# *Autonomous Driving Supercomputer Assembly Air Cooling of Rear On-Board Cooling System Heat Exchanger*

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***Abstract*** *— The Autonomous Driving Supercomputer Assembly for autonomous vehicles is likely to fail if it is not adequately cooled during test. The project research is divided into three phases: demonstrating through mathematical models a viable air/water measurement system to implement at a production level in autonomous vehicles testing, a laboratory environment for Supercomputer Assembly elements and Heat Exchanger system simulation, and plant environment test. Each phase will represent the Road-to-Lab-to-Math methodology. The results confirm air cooling is a viable option and will be needed to do multiple tests on supercomputers given the cooling rate of internal temperatures. The initiative to work with the Road-to-Lab-to-Math methodology comes from the benefits of reducing costs and physical testing at General Motors Plants. The air cooling can significantly save cycle time; additionally, air cooling will reduce the risk of water/coolant damage to the parts and lessen the need for a second test stand for the production line, saving $500K-$1M.*

***Key Terms*** *— Autonomous Vehicles, General Motors, Road-to-Lab-to-Math, Supercomputers*

## PROBLEM STATEMENT

This section will discuss the problem the Autonomous Vehicles (AV) at General Motors are facing at Manufacturing Plants and how the Road-to-Lab-to-Math methodology would mitigate the situation efficiently. Autonomous Driving Supercomputer Assembly (ADSCA) for Autonomous Vehicles (AV) at General Motors is at high risk of temperature failures if not actively cooled through the Rear On-Board Cooling System (ROCS), including the vehicle side of the Heat Exchanger (HEX). While performing the test, the assembly still has not been connected to the vehicle, and therefore, the plant must understand the requirements and conditions to recreate the side of the vehicle at the plant. The RLM methodology will mitigate the problem of performing the research during production hours. Even if the production is a low volume one, creating a real scenario through the first two (2) phases will ease the related work at the plant.

## RESEARCH DESCRIPTION

Currently the Autonomous Driving Supercomputer Assembly for Autonomous Vehicles are likely to fail if is not properly cooled. Plants would prefer to use air over water/coolant to reduce spillage and possible damage to parts. The problem and significance are stated by the Product Team from a validation test case where the chiller was turned off while the supercomputer and the Rear On-board Cooling System are running, several critical components exceeded their operating limits within three (3) minutes. The Product Team states that ADSCA testing in the plant will require cooling.

## LITERATURE REVIEW

'Road-to-Lab-to-Math' is a methodology to reduce the effort of On-road testing and replace it with laboratory testing and mathematical models. Also, on-road testing of prototype vehicles is expensive as it requires physical parts. Replacing these parts with mathematical models or simulating vehicle like environment on engine helps in reducing cost as well as effort to prepare prototype vehicles [1].

The research will concentrate on the RLM methodology & initiative. The RLM methodology stands for Road-to-Lab-to-Math. For RLM to be successful, the Design Project Manager must understand specific areas in the manufacturing organization where the project can readily provide impactful contributions. As a global organization as manufacturing, it is essential to understand the processes and requirements that drive production decisions. A unified effort on capability growth can serve as an efficient business model to accelerate advanced vehicle design. The production area is extremely sensitive to post-production development and changes. The methodology aids to reduce any downtime in the operation and management of any production phase, expected on AV.

Autonomous vehicles (AVs) use technology to partially or entirely replace the human driver in navigating a vehicle from an origin to a destination while avoiding road hazards and responding to traffic conditions [2]. In Figure 1 [3], the Society of Automotive Engineers (SAE) outlines six (6) levels of driving automation, extending from 0 (fully manual) to 5 (fully autonomous). The U.S. Department of Transportation has approved these levels.

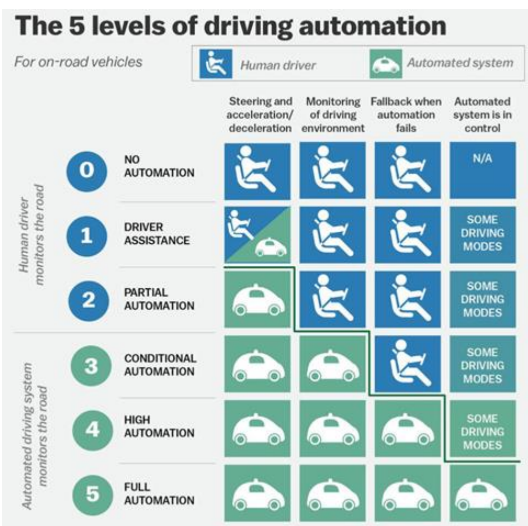


**Figure 1**
**The SAE Five Levels of Driving Automation**

## RESEARCH CONTRIBUTIONS

The research project will deliver a viable measurement system through mathematical models and the requirements to simulate in a laboratory environment the actual conditions needed to air-cool the Autonomous Vehicles Supercomputers in the plant. The initiative of using the Road-to-Lab-to-Math methodology is to innovate the development methodologies inside the company. The contribution of this approach comes from the benefits of reducing costs and physical testing at General Motors Plants.

## METHODOLOGY

The methodology for this project will follow the RLM initiative. The research project will be divided into three phases: demonstrating through mathematical models a viable measurement system, lab environment ADSCA heat output and Heat Exchanger system simulation, and plant natural environment test. Each stage will represent the Road-to-Lab-to-Math methodology.

- **MATH:** The mathematical models will simulate and collect data for Heat Exchanger and Supercomputer Assembly power requirements. Initially, the heat rejection by air will be proved at the test supplier. The simulation will determine if 3000 lpm & 25 PSI are feasible for the Heat Exchanger air conditions and integrity of the component.
- **LAB:** Laboratory example system data for Heat Exchanger/heating element uses air cooling and heating elements to simulate ADSCA. The second phase at the laboratory will include a test setup schematic. The initial test aims to collect one data set and characterize if the temperature rise is predictable enough that a curve fit can be used to predict the 25-minute temperature from a 10-minute temperature. Doing this will allow for shorter tests during the data collection phase. A complete examination will be used for the verifying stage.
- **ROAD:** Plant testing with multiple ADSCA with no cooling during testing will prove the third phase or stage for the RLM methodology, which is the road. The manufacturing plant is an active & fast-paced environment with

tremendous traffic of products & processes. The goal is to measure the heat rise of A loop and B loop of ADSCA's during test flashing, stop the test once it reaches 40 °C in the Heat Exchanger loops or an internal computer temperature of 50 °C, and compare lab vs road data and decide about air active cooling at the plant.

## Results and Discussion

The first step is defining the requirements to maintain loop A/B temperatures. Into the A/B sides, the ADSCA (product) can provide coolant up to a maximum of 50 °C at a minimum flow rate of 8lpm. In-Vehicle, on the cold side (Loop C) of the HEX, there is a maximum of 43 °C coolant at ten lpm. When the vehicle is in Active cooling, it runs about 26 °C on the C side of HEX. It floats to 41-43 °C on the C side when out of active cooling. In conclusion, in collaboration with Product Engineering, a goal of 40°C on the coolant temperature of A/B Loops on the output side of the HEX for A/B loops, which has ten °C headroom on the vehicle specification.

The test connection was defined through loop C due to availability at the HEX because the assembly had not been integrated into the vehicle when performing the test. The requirements are the following:

- No damage to sealing surface allowed
- Prefer to seal around the barb
- If air is feasible, the verification stage must include multiple heat exchangers run through the process and inspected by HEX supplier.

The simulation of air cooling through HEX will include data collected from plant and supplier. (Please see Table 1 & 2). The plant believes they can provide 3000 lpm of air at 25 PSI. Air should be around room temperature, however, would like to see the sensitivity around room temperature as chilled air might be an option. The supplier based on the inlet temperature and the flow rate will provide the Heat Transfer.

**Table 1**

**Plant Expected Capabilities**

| **Plant Expected Capabilities:** | | | | |
|---|---|---|---|---|
| **Loop C(cold)** | | | | |
| Max Air Flow@25 PSI | Air Inlet Temp | Max Air Inlet pressure | Air pressure drop | Heat Rejection |
| (lpm) | (°C) | (Psi) | (kPa) | (kW) |
| 3000 | 10 | 25 | 84.6 | 3.51 |
| 3000 | 15 | 25 | 83.8 | 2.90 |
| 3000 | 20 | 25 | 83.1 | 2.31 |
| 3000 | 25 | 25 | 82.3 | 1.72 |

**Table 2**

**Theorical Supplier Data**

| **Theoretical Supplier Data:** | | | | |
|---|---|---|---|---|
| **Loop C(cold)** | | | | |
| Max Air Flow@25 PSI | Air Inlet Temp | Heat Rejection | Is Heat Rejection less than 2 kW? | If yes, then what is the air flow required to reject 2 kW? |
| (lpm) | (°C) | (kW) | (Y/N) | (lpm) |
| 3000 | 10 | 3.51 | N | N/A |
| 3000 | 15 | 2.90 | N | N/A |
| 3000 | 20 | 2.31 | N | N/A |
| 3000 | 25 | 1.72 | Y | 4000 |

The supplier stated no damage will occur from running 3000 lpm air through HEX at 25psi, and data proved it is feasible that air, less than 25C at 3000 lpm will have sufficient heat rejection for 2KW.

To generate the control signal levels, we will use the OEM data to predict what control signals will work in Table 3. Specifically, we will use the temperature data to predict the effect of temperature. Then, we will use the fact that mass flow should be directly proportional to heat rejection to predict the effect at lower flows.

**Table 3**

**Predicted Data (based on Simulation Data)**

| | Flow lpm | | | | |
|---|---|---|---|---|---|
| Temp °C | 500 | 800 | 1200 | 3000 | |
| -15 | 1.08 | 1.73 | 2.59 | 6.48 | Predicted Heat Rejection in KW |
| -10 | 0.98 | 1.57 | 2.36 | 5.89 | |
| -5 | 0.88 | 1.41 | 2.12 | 5.29 | |
| 0 | 0.78 | 1.25 | 1.88 | 4.70 | |
| 5 | 0.68 | 1.09 | 1.64 | 4.10 | |
| 10 | 0.58 | 0.93 | 1.40 | 3.50 | |
| 15 | 0.48 | 0.78 | 1.16 | 2.91 | |

In Figure 2, the last data collected was ADSCA flashing power usage. Please refer to chart below. In conclusion, the flashing power use is approximately 1100 Watts.

| Voltage | 13.25 | | | | | |
|---|---|---|---|---|---|---|
| | Single Probe Current Measured (A) | Assumed Total Current (A) | Duration (s) | Power (W) | Watt*Sec | |
| Boot Up Peak | 46 | 92 | 60 | 1219 | 73140 | Non production |
| Steady State | 37 | 74 | ~~120~~ | | | Non production |
| PDB Update | 39 | 78 | ~~300~~ | | | Non production |
| | | | | | 0 | |
| Start Sideload | | | | | 0 | |
| | 40 | 80 | 60 | 1060 | 63600 | |
| | 42 | 84 | 30 | 1113 | 33390 | |
| | 50 | 100 | 10 | 1325 | 13250 | |
| | 45 | 90 | 20 | 1192.5 | 23850 | |
| | 40 | 80 | 120 | 1060 | 127200 | |
| Uploading | 40 | 80 | 200 | 1060 | 212000 | |
| | 40 | 80 | 10 | 1060 | 10600 | |
| | 40 | 80 | 10 | 1060 | 10600 | |
| Reboot | 46 | 92 | 60 | 1219 | 73140 | |
| Wait for ping | 40 | 80 | 90 | 1060 | 95400 | |
| | | Total Time | 670 | | | |
| | | | Average | 1130 | **736170** | **Total Watts*Sec** |
| | | | Max | 1325 | **1099** | **Avg Watts Time Weighted** |
| | | | Median | 1060 | | |

**Figure 2**
**Flashing Power Usage**

Simulation data shows that cooling with air is a feasible option for cooling. The simulation assumed a steady state, but we are okay with temperature rise over the 20 minutes if it stays < 40 °C. Due to the constriction at the inlet, it is impossible to achieve 3000 L/min air at 50 psi. The data collected shows that heat rejection provided by air could still be sufficient; further investigation on airflow at various temperatures may give more tolerance. Data from actual ADSCA proves that flashing consumes less power than expected at approximately 1100 W instead of 2000 W. Lower power increases the feasibility of air cooling. The following steps evaluate the HEX setup to simulate ADSCA to determine heat rejection with air cooling and heat input.

The second phase of the project design will be testing at the test supplier (See Figure 3). The supplier will provide room for laboratory staging and prove parameters collected in mathematical simulations (air cooling and heating elements to simulate ADSCA).

The initial test aims to collect one data set and characterize if the temperature rise is predictable enough that a curve fit can be used to predict the 25-minute temperature from a 10-minute temperature. Doing this will allow for shorter tests during the data collection phase as references in Figure 4. A complete examination will be used for the verification stage.

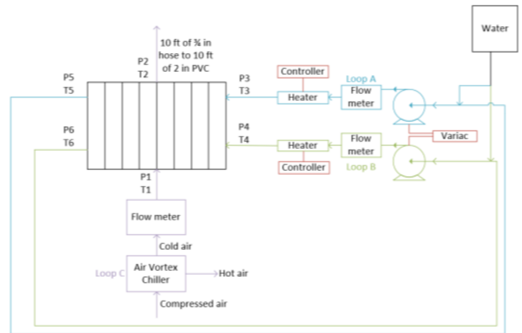


**Figure 3**
**Test Setup Schematic**

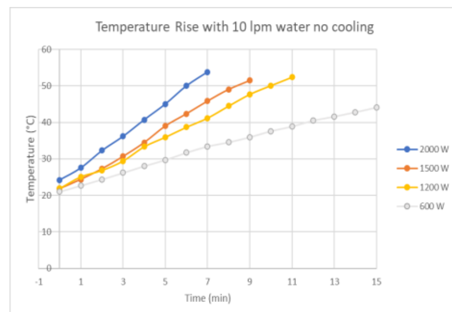


**Figure 4**
**Temperature Rise Without Cooling**

The actual conditions used were different from the planned ones. The air temperature was hard to control. The lowest temperature reached was -7.5 ºC. Also, it was unable to keep a stable temperature throughout each test. (Refer to Table 4). The temperature rose a significant amount during testing. The wattage was larger than the heater's stated output wattage—most tests were done at 2.4 kW total instead of 2 kW. Later in testing, the wattage was measured and controlled. The starting water temperature varied depending on room temperature and how long it was allowed to cool between tests. More tests were conducted than initially planned at different parameters after receiving data.

In Figure 5, Orthogonal Array Tool was used to test different air temperatures and flow against a noise factor of the water pump flow ranges of 8 to 10 lpm. Water pump flow is a noise factor because it is uncontrollable. Wattage used was 2400 W total.

**Table 4**
**Actual Conditions Used**

| Test | Total Heat In (kW) | Air Flow (lpm) | Starting Air Temperature (°C) | Water Flow (lpm) |
|---|---|---|---|---|
| 1 | 2.4 | 1200 | 0 | 10 |
| 2 | 2.4 | 1300 | -6 | 10 |
| 3 | 2.4 | 1000 | -2 | 10 |
| 4 | 2.4 | 1000 | 5 | 10 |
| 5 | 2.4 | 1000 | 1 | 8 |
| 6 | 2.4 | 1200 | -2 | 8 |
| 7 | 2.4 | 1000 | -2.7 | 8 |
| 8 | 2.4 | 1200 | -7.5 | 8 |
| 9 | 2.4 | N/A | N/A | 10 |
| 10 | 2.4 | N/A | N/A | 8 |
| 11 | 0.6 | 1000 | -5.8 | 10 |
| 12 | 0.6 | 1000 | 1 | 10 |
| 13 | 0.6 | 1000 | 0.5 | 10 |
| 14 | 0.6 | N/A | N/A | 10 |
| 15 | 2.4 | 1000 | 23 | 10 |
| Test | Total Heat In (kW) | Air Flow (lpm) | Starting Air Temperature (°C) | Water Flow (lpm) |
| 16 | 2.4 | 1000 | 21 | 8 |
| 17 | 2.4 | 1200 | 26 | 10 |
| 18 | 1.2 | 1000 | 0 | 10 |
| 19 | 1.5 | 1000 | 0 | 10 |
| 20 | 1.2 | N/A | N/A | 10 |
| 21 | 2 | 1000 | 10 | 10 |
| 22 | 1.5 | N/A | N/A | 10 |
| 23 | 2 | N/A | N/A | 10 |
| 24 | 2 | 1000 | 7.6 | 10 |
| 25 | 0 | 1000 | 20 | 10 |
| 26 | 2.25 | 1200 | 22 | 8 |
| 27 | 1.2 | 500 | 15 | 10 |
| 28 | 1.2 | 750 | 9 | 10 |
| 29 | 1.2 | 1000 | 10 | 10 |

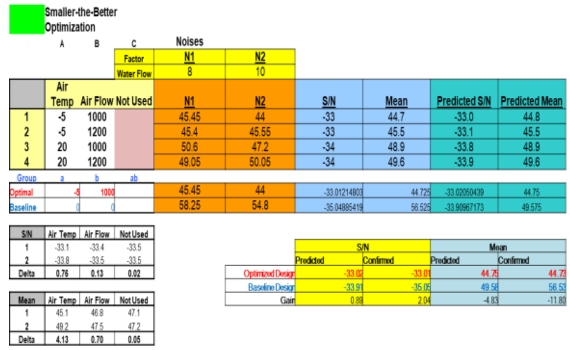

**Figure 5**
**Orthogonal Array Tool**

In Figure 5 & 6, both the Signal to Noise and Sensitivity indicate the air temperature used to cool the heat exchanger is much more critical than the air flow rate.

In conclusion, the HEX rate is insensitive to the air flow rate; however, the HEX is sensitive to the air temperature used for cooling as stated in Figure 8 & 9.

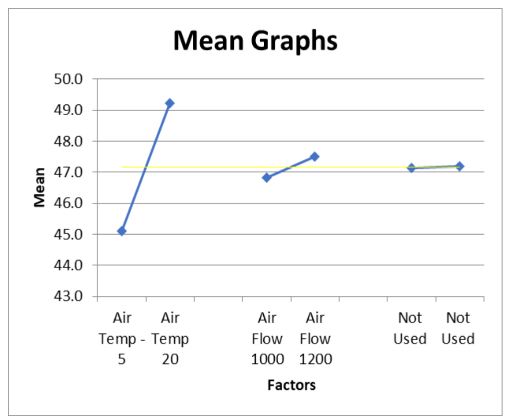


**Figure 6**
**OA Mean Graphs**

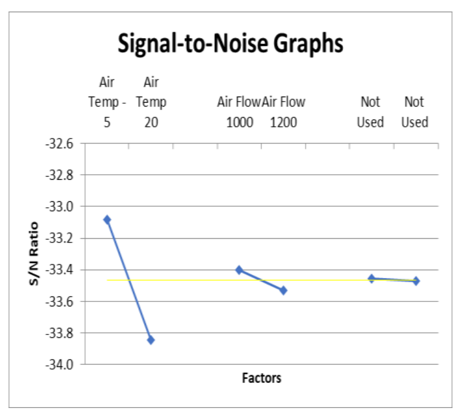


**Figure 7**
**OA Signal-to-Noise Graphs**

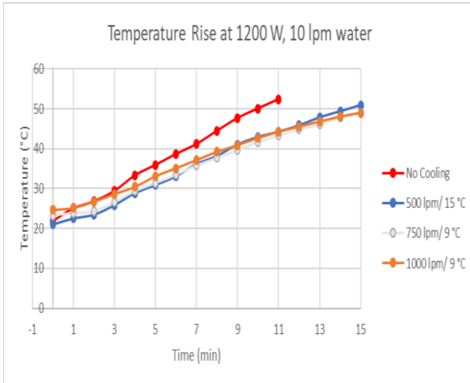


**Figure 8**
**Confirmation of Effect of Flow Rate**

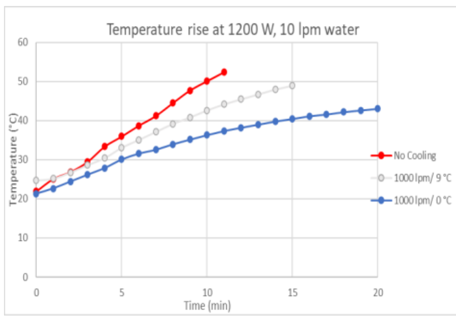


**Figure 9**
**Confirmation of the Effect of Temperature**

The last stage or phase of the project will be to understand the constraints through plant testing with multiple ADSCA with no cooling during testing and compare the data collected on previous steps with actual raw data from the plant.

The first step in the final phase is to measure and test 4 ADSCAs. (See Figure 9). During test flashing, calculate the heat rise of loop A/B in & out. Stop the test once it reaches 40 ºC in the HEX loops or an internal computer temperature of 50º C.

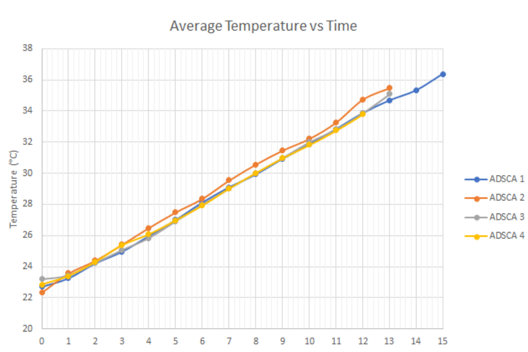


**Figure 9**
**No cooling – ADSCAs**

It was calculated based on linear the temperatures in Figure 10. Red line signifies 17 minutes, the time of the flashing test. Linear trendline R2 = .995 to .999. At end of test (17 min), the estimated temperature from each test does not go above 40°C.

The ROCS cool down (Figure 11) was characterized at the plant. The red lines signify when the computer was turned on to measure the internal temperatures. Rise after computer turned on due to recirculation of liquid and computer turning on. The computer turned off after 2 minutes after internal temperatures were found. Internal temperatures dropped by approximately 1.5°C over 54 minutes. ROCS temperature dropped by about 4°C over 42 minutes. External cooling will be needed to do multiple tests in one day.

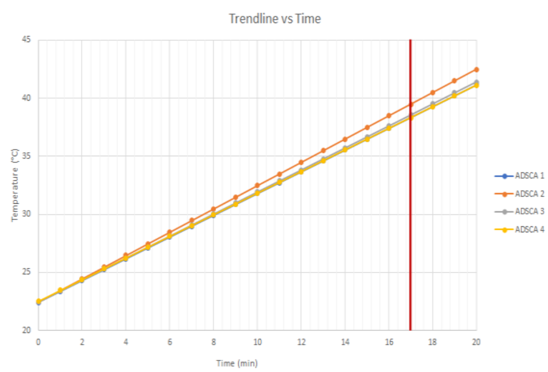


**Figure 10**
**Temperatures Based on Linear Trendline**

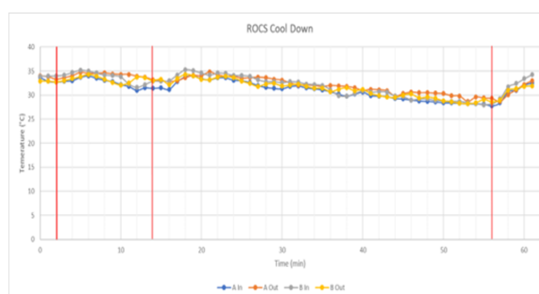


**Figure 11**
**ROCS Cool Down**

## RESEARCH LESSONS LEARNED

There are excellent lessons learned during this project. First, air cooling is a viable option for liquid cooled system under certain conditions.

Wattages at or below 1500W can be evaluated for air cooling. Additionally, air flow rate does not significantly affect the heat exchange rate in the range of 500-1200 lpm air through the cooling loop. Air temperature has a significant effect on heat exchange rate. It can be concluded that no cooling on ADSCAs is an option for initial testing; however, cooling will be needed to do multiple testing on ADSCAs given cooling rate of internal temperatures.

## CONCLUSION

In conclusion, the initiative to work with the Road-to-Lab-to-Math methodology is coming from the benefits of reducing costs and physical testing at General Motors Plants. The introduction to this type of methodology is crucial to reduce timing programs development and testing to newer and future products. The design project will help to identify continuous improvements and learn lessons to place in practice at the manufacturing organization. The air cooling can significantly save cycle time, additionally air cooling will reduce the risk of water/coolant damage to the parts. Air cooling will reduce the safety risk to personnel due to water/coolant spillage, and finally will reduce the need for a second test stand for the production line saving $500K-$1M. Startups and R&D companies are catching up using virtual, development, testing and validation methods. [4] Consumers benefit from using AD systems in many ways, including greater levels of safety; ease of operation for parking, merging, and other maneuvers; additional fuel savings because of the autonomous system's ability to maintain optimal speeds; and more quality time. Consumers understand these benefits and continue to be highly willing to consider using AD features, according to our research. To stay competitive General Motors should use simulation instead of actual road testing to accumulated miles and testing and scale to multiple countries. It is imperative that General Motors must also move more to the virtual playing field and lead the way.

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