

Smart Rear Defog

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ABSTRACT

Smart Rear Defog can be defined as an optimized control algorithm that sets the state of a vehicle's rear defog relay based on a logical assessment of vehicle parameters and environmental conditions. The use of the optimized control algorithm will minimize the amount of user interaction needed to operate the rear defogger and it will minimize the amount of heat rejected to the environment which in turn will improve the vehicle's real world fuel economy or electric range. This paper provides a detailed description of the smart rear defog control system as well as evidence to demonstrate its robustness to variances in environmental conditions and vehicle usage compared to the traditional rear defog system commonly used in many vehicles today.

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INTRODUCTION

Automobiles are often exposed to environmental conditions that allow condensation such as fog, frost, ice or precipitation such rain and snow (hereafter referred to as condensation) to collect on the vehicle's rear glass surface. This undesirable situation can limit the driver's rearward visibility. Since the 1970s, rear defog systems have been implemented on almost all passenger vehicles equipped with a rear glass. The typical rear defog system includes a manual activation/deactivation button, a relay, a rear glass resistive grid and possibly an automatic control algorithm to automatically set the state of the rear defog relay. The automatic control is advantageous for many reasons. Most importantly, it limits the duration of a rear defog activation in the event that the driver forgets to manually turn it off. It also helps prevent energy loss to the environment, to protect the 12v energy storage and energy generation systems, and to prevent wear on the rear glass heating elements.

The traditional automatic control algorithm, used by many OEMs limits the duration of the rear defog system by implementing a 10 or 15 minute timer when the rear defog system is activated. Sometimes, there is a secondary timer of shorter duration for any subsequent activation (e.g. 5 minute timer). Some OEM suspended the timer to prolong the rear defog activation when the vehicle travels at high vehicle speeds. This allows the system to provide more heat energy to the rear glass to compensate for the larger amount of convective heat loss from the rear glass. Some OEMs provide automatic activation of the rear defog system during a remote

start event or during a Key-ON event when the vehicle is exposed to a climate colder than 5°C. This "customer exciter" feature allows the customer to engage the rear defog system without having to physically enter the cold vehicle and press a button.

The traditional rear defog system was designed to meet the voice of the customer which states that the rear glass must be cleared in a reasonable amount of time. Translated into engineering requirements, it means that after 30 minutes of operation, a minimum of 75% of the rear vision area must be cleared [1] when the outside air temperature is at -20°C (-4°F). Today, the voice of the customer has evolved and the new expectation is that the rear defog system must clear the rear glass using the least amount of energy. In order to satisfy the new customer requirements, the entire rear defog system must be re-evaluated to see if there are any design opportunities that can be implemented to balance the tradeoff between maximizing the activation time to clear the rear glass while minimizing the amount energy used by the system. The design objective will be to maintain the rear glass clearing performance and at the same time improve the vehicle's real world fuel economy. (Note: According to the EPA, the real world fuel economy can be expressed as a fuel consumption rate or an electric range that consumers are achieving in the real world [2]. The reasons why the EPA defines "real world" is because the current EPA test methods to determine fuel consumption rate or electric range does not include rear defog activation during their cold cycle FTP fuel economy evaluations)

The following sections of this paper will discuss the systematic approach taken to analyze and develop a new optimized rear defog system hereafter referred to Smart Rear Defog. Techniques such as a Design for Six Sigma (DFSS) ideal function and robust assessments will be discussed to demonstrate to what degree the smart rear defog system performs better than the traditional rear defog system. Lastly, a simulation study will be presented to validate the potential fuel economy or electric range savings that could be achieved when using the smart rear defog system vs. the traditional rear defog system.

REAR DEFOG TECHNICAL BACKGROUND

Rear defog systems are design to raise the rear glass surface temperature to a level where any condensation on the rear glass can transform from a solid state to a liquid state and/or to a vapor state. The phase change process can take several minutes depending on the amount of heat energy transferred into the rear glass by the rear defog heating system and on the temperature, quality, and the quantity of the condensation that has collected and formed on the rear glass. (see [Appendix A](#) for additional details) The function tree shown in [Figure 1](#) outlines the different sub functions that make up a rear defog system. Each sub function plays a role in meeting the needs of the customer. The paragraphs below outline that only the “Auto” sub function has the potential for optimization.

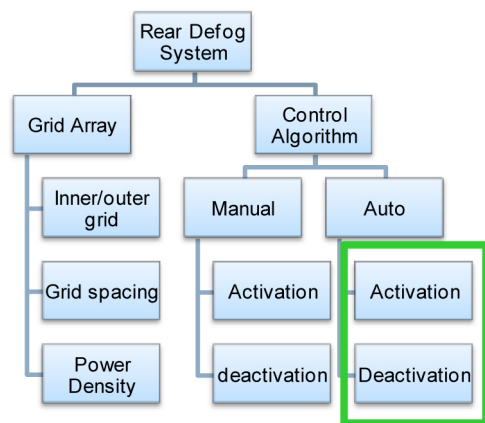


Figure 1. Typical Rear Defog System Function Tree

Grid Array

In a heated back window, electrical energy is transformed into heat energy in a grid of resistive elements applied to the glass surface. The elements form a group of parallel resistors covering the area to be defogged. The resistive elements are made of a silver frit screen printed on the glass and fired to the surface in the glass fabrication and bending process [3]. Physical parameters such as grid spacing and construction have been optimized for the most efficient heat generation and heat transfer through the glass. The amount of power

(w/m²) required to defog the glass varies with the installation angle due to heat loss from air flow over the glass. A static vehicle (with little to no airflow) requires a relatively low level of power. A nearly vertical glass such as a pick-up truck rear glass installation will have a power requirement of 500w/m² minimum while a low angle sports car window can be as high as 955 w/m². The relationship between watt density (w/m²), installation angle (degree) and defog performance was experimentally established and validated at the Delco Labs division of GM. The relationship was also empirically validated in the work performed by Nippon Sheet Glass co. [4]. [Figure 2](#) shows the optimized power density curve for a given rear glass installation as well as examples of industry minimum allowable power densities.

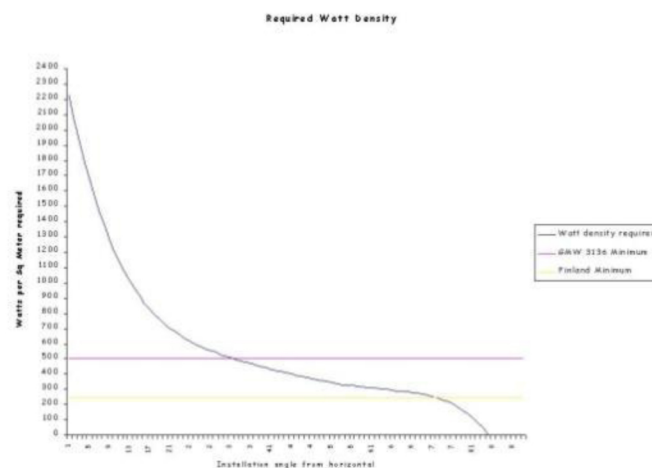


Figure 2. Relationship between power density and rear glass installation angle. (See [Appendix B](#) for a larger version)

Control Algorithm

The control algorithm has two main sub functions. The manual operation is comprised of a manual button that can be engaged and disengaged by a human operator. The ability to instantaneously activate the rear defog system is often needed when ambient conditions change quickly leading to fog or frost on the rear glass. The manual operation has little opportunity for optimization due to the simplicity of its operation. The automatic operation, on the other hand, is designed to provide the operator with some convenience features. For example, the automatic control algorithm can sometimes automatically activate the rear defogger during a remote start event or automatically deactivate the rear defogger to avoid having the system stay on too long if the operator forgets to turn it off.

When looking at the entire function tree, it appears that the only function with the potential for optimization is the automatic activation and the automatic deactivations sub functions.

SMART REAR DEFOG SYSTEM

The smart rear defog system is an enhancement to the traditional rear defog system in that it optimizes the operation of the automatic activation and the automatic deactivation sub functions to improve real world fuel economy (or electric range) while maintaining customer defog performance expectations. The enhancements conceived for the smart rear defog system were inspired by two lateral technologies. For the automatic activation function, the vehicle's front windshield fog detection system was considered. This system uses sensors to determine the dew point temperature of the air near the surface of the glass. A determination of risk of fog is established when comparing the temperature of the windshield to that of the ambient air dew point temperature near the glass. When the risk of fog is high, heated air is blown over the glass to raise its temperature above the dew point temperature. For the automatic deactivation function, the household electric toaster was considered as a lateral technology. During the past 50 years, the electric toaster has employed a temperature activated extraction mechanism that ejects the toasted bread and turns off the power going to the electric coils. This approach makes the process of grilling bread robust to bread type, bread initial temperature, bread thickness, and bread size. Previous to this technology, the toaster used a fixed based timer that often led to customer complaints regarding burned toast.

The enhanced smart rear defog system uses these two lateral technology examples in the following way. For the auto activation feature, calculations are made to determine the probability of condensation on the rear glass similar to the front windshield fog detection system. The customer convenience feature of automatic rear defog activation will have an improved real world fuel economy or electric range value when the system is activated when the risk of condensation is high vs. the traditional approach of activation when the outside ambient temperature is lower than a predetermined threshold. Similarly, deactivation of the rear defogger using a temperature based system, like the toaster, has the potential of improving fuel economy and electric range if the rear glass surface temperature reaches the desired rear glass temperature threshold before the expiration of the traditional fixed based timer used in vehicles today.

Technical Details

The relative positions of the important physical devices that comprise the smart rear defog system are shown below.

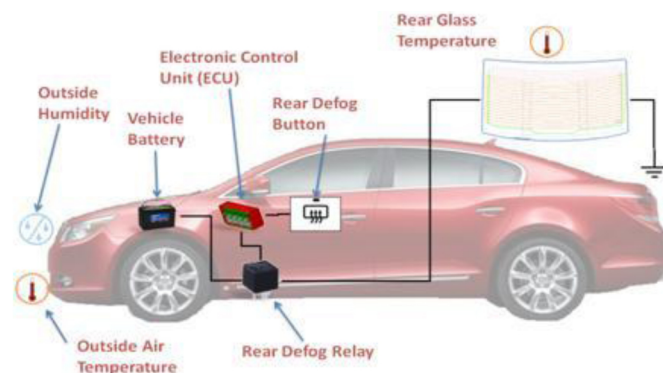


Figure 3. Relative position of key rear defog components

Critical inputs

Rear glass surface temperature can be obtained by physically mounting a temperature sensor on the surface of the rear glass. Ideally, the sensor is mounted on the exterior surface of the glass between any two of the electric grid elements. Although this location is not physically practical (packaging, durability, esthetics, etc...) it does represent the element of glass that is the farthest from the heat source (i.e. when equipped with a rear defog grid). Alternatively, the rear glass surface temperature can be estimated using a passenger compartment thermal heat energy model which uses existing sensor inputs such as the HVAC module's duct air temperature sensors, the passenger compartment air temperature sensor, the solar intensity sensor, the outside air temperature sensor, etc... For the purpose of this paper, no further mention will be made regarding a heat energy model and the estimate of the rear glass surface temperature. Instead, the assumption will be made that the rear glass surface temperature is obtained using a physically mounted rear glass surface temperature sensor that is located between the rear defrost grid elements on the outside surface of the rear glass.

Outside air Temperature (OAT) can be obtained by physically mounting a temperature sensor outside the vehicle under the front grill.

Outside Ambient Air Humidity can be obtained by physically mounting a humidity sensor located someplace on a vehicle that is in direct contact with outside air (e.g. co-located with OAT sensor or co-located with air induction temp sensor). This humidity sensor can be used in conjunction with these temperature sensors to compute an approximate value for the outside air dew point temperature.

Vehicle Speed can typically be obtained from the vehicle's Controller Area Network (CAN) data and is required to estimate the amount of convective heat loss due to the air moving across the exterior surface of the rear glass.

Control algorithm

The electronic control unit (ECU) contains the rear defog algorithm. Figure 4 is a flow diagram for the Smart Rear Defog algorithm which is located inside the electronic control unit (ECU).

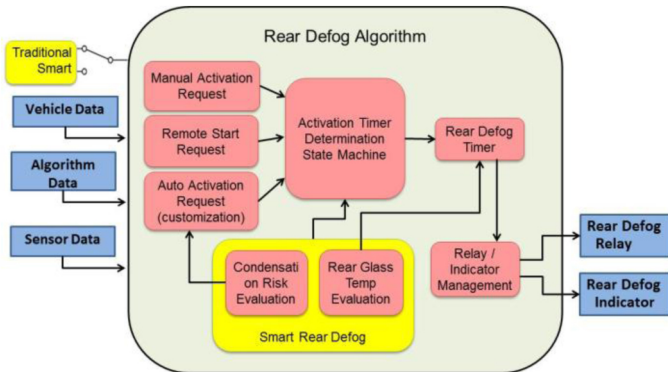


Figure 4. Smart Rear Defog algorithm flow chart

At a high level, the algorithm receives multiple inputs such as button press, outside air temperature, outside air dew point, and vehicle speed. An activation request is determined using the input data that enters into the model. Similarly, the duration of the activation timer is predicted using the input data that enters the model. The activation timer value is sent to the rear defog countdown timer block. The timer counts from its initialized value down to zero. The timer can be suspended or it can be stopped depending on various vehicle inputs and model decisions. When the timer is greater than zero, a rear defog relay activation request is sent to the relay/indicator management block. The actual state of the relay and the LED indicator are managed separately from the activation request and relay request so that vehicle specific human machine interface (HMI) requirements can be satisfied.

In order to allow the automatic activation request to be set to true, either a manual button press needs to occur or the estimation of the probability of condensation needs to be high at the start of a remote start event or following a key On event. The probability of condensation is determined by comparing the difference between the rear glass surface temperature and the outside air dew point temperature. If the difference is small or negative (i.e. the rear glass surface temperature is less than the outside air dew point temperature) then the probability of condensation will be high. If the difference is large and positive (i.e. the rear glass surface temperature is above the outside air dew point temperature), then the probability of condensation will be low. The equations used to determine the probability of condensation are provided below.

Let $T_{DewPoint}$ = Dew point temperature as a function of outside air temperature and outside air humidity

Let $T_{RearGlass}$ = Outside surface of the rear glass surface temperature estimated or measured

Let T_{Offset} = A calibratable customer convenience correction factor used to balance the design trade-off between fuel economy and auto activation opportunity. The larger the correction factor value, the more likely a high probability of condensation will be observed and the more likely the fuel economy will be negatively impacted.

Let K_p = A calibratable proportional gain adjustment used to scale the instantaneous response by a factor that will change the output to be closer to the ideal performance response.

If $(T_{RearGlass} - T_{DewPoint}) * K_p - T_{Offset} \leq 0$, Then Probability of Condensation is High -> Allow auto activation

If $(T_{RearGlass} - T_{DewPoint}) * K_p - T_{Offset} > 1$, Then Probability of Condensation is Low -> Prevent auto activation

The deactivation of the rear defog system can be executed when the rear defog button is pressed or the vehicle run mode is switched ACC or OFF. Alternatively, when the countdown timer has elapsed (meaning the timer value is equal to zero) the rear defog system will automatically shut off. The timer can also be forced to value of zero if the rear glass surface temperature is evaluated to a value greater than a predetermined temperature threshold value (e.g. 5°C). The equations used to determine the when to force the rear defog timer to zero are provide below.

Let $T_{RearGlass}$ = Outside surface of the rear glass surface temperature estimated or measured

Let $T_{GlassThreshold}$ = a calibratable rear glass temperature threshold at which point any condensation on the rear glass will, on average, be liquefied.

If $T_{RearGlass} \geq T_{GlassThreshold}$, Then set countdown timer value = zero

ROBUST ASSESSMENT

A Design For Six Sigma (DFSS) robust assessment was conducted to determine if the smart rear defog automatic activation and automatic deactivation concepts described above are more robust (less sensitive) to variations in environmental conditions and driver operation behaviors than other concepts such as today's traditional approach. The

winning concept was selected based on its ability to transfer the heat energy provided by the rear defog heating elements into useful energy to liquefy the condensate on the rear glass while minimizing the amount of energy rejected to the ambient environment. It was also selected based on the amount of convenience it provided the customer. Inherently, the winning concept will improve the vehicle's real world fuel economy and minimize the amount of interaction the system has with the vehicle's occupant(s).

The robust assessment was conducted inside a climatic wind tunnel to evaluate the robustness of various concepts. Although some real world environmental conditions could not be replicated (such as radiation to the night sky), the facility did provide a stable and repeatable mean for setting the normally uncontrollable noise factors that influence the performance of the rear defog system during normal everyday use. The noise conditions used in the study are listed below.

External Noise

- Outside ambient air temp (-20°C , -7°C , $+2^{\circ}\text{C}$)
- Condensation on rear glass (none, $0.08\text{ml}/\text{cm}^2$ on outside glass, interior fog on inside glass ($70\text{g}/\text{h}/\text{seat} \times 40\text{ min}$))
- Outside Air Relative Humidity (50%, 95%)
- Vehicle Operating State (Heat loss from rear glass while idling, stop/go city traffic, highway driving)
- Solar irradiance (none, $700\text{ W}/\text{m}^2$)
- Cabin temperature (cold start, pre heated to 23°C)
- Customer usage (vehicle off and soaking at ambient for 2hrs vs 40 minutes)

Internal Noise

- Effects of wear of the rear defog grid (2008 built engineering durability vehicle vs. 2010 built new production build)
- Vehicle Type (different rear glass angles)

Manufacturing Noise

- Manufacturing noises such as deviations from the nominal grid spacing or resistance output were not evaluated.

In order to simplify the experiment, surrogate noise strategies were used to combine many of the noise factors. Vehicle Type (e.g. sedan vs. SUV) was used to combine the effects of wear, glass angle, and the effects of cabin temperature. FTP-like City and Highway driving schedules were used to invoke effects of vehicle operation states.

The actual test runs were constructed to have three segments; a preconditioning segment, a static soaking segment and a dynamic drive segment. The precondition segment fixed the settings for ambient air temp, relative humidity and precipitation quantity. The static soaking segments were set to either 2hrs or 40minutes with the vehicle in the OFF state during the soak. The dynamic drive

segments were set to either idle, city schedule or highway schedule with the rear defogger active. The test stopped when the rear glass condensation was completely liquefied or when the rear glass surface temperature reached 10°C .

The "actual" rear glass clearing performance was determined manually using a digital video camera, an LED and a graduated scale marked on the rear glass. First, a camera which records digital video with a digital clock overlay was installed in the vehicle and was placed such that it can clearly see the graduated scale on the rear glass. An LED was also installed and placed in the view of the camera. The LED was directly tied to the power source that goes to the rear glass heating elements. When power is supplied to the rear heating elements, the LED is illuminated. The start time of the test is manually determined when the LED is illuminated. The end time of the test is determined when the rear condensate on the rear glass is 100% liquefied or when the rear glass reaches 10°C . The progressive glass clearing performance is also measured by logging the time to liquefy the condensate to 35% and 65%. Markings on the rear glass help to determine the % of liquefaction. (see [Appendix C](#))

Ideal Functions and Concepts

Two distinct ideal functions were studied during this robust assessment to evaluate the effectiveness of the signal/response relationship in the presence of noise factors for the different concepts. A concept that is efficient in transforming an input signal into a response signal will use less energy and minimize the potential for undesired symptoms. Similarly, a concept that is consistent in transferring an input signal into a response signal is less susceptible to noise factors and less likely to have undesired symptoms.

For the automatic activation system, the ideal function uses a measurement thinking approach. The input signal is the difference between the observed (actual) rear glass surface temperature and the observed (actual) outside air dew point temperature and the response is the difference between the system estimated (measured) rear glass surface temperature and the system estimated (measured) outside air dew point temperature. For the automatic deactivation system, the ideal function also uses the measurement thinking approach. The input signal is the energy provided to the rear glass to liquefy the condensate on the rear glass and the response is the actual energy required to liquefy the condensate on the rear glass. Since the power provided to the rear glass remains constant during each test, the "time" to liquefy the condensate on the rear glass was used as a surrogate for energy. If the rear defog system remains on too long, too much energy will be provided at the rear glass and the system will use more energy. If the rear defog system does not remain on long enough, the rear glass condensate will not liquefy and will require multiple manual reactivations. The p-diagram below highlights the transfer function, input signals, the uncontrollable noise inputs, the concepts and the undesirable symptoms.