Increasing EDV Range through Intelligent Cabin Air Handling Strategies

Annual Progress Report

Daniel Leighton and John Rugh

NREL is a national laboratory of the U.S. Department of Energy
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I. Vehicle Technology Evaluations

I.1.A. Increasing EDV Range through Intelligent Cabin Air Handling Strategies [1000487.00]

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End Date: September 30th, 2015

I.1.A.1. Abstract

Objectives

- Identify cabin air recirculation strategies to increase the fraction of recirculation possible without causing windshield fogging to reduce electric vehicle (EV) cabin heating energy consumption in cold weather.

Accomplishments

- Computational fluid dynamics (CFD) simulations of a Ford Focus Electric demonstrated that a split flow heating, ventilating and air conditioning (HVAC) system with rear recirculation ducts can reduce cabin heating loads by up to 57.4% relative to full fresh air usage under some conditions (steady state, four passengers, ambient temperature of -5°C).
  - The primary challenge is the increased complexity and cost due to packaging constraints.
- Simulations also showed that implementing a continuous recirculation fraction control system into the original equipment manufacturer (OEM) HVAC system can reduce cabin heating loads by up to 50.0% relative to full fresh air usage under some conditions (steady state, four passengers, ambient temperature of -5°C).
  - This is a substantial energy savings benefit that is attainable at the relatively low cost of additional control logic and potentially a redesigned recirculation actuator door.
- Identified that continuous fractional recirculation control of the OEM system can provide significant energy savings for EVs at minimal additional cost, while a split flow HVAC system with rear recirculation ducts only provides minimal additional improvement at significant additional cost.
  - Recommend implementation of continuous recirculation fraction control for OEM system instead of split flow system.

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I.1.A.2. Technical Discussion

Background

Plug-in hybrid electric vehicles, battery electric vehicles (BEVs), and internal combustion engine vehicles with fuel-efficient, down-sized engines increasingly lack sufficient “free” waste heat to condition the cabin in cold weather. The lack of sufficient waste heat to fully condition the cabin means that they must resort to alternative heating systems such as electrical resistance heaters and heat pumps. These heating technologies consume additional energy for thermal management, which reduces vehicle efficiency. In BEVs this effect is particularly acute due to the complete absence of engine waste heat and the limited battery energy available for vehicle propulsion. In fact, testing of a 2012 Nissan Leaf by Argonne National Laboratory demonstrated that operating the vehicle at an ambient temperature of 20°F approximately halved the vehicle range for the Urban Dynamometer Driving Schedule (UDDS) drive cycle when compared to 72°F [1], which is predominately due to energy used to heat the cabin via an air-side electrical resistance heater. Technologies that are able to reduce the amount of energy spent by the battery to condition the vehicle cabin will help to increase customer acceptance of electric drive vehicles (EDVs) by reducing range anxiety, which will in turn increase EDV penetration into the national vehicle fleet.

Introduction

Denso Corporation found that as much as 60% of the energy used to heat cabin air in a light-duty vehicle is due to the necessity of conditioning outside fresh air, which is also known as the ventilation loses [2]. This represents a significant potential EDV range increase in cold weather through a reduction in the amount of fresh air used during cabin heating. To reduce the energy consumption dedicated to conditioning fresh air, recirculated air from the cabin can be re-conditioned. Using current technologies, cabin air recirculation is limited due to issues of windshield fogging. One method to increase the fraction of air that can be recirculated is to focus fresh air on areas that need it the most, namely the windshields and occupant faces. To achieve higher recirculation fractions, the conditioned cabin air can be split into two separate airstreams, one fresh and one recirculated stream. These separate airstreams can then be directed through the cabin based on occupancy and fogging prediction.

The literature contains several examples of approaches for split flow systems that separate the fresh and recirculated air streams. Denso Corporation manufactures a split flow HVAC module that separates the flow streams within the HVAC module itself using a variable-diameter blower wheel and separation baffling for the heat exchangers [2]. Ford Motor Company holds a patent on suction surfaces that are distributed throughout the vehicle, as shown in Figure I-1 [3]. These suction surfaces are powered recirculation return ducts that can be embedded within the seats and structure of the vehicle both at the front and rear seating rows rather than the typical single recirculation "door" that opens on one side of the HVAC module itself. The HVAC module is typically located within the instrument panel on the passenger side of the vehicle, which theoretically sets up a cabin air flow pattern with a limited amount of recirculation air that reaches the rear of the vehicle.

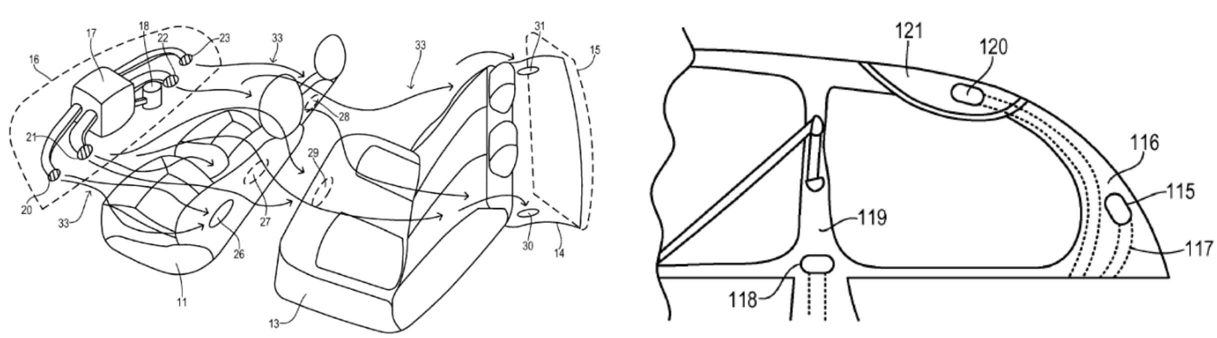

Figure I-1: Ford Motor Company patent drawings for proposed "suction surface" locations

Source: Ford Motor Company, US Patent 20120315835A1, "Automotive HVAC System with Suction Surfaces to Control Local Airflow"

CFD simulations were performed to efficiently explore the different split flow configuration options. The simulations allowed multiple configurations for recirculation return ducting and exhauster placement without needing to construct the physical ducting in an experiment vehicle. The CFD simulations also allowed direct quantification of the relative humidity (RH) of the air at all of the glass surfaces of the vehicle to detect fogging conditions, as well as quantification of the energy savings benefits of a variety of recirculation enhancement strategies.

Approach

A three-dimensional (3D) computer-aided design (CAD) model of the interior cabin of a Ford Focus BEV was provided to the National Renewable Energy Laboratory by Ford Motor Company. This 3D CAD model was used to create a mesh of the cabin interior airspace for 3D CFD modeling of the interior cabin airflow [4]. The model was then modified to add split flow ducting as shown in Figure I-2. The CAD model shown represents the final iteration of duct locations used in the final results.

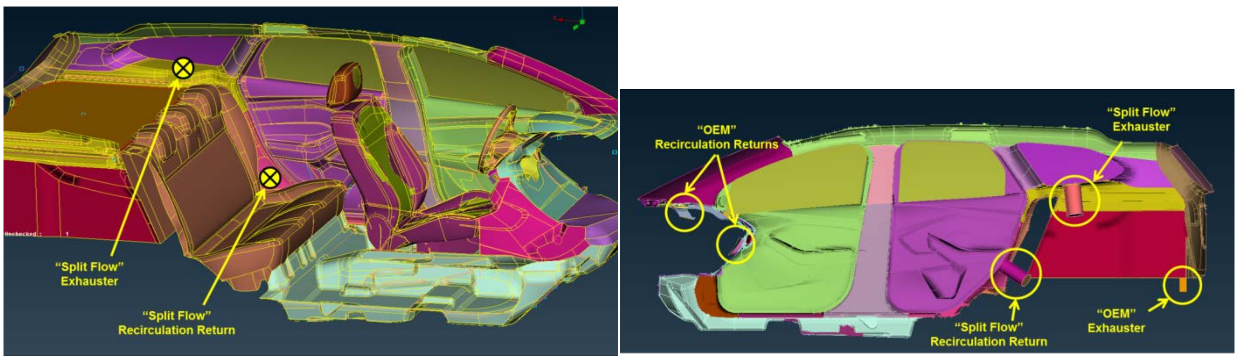

Figure I-2: Recirculation return and exhauster locations in Ford Focus CAD cabin model

The results from vehicle cabin simulations using steady-state CFD analysis were used to measure the impact of various enhanced cabin airflow techniques, including a split flow system with rear recirculation ducts. The effect of these technologies on windshield fogging during heating mode was assessed, the energy savings due to reduced fresh air usage was quantified, and best design practices were identified.

The CAD model includes the vent ducting of the HVAC system itself to capture the effect of vent design on the local airflow. This is important because the ducting can impart swirl and other turbulence into the air flow distribution, which affects the windshield fogging predictions. The defrost/demist vents are highlighted in green on the left of Figure I-3. In the case of split flow, this is where the fresh air enters the vehicle. The red floor outlets for the front and rear passengers are where the recirculated air flow re-enters the vehicle cabin.

The CAD model also includes four human passenger models, which provide wall boundary conditions for airflow as well as moisture inlet boundaries to the cabin. The human passenger models are shown on the right side of Figure I-3. Mouth and chest mass flow inlet boundaries are created on each of the four human models to simulate the respiration and perspiration water mass flow rates into the cabin air volume. The total water introduced to the cabin air from the human models is 280 grams per hour, which is a flow of 70 grams per hour per passenger as specified in SAE standard J902 [5]. This is executed as 15 grams per hour of respiration and 55 grams per hour of perspiration.

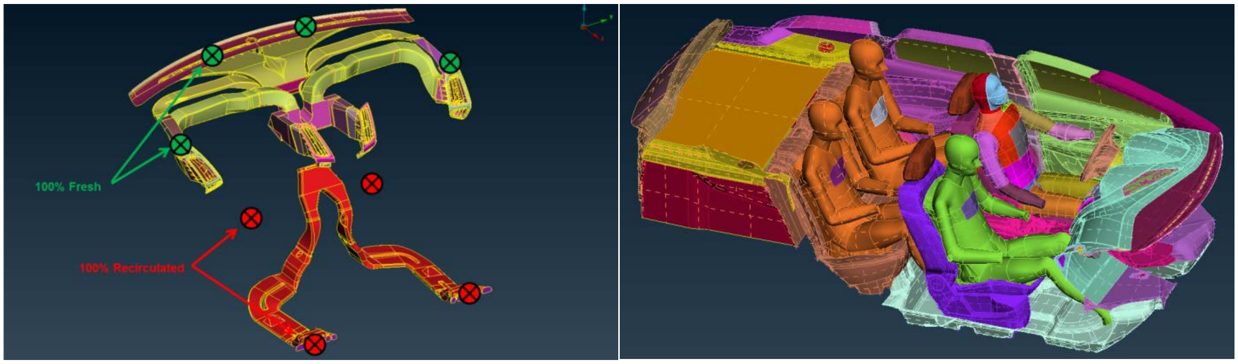

Figure I-3: Left - Cabin inlet vent CAD geometry; Right - Human passenger CAD models in four seating locations within cabin

To simplify the simulations and focus on exploring different configurations for the split flow system, a single representative test condition was chosen as a metric for comparison between the different technologies. The ambient outdoor air temperature was chosen as -5°C because it represents a substantial heating case in which the recirculation is limited by windshield fogging. It was assumed that the outdoor RH was worst case, at 100%. It is worthy to note that at such low ambient temperatures the absolute humidity is very low even at 100% RH. The air velocity over the outside of the vehicle was fixed at 30 miles per hour, head-on, which represents the moderate speeds seen in mixed city/highway driving during a commute. This moderate vehicle speed was used to calculate the convection coefficients on the exterior shell surfaces as part of the calculation of the heat lost through the vehicle walls. The conduction through the walls was calculated based on known material properties and dimensions, and the interior convection coefficients were calculated by the CFD model. The CFD simulations are steady-state, and therefore require representative cabin HVAC air flow rate and vent temperatures. A vent inlet temperature of 50°C was chosen based on experimental measurements, and an HVAC blower volumetric air flow rate of 105 cfm was chosen based on maintaining reasonable cabin air comfort temperatures for the steady-state simulation. This represents roughly half of the maximum possible blower air flow rate.

Based on experimental data, 37% of the volumetric air flow rate through the HVAC system was distributed to the defrost/demist vents, and 63% was distributed to the foot well vents in the OEM system. In the fractional recirculation control simulation case, the OEM system ducting is used. The recirculation air leaving the cabin mixes with fresh outside air within the HVAC module and is then distributed to all of the cabin inlet vents. When continuous fractional recirculation control is used, it only affects the proportion of mixed recirculation and fresh air; the air flow rates to the vents remain constant. In the split flow configuration simulations, 100% of the recirculation outlet air is reconditioned separately and sent to the floor vents, while 100% fresh outside air is conditioned and sent to the defrost/demist vents. When the split flow recirculation fraction is changed, the air flow rates to the defrost/demist vents and floor vents are proportionally altered. For example, if the recirculation fraction is 75%, then 75% of the 105 cfm total air flow rate is sent to the foot vents, and the remainder is sent to the defrost/demist vents. Table I-1summarizes the different configurations presented in the results.

Table I-1: Test configuration descriptions

Configuration	Exhauster Location	Recirculation Location
OEM Fresh	Trunk floor	None
Fractional Recirculation Control	Trunk floor	HVAC module (within dashboard)
Split Flow	Behind C-pillar	Rear passenger waist level
Split Flow w/ OEM Exhausters	Trunk floor	Rear passenger waist level
Split Flow w/ OEM Exhausters and Recirculation	Trunk floor	HVAC module (within dashboard)

Results

An example of the air flow patterns in the split flow configuration is shown in Figure I-4 for a 63% recirculation fraction. It is notable that the highest air flow velocities occur at the inlet vents and outlet recirculation return ducts and exhausters. The area of these duct openings must be sized to prevent excessive air velocities that may cause discomfort and noise. In the center of the cabin, the airflow velocity is generally very low. The original theory was that in a split flow system, the foot well vents that supply re-conditioned recirculation air will flow through the bottom level of the cabin and exit through the recirculation ducts near the rear passengers' waists, while the fresh air supplied at the defrost/demist vents will flow through the upper level of the cabin past the passengers' heads and out of the exhausters near the rear windshield behind the C-pillar. Although this two-layer flow pattern undoubtedly occurs to a small degree, simulations showed that the expected distinctly separate regions of flow are not apparent.

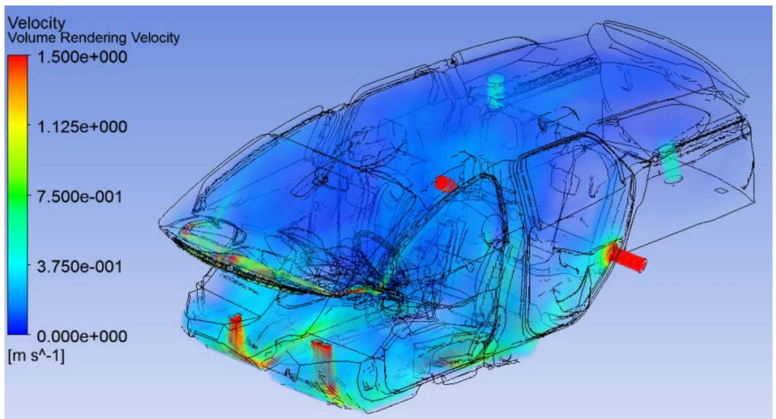

Figure I-4: Cabin air velocity field of split flow case with rear split flow recirculation return ducts and exhausters at 63% recirculation

The fogging prediction of the windshield is a key parameter used to determine the maximum allowable fraction of recirculated cabin air. To this end, the RH at the inner glass surfaces will be the metric used to compare different cases. RH is a function of the water content of the air flowing over the windshield, but is also a function of the glass surface temperature itself. Figure I-5 shows the inner surface temperature of the front windshield in the fractional recirculation control case to demonstrate the effect of the defrost vents heating the inside of the glass while the exterior airflow is cooling the glass. It is apparent that the average windshield inner surface temperature is dominated by the heat transfer from the defrost vent air, but that there are strong non-uniformities caused by differences in local defrost flow velocity.

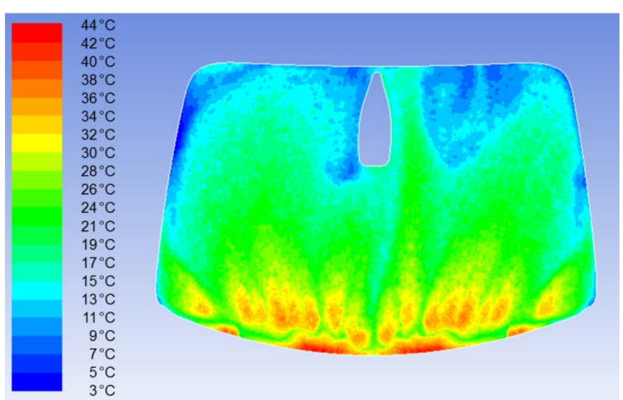

Figure I-5: Front windshield interior surface temperatures of the fractional recirculation control case

A comparison between the fractional recirculation control case and the split flow system using the rear recirculation return ducts and split flow exhauster locations is shown in Figure I-6. This figure shows the inner front windshield surface RH levels when a recirculation fraction of 63% is used in both cases. In both cases, the entire windshield surfaces are below 100% RH, which indicates that no fogging occurs under these conditions. The notable difference between the two cases is that the split flow system has a qualitatively lower average RH, which is expected since it is receiving 100% fresh outside air, whereas the fractional recirculation control system windshield is receiving the mixed fresh/recirculation air at a 37%/63% fraction. In this comparison the air flow rate and temperature of the defrost vents is the same in both configurations.

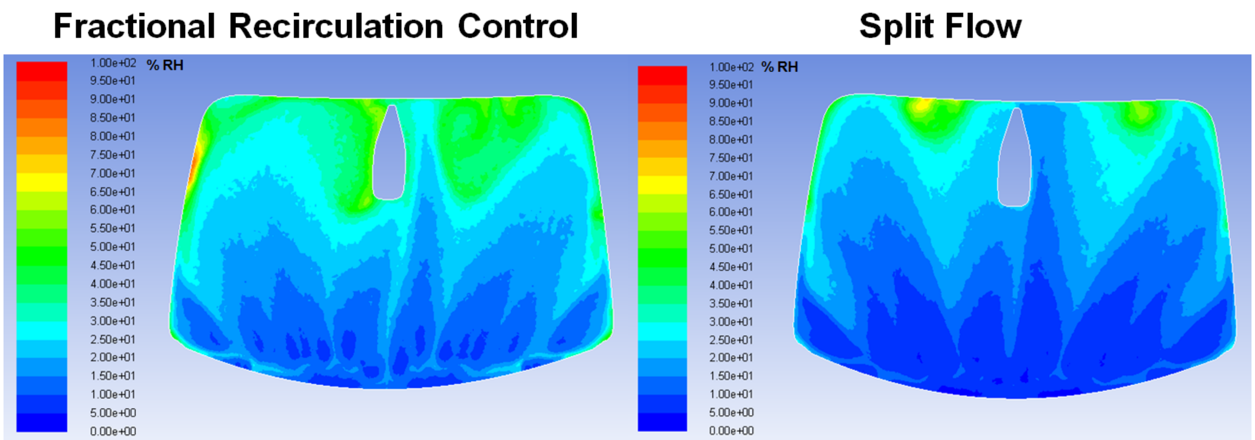

Figure I-6: Windshield RH of fractional recirculation control (left) and split flow (right) at 63% recirculation fraction

Of more interest is how high the recirculation fraction can be increased before windshield fogging begins, which is determined to occur when the RH reaches 100% in any section of the windshield. Again, a comparison between the windshield RH for the fractional recirculation control system and the split flow system using the rear recirculation return ducts and split flow exhauster locations is shown in Figure I-7. In this case, the recirculation fraction of the split flow system has been increased to 84.5%, which means that the flow rate of the 100% fresh air being delivered by the defrost vents must be reduced as a fraction of the total 105 cfm HVAC air flow rate. This equates to a 58.1% reduction in air flow rate from the defrost vents when compared with the fractional recirculation control case. In the fractional recirculation control case, the recirculation fraction has been increased to 75%, which means that the absolute humidity of the vent air is increased compared with the previous case, which elevates the RH at the interior windshield surface. The most notable effect occurs in the split flow case, where it is apparent that the windshield surface RH near the defrost vent outlet is still very low, but that the lower flow rate does not "project" very far up the height of the windshield, which allows the higher humidity cabin air to flow back as a plume onto the upper windshield, which becomes the limiting factor for fogging.

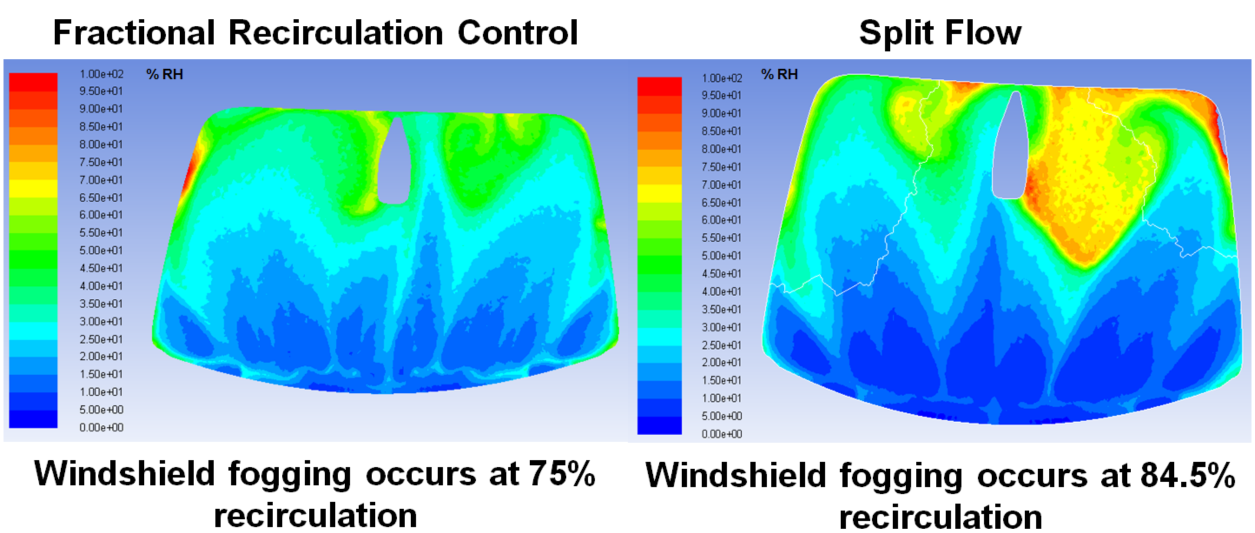

Figure I-7: Windshield RH of fractional recirculation control (left) and split flow (right) at highest recirculation fractions before fogging point

When examining what the maximum allowable recirculation fractions are for the various system configurations, it is important to examine not only the RH at the inner surface of the front windshield, but also the RH at the inner surfaces of the other glass panes within the vehicle. Figure I-8 shows three different simulation cases for the RH at the inner glass surface for the front windshield (left side), side windshields (three panes each side), and rear windshield (right side). The two cases discussed previously for the maximum allowable recirculation fractions before front windshield fogging occurs show that there are small areas of predicted fogging on other portions of the glass surfaces (top and middle plots). In fact, the split flow system produced moderate amounts of fogging at the rear glass. Based on this result, the simulation was re-run for the split flow case using the OEM exhausters that are below the rear glass at the floor of the trunk instead of the "split flow" exhausters that are behind the C-pillar. The result is shown in the third (bottom) plot, and it is apparent that the OEM exhausters are superior to the "split flow" exhausters due to more flow over the rear glass. Because these OEM exhauster locations are typical for vehicle packaging, it is recommended that they be used for the split flow system to reduce complexity and cost. The OEM exhausters were used in the remaining analysis of the split flow system. It is also important to note that simple 2D wall conduction models are used, not detailed 3D wall simulations. The consequence of this is that at the junction of different wall surface materials, the accuracy of the wall temperature prediction is reduced, such as at the edges of the glass surfaces where they connect with sheet metal walls.

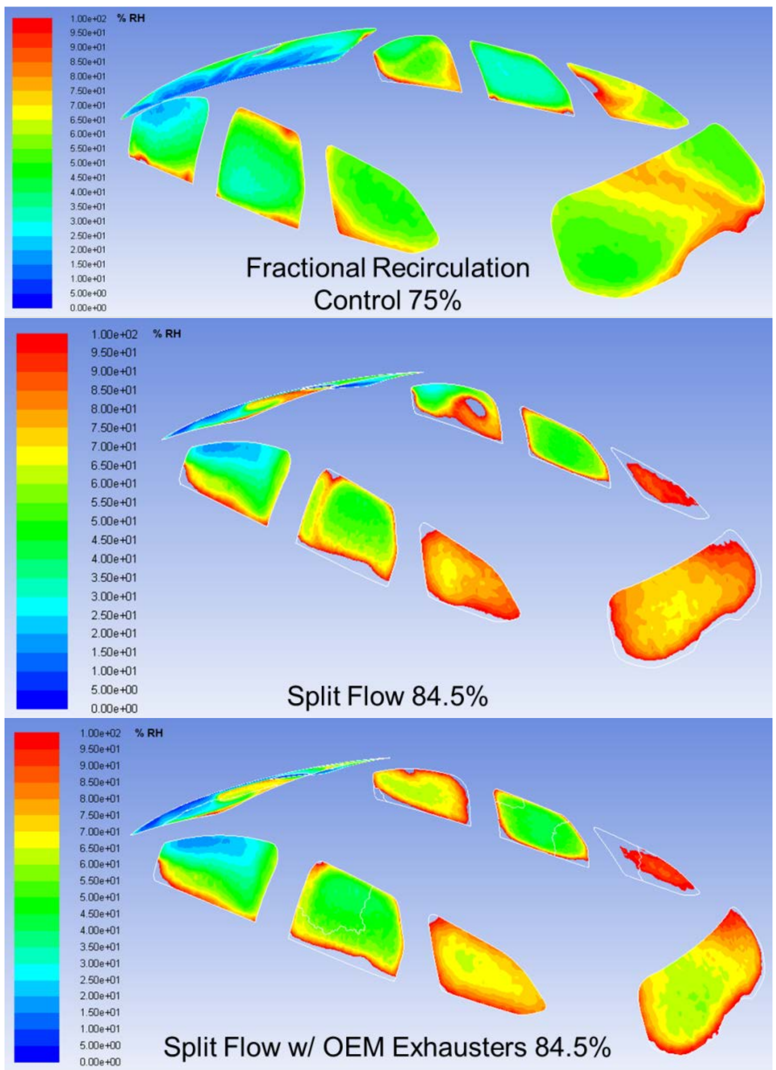

Figure I-8: Vehicle glass surface RH of fractional recirculation control at 75% recirculation (top); split flow at 84.5% recirculation (middle); and split flow with OEM exhausters at 84.5% recirculation (bottom)

Another question of interest is how well a split flow HVAC module works when using unmodified OEM exhausters and recirculation return, i.e., a drop-in of a split flow HVAC module. A recirculation fraction of

63% was used to make a performance comparison between the three different system configurations in Figure I-9. The comparison shows that the drop-in split flow HVAC module (middle) performs similarly to the fractional recirculation control case (top) with the exception of superior performance at the front windshield. A comparison of the split flow drop-in (middle) with the split flow system using rear recirculation return ducts (bottom) shows that the performance difference is generally positive, but small.

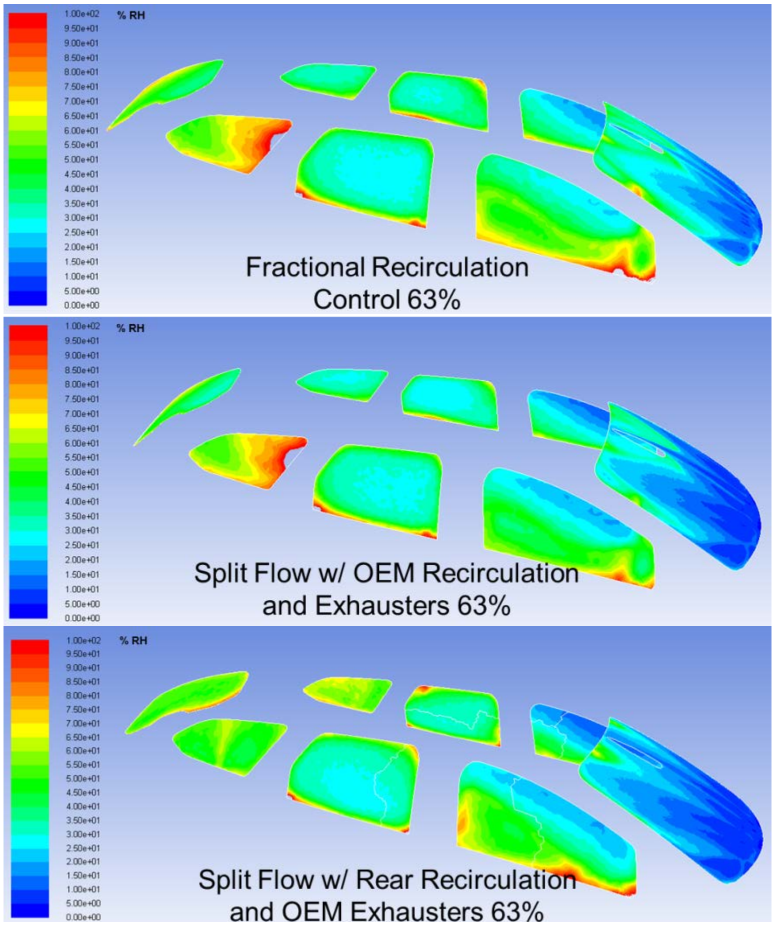

Figure I-9: Vehicle glass surface RH at 63% recirculation for fractional recirculation control (top); split flow with OEM recirculation ducts and exhausters (middle); and split flow with rear recirculation ducts and OEM exhausters (bottom)

The RH of the bulk cabin air is another metric that is informative for discerning what is occurring within the vehicle air space. Figure I-10 compares the air RH for the fractional recirculation control case at 63% recirculation (top) to the split flow system with rear recirculation ducts (bottom) over a virtual plane down the center of the vehicle from front to back. The most notable finding in this comparison is that the split flow system with rear recirculation return ducts can significantly lower the average air RH in the rear seating area of the vehicle, which can be disadvantageous to rear occupant comfort under some conditions. The other notable outcome is that two-layer flow does not significantly develop as discussed previously for the air velocity plot; the RH gradient in the vertical direction is slight, if any.

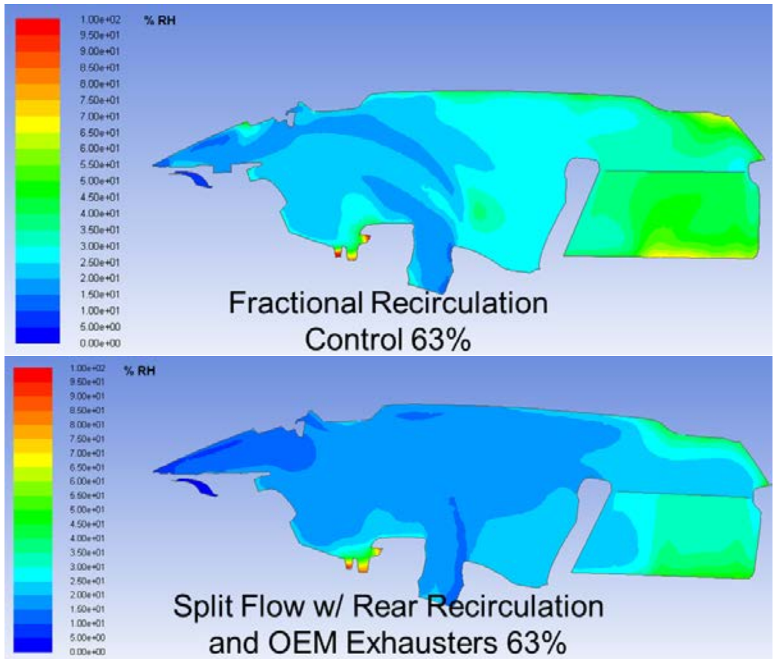

Figure I-10: Air RH at center plane along length of vehicle of fractional recirculation control at 63% recirculation (top) and split flow with OEM exhausters at 63% recirculation (bottom)

The maximum energy savings associated with the different configurations is calculated at the point where any further increase in the recirculation fraction will induce windshield fogging. It is assumed that the reduced thermal load of the cabin is directly proportional to the amount of energy required to provide it. This is approximately true for electrical resistance heating or a heat pump, although results could differ slightly depending on the exact system design. The required heating capacity for the cabin is calculated based on the simulation results for inlet and outlet conditions at the tested recirculation fraction. Table I-2 summaries the energy savings. It is important to note that these energy savings results are only for the specific case tested, which is a steady-state case with four passengers where the vehicle is travelling at a constant 30 mph at an ambient temperature of -5°C. In other common cases, such as a transient cabin warm-up period, the energy savings benefits would likely be reduced.

Table I-2: Steady-state energy savings summary

Configuration	Recirculation Fraction	Required Heating Capacity	Energy Savings
OEM Fresh	0%	2.98 kW	0%
Fractional Recirculation Control	75%	1.49 kW	50.0%
Split Flow w/ OEM Exhausters	84.5%	1.27 kW	57.4%

Conclusions

CFD simulations demonstrated that continuous fractional recirculation control using standard OEM ducts and recirculation doors allows a recirculated air fraction of up to 75% before windshield fogging occurs when there are four passengers and the ambient temperature is -5°C. A 75% recirculation fraction results in a cabin heating load reduction of 50.0% relative to using full fresh air, which equates to a 50.0% energy savings for a generic heating system such as an electrical resistance heater or heat pump. This is a substantial energy savings for EDVs in cold weather at the relatively low cost of additional control logic, sensor, and potentially a redesigned recirculation actuator door. The actual EDV range increase that this energy savings would equate to would be heavily dependent on vehicle usage.

The primary investigation of this CFD simulation study was to measure the effect of a split flow recirculation system. CFD results showed that having split fresh and recirculation air streams with a return duct at the rear of the vehicle allowed up to a 84.5% recirculation fraction before windshield fogging, which equates to an energy consumption reduction of 57.4% relative to full fresh air use. Although the split flow system provides significant benefit, the slight difference in energy savings of the split flow system over the fractional recirculation control system is unlikely to be justifiable due to the increased system complexity. The increased complexity is particularly apparent in the packaging challenge of running recirculation return ducts from the rear of the vehicle to the instrument panel. Also, the energy savings estimate is based on thermal load reduction and does not take into account any potential increase in HVAC blower electrical power due to the additional pressure drop of the return ducts. With that in mind a fractional recirculation control system is recommended as an effective option to reduce heating loads. In fact, Corporate Average Fuel Economy (CAFE) regulations provide off-cycle greenhouse gas credits to OEMs for implementing improved recirculation strategies, and OEMs are beginning to implement fractional recirculation controls.

Although the additional energy savings benefit of the split flow system over the fractional recirculation control system is small, an auxiliary benefit of the split flow system is potentially improved passenger thermal comfort. The split flow system provides drier air to the front windshield, which would allow a reduction of airflow through the defroster/demister vents. This is advantageous because defrost/demist flow can cause discomfort for the front passengers due to "dry eyes."

I.1.A.3. Products

Presentations/Publications/Patents

1. Leighton, Daniel. "CFD Modeling of Cabin Airflow Using Split HVAC and Dynamic Extractors." SAE 2015 Thermal Management System Symposium, Troy, MI, September 29 - October 1, 2015.

I.1.A.4. References

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