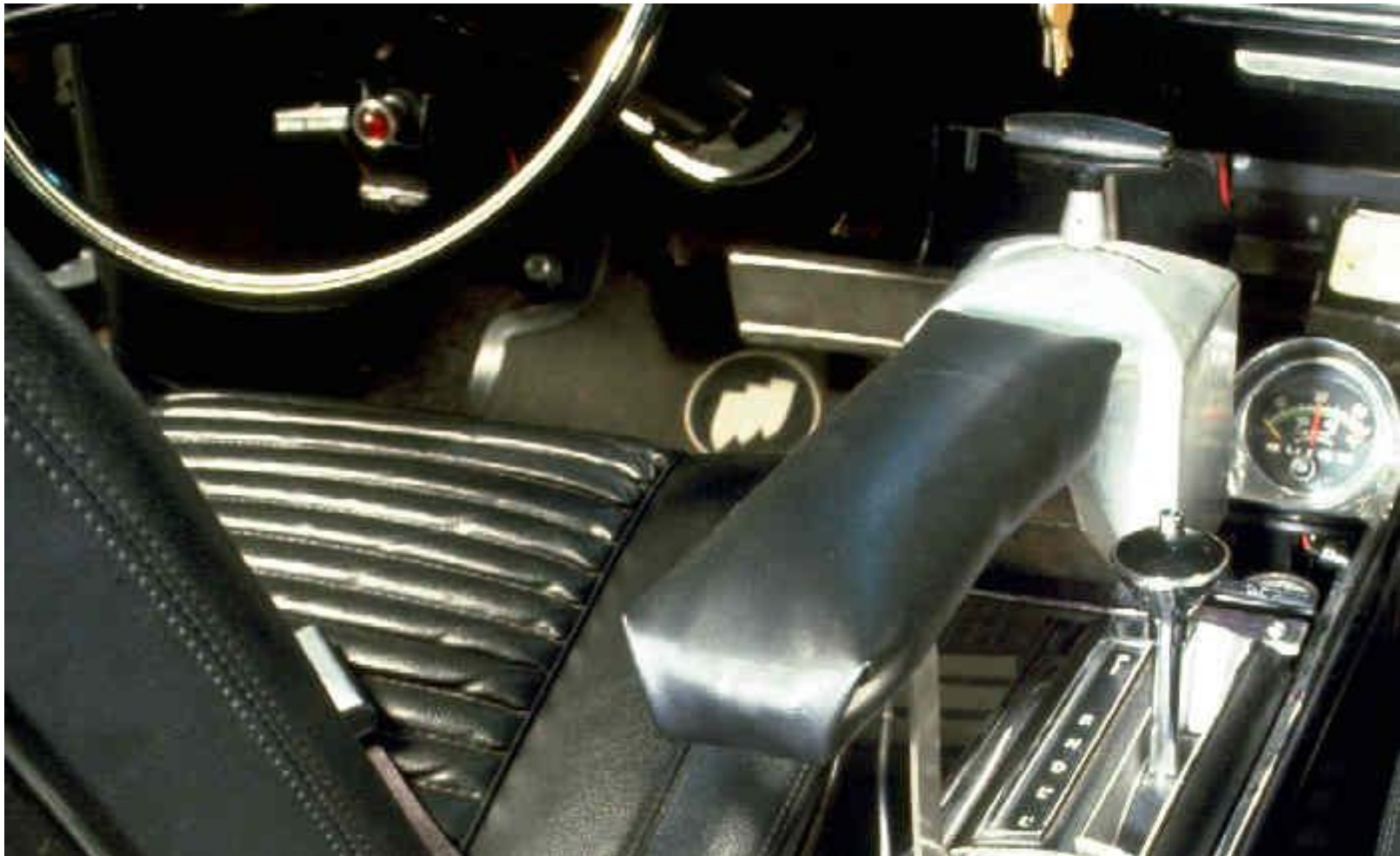




But the size of the VRV car itself and limits on tires and control system bandwidth were constraining. We could not produce Formula 1 handling properties, but there was still a lot of range in handling qualities available for study.



One interesting configuration was a stick that when rotated would turn the car in a responsive manner around curves, but when moved sideways would produce pure sideslip for lane changes or parallel parking.



This shows the VRV set up for disturbance testing with drivers while measuring ambient wind. It was a very interesting vehicle.



From this point on the major application of effort was to new vehicle design, assisting the various car programs. And there was continued development and improvement in both testing capability and simulation methods. These worked together.

For example, in the vehicle development process, the prototype was response tested as well as subjectively evaluated to see how it compared with the original target objectives. Then the original computer simulation could be updated and the optimal changes for improvement set forth. These changes had a high probability of being right.

The old days of “cut and try” were over forever.

But there were also new studies such as on-center handling properties, where Dick Topping on simulation, and Ken Norman on test procedures made fine contributions.

As more recent leaders of the department, Dick Rasmussen and Ron Leffert have been most instrumental in turning the technology into an effective and efficient design tool. The Vehicle Dynamics Lab is now an integral part of handling design in GM.



In closing I must say it has been a great experience seeing it happen. I think the results are exactly what Maurice Olley, Ken Stonex and Bob Schilling wanted to have nearly 50 years ago when they met with Bill Milliken at the GM Proving Ground.

I wish I could have been there on that most interesting day that he writes about in his book. I would like to have heard Maurice Olley stand up and say “We should do it !” and with those words, start us off on an exciting and ultimately successful adventure.

Thank you very much for allowing me to talk to you today.

## **Addendum**

The foregoing is as it was presented with very minor additions and modifications to provide a little more information.

This presentation was made within a program with four additional papers.  
The other speakers were:

Bill Milliken - Maurice Olley  
Leonard Segel - Calspan and the Equations of Motion  
Hans Pacjeka - Europe  
Marion Pottinger - Tires

The session was taped, but the quality is very poor.

The moderator was Tom Gillespie who, with Rajiv Gupta as Chairman, set up the session, held in Troy, Michigan, which was well attended.



The participants, Tom Gillespie, Tom Bundorf, Bill Milliken, Marion Pottinger, Hans Pacejka, and Len Segel, the photo taken at a dinner on the previous day.