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DOMUS

Design OptiMisation for efficient electric vehicles based on a USer-centric approach

DOMUS – Deliverable Report

D1.2 Assessment Framework

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1 Publishable summary

This document describes the framework by which the DOMUS vehicle will be virtually assessed. Additionally an excerpt is given of what the testing conducted in DOMUS will be focused on. Specifically, the document describes the assessment activities for either a passenger vehicle, or a change to the configuration or control system of the passenger vehicle. The assessment framework incorporates a set of scenarios under which the vehicle might find itself and a fitness function over time in terms of the design objectives of minimizing energy consumption at an acceptable safety level and holistic comfort.

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2.2 Abbreviations

3 Introduction

This report describes the framework by which the DOMUS vehicle will be virtually assessed. This framework incorporates scenario specifications as well as a novel fitness function that takes into account the design objectives of the project.

3.1 Relationship to the DOMUS project objectives

The aim of the project is to increase the driving range or minimize the energy consumption while maintaining an acceptable comfort level and safety. However, these three variables are not independent of one another, and hence an attempt to, say, decrease the energy consumption may end up decreasing the comfort to an unacceptable level. This document provides a framework for safety, energy and comfort assessment of a combined car cabin and climate control system, by formulating the problem as a multi-objective optimization. It provides a means by which the consolidated improvements from other work packages will be assessed in terms of the overall design objectives of minimizing energy consumption, while maintaining an acceptable safety level and holistic comfort.

3.2 Relationship to other work packages

The assessment framework aims to define a user-centric framework that will be used by other work packages: WP2.2, WP2.3 and WP5.2.1 – to identify whether one cabin comfort system performs better than another. Cabin comfort system refers to the combination of the physical cabin environment, the heating and cooling subsystems, and the control system that governs them. In the above context, "performs better" means that energy is minimized, safety is maintained, and comfort is acceptable. The assessment framework will be used in WP5 to tune the control logic to perform the online control of the comfort system and in WP2 to optimize the selection of cabin elements and subsystems and also to provide a basis for the virtual assessment of novel cabin designs. Moreover, this assessment framework provides a basis for the design assessment framework in WP2 which is detailed in Section 7.

3.3 Terminology

3.3.1 Use case

A use case involves a person (can be a fictional person or actors) interacting with the car or the car's comfort system under certain circumstances. A use case may involve characterizing and naming the individuals (such as, Albert – the 55 year old, married, empty nester). A use case may specify aspects related to the situation (such as "it's a shopping run") that imply things about the car's use and the user's likely set of requirements.

3.3.2 Scenario

A scenario or test case is distinct from a use case as it contains specific details that relate to the set-up of a simulation run. In principle, each use case should relate to at least one scenario. For example, the scenario might be specified as follows: driver plus one front passenger; external ambient temperature 5C; internal temperature initially 8C; internal humidity 95%; rainy weather; duration 20 minutes; drive starts in 3 minutes.

3.3.3 Driving condition

The driving condition is a typical and unique driving instance that is defined by the outside temperature, humidity, trip distance, time of day, status of window, etc., without having to specify explicit values for these parameters. The driving condition affects a user's perception of comfort, their energy usage behavior and their overall safety perception.

3.3.4 Experimental use case

An experimental use case is a condensed version of a use case, which describes the conditions for the human-in-the-loop experimentation toward developing a holistic comfort model. One experimental use case consists of a number of experimental and controlled factors, which are further defined in section 4.

3.4 Motivation

Existing vehicle comfort assessment methods proceed by performing some variant of the following test:

1. The vehicle is stored in a climatic wind tunnel (CWT) for a period of time to bring the ambient and internal temperature to either a low temperature (e.g., -18C) or a high temperature (e.g., 43C). These two tests are referred to here as warm-up and cool-down, respectively.
2. The HVAC system is set to “auto”. The car is started, and the fans are set to maximum airflow.
3. Temperatures are monitored until a comfortable temperature is achieved. The test result is simply the time taken (referred to as the “time to comfort”).

While this test approach is simple and effective at identifying common problems with the HVAC system, there are several problems with it:

1. The test conditions are atypical. Users do not always use maximum fan rates. Temperatures are at the extreme range, while in ordinary use, more time will be spent at milder temperatures.
2. It does not consider subjective comfort. Even simplified mathematical models of comfort, such as Nilsson’s Equivalent Temperature, would better represent subjective comfort as they account for other factors (such as clothing and radiant heat).
3. It considers all uncomfortable situations to be equally uncomfortable. e.g., a comfort system that provides comfort after 10 minutes will be considered equivalent to any other system that provides comfort after 10 minutes no matter how uncomfortable the user is during the first 10 minutes.
4. It does not consider how well comfort is maintained after being achieved.
5. It does not support the case for pre-heating the car cabin.
6. It does not consider the effect of different passenger locations.

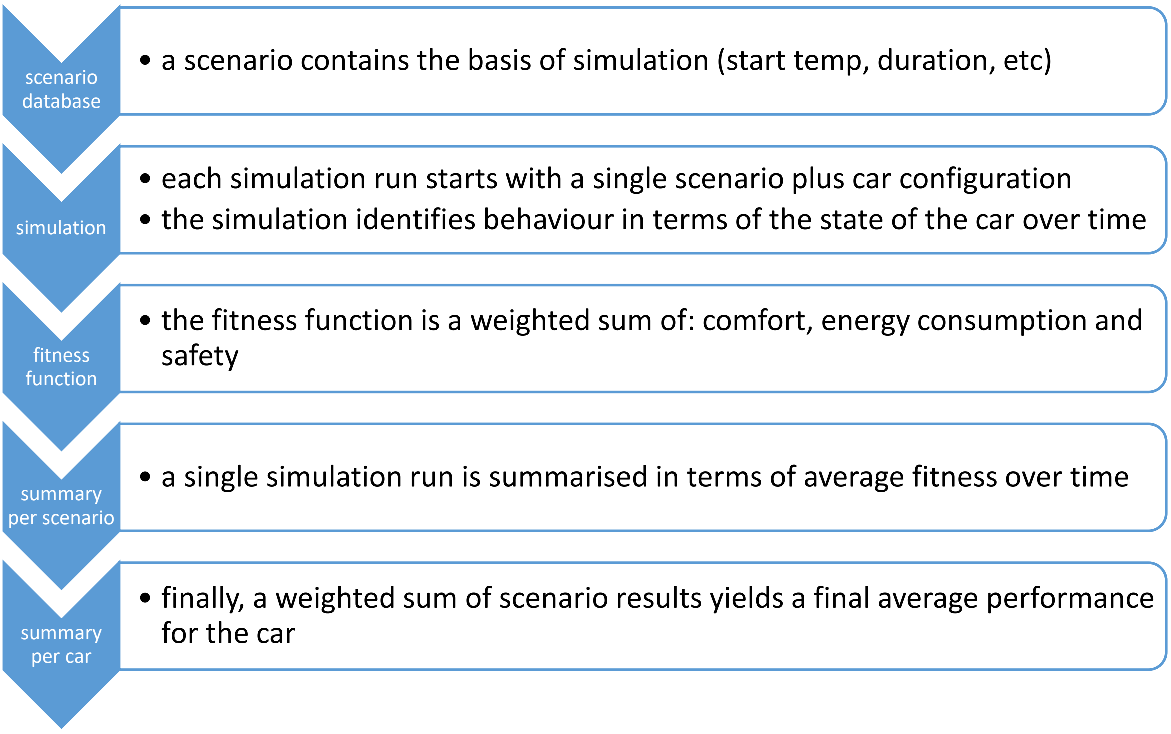
Thus, there is a need for an improvement to the traditional assessment methodology.

3.4.1 Proposed assessment method

Based on expert interviews (interview transcripts are given in Appendix B), the proposed assessment framework makes use of the following recommendations:

1. It must take into account the user’s perception of comfort.
2. The assessment method should be adjusted by experimental data.
3. If it is a holistic assessment, it needs to match the holistic user perception, i.e., a user has a perception of what fuel consumption is good or bad, what safety is acceptable or not, what is comfortable, so that they might take decisions to adjust different systems of the car based on their own perception of these variables.
4. A good assessment framework should reflect as much as possible a wide variety of users. It should take into account the variation that exists in the real population.

The proposed assessment method is summarized in Figure 1 and Figure 2. Note that the basis for this summary is to assume that the assessment occurs in simulation, however, in principle, the method could also be used in a CWT with a real car. In a CWT, however, only thermal comfort measurements are carried out, and hence other measurements related to energy consumption and safety may have to be added, if a holistic assessment is desired.



- a scenario contains the basis of simulation (start temp, duration, etc)
- each simulation run starts with a single scenario plus car configuration
- the simulation identifies behaviour in terms of the state of the car over time
- the fitness function is a weighted sum of: comfort, energy consumption and safety
- a single simulation run is summarised in terms of average fitness over time
- finally, a weighted sum of scenario results yields a final average performance for the car

Figure 1: The assessment framework is based on a simple process that begins with the set of scenarios and finishes with a single numerical value for the car.

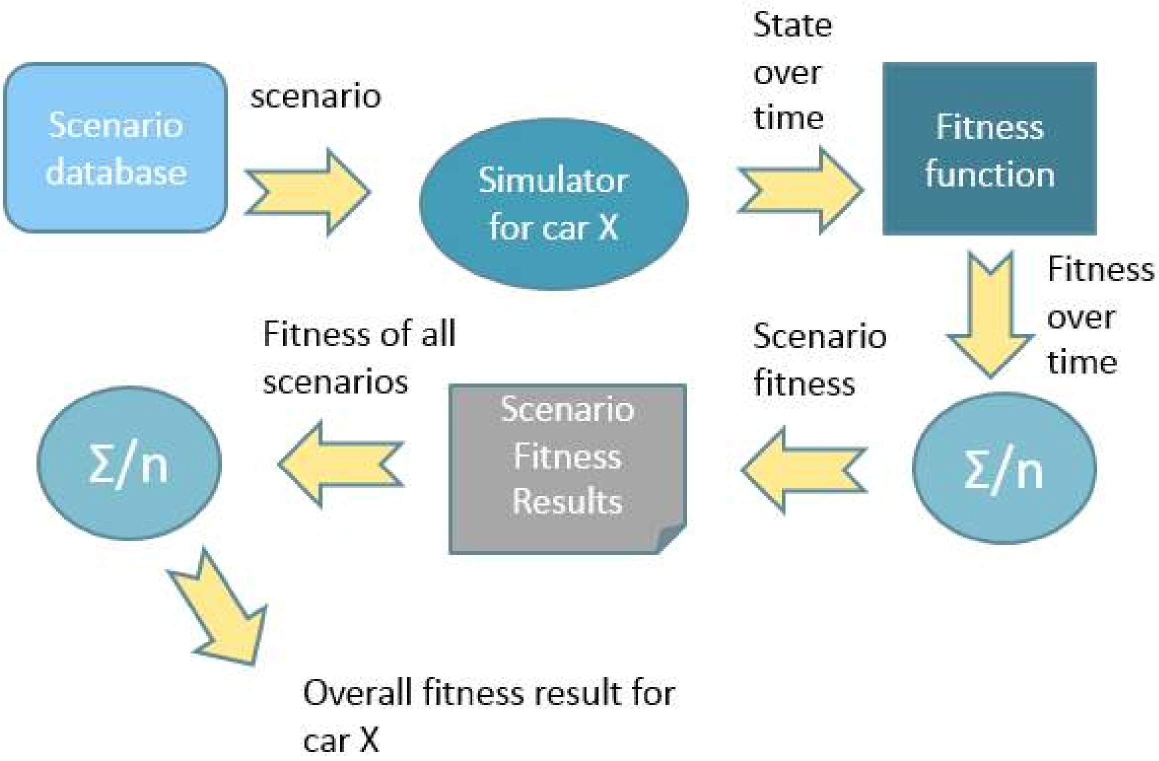


Figure 2: Assessment framework

The process begins with the definition of a scenario database. The scenario database consists of the scenario definition and a numerical weight, given in Section 6. The scenario definition is used to control the simulation run whereas the numerical weight is used to allow some scenarios to be weighted more highly in terms of their likelihood than others. For example, a particular scenario, where the inside of the car is hot, but the outside environment is cold, may be rare in practice. If a comfort system performs better in most cases but poorly in this case, it makes sense to penalize it only slightly. This weight, which represents the likelihood of the scenario, helps to ensure that the assessment method is fair.

Each simulation run must begin based on the definition in the scenario combined with the definition of the car and its configuration. Any characteristic that the simulation needs to know that is not provided by the car or its configuration must be provided by the scenario. For example, if the simulation needs to know the initial air temperature within different zones of the car, the scenario must define it.

To ensure that results are comparable, each simulation run for a particular scenario must continue for a fixed duration.

The output of simulation is the system “state” over time. By the term “state”, we mean a vector of values including such things as the air temperature within different zones, the ambient environment temperature, wind-speed, and rainfall. The domain of the fitness function is implicitly defined by the range space of this state vector, and thus there must be some alignment between the simulation and fitness function in terms of what components make up the state vector. For example, the fitness function must assess the energy use per unit time (or power). Thus, power consumption must be derivable from the state vector. Similarly, all factors that are required for determining passenger comfort (possibly at several positions within the car) must be derivable from the state vector.

The fitness function assesses the fitness of the state of the car at any point in time. The fitness function is a weighted sum of three main factors: comfort, energy use, safety. Such a holistic assessment does not currently exist in literature, and goes beyond the understanding of comfort in current comfort models. In the case of energy use, the weight is negative since energy use is generally a cost rather than a benefit.

The weights of the fitness function can also be seen as converting each factor into common units (e.g., money per unit time or $/sec). This is a useful approach since it means that the fitness function can be understood in financial terms. It also supports rationales for each weight (for example, how much you would be willing to pay to avoid discomfort per unit time).

For example, raw energy use might be expressed in terms of kWh. In basic terms, the user pays a certain amount of money for each kWh (e.g., $0.10). Furthermore, the value to the user might be higher once it is stored in the batteries, since it takes time and may be inconvenient to recharge the batteries (say, e.g., $0.20, thus, the weight associated with energy use will be -0.2 $/s/kWh). A similar approach might be used to yield reasonable weights for comfort and safety. By this process, all factors are unified into a single combined value.

While comfort is an important aspect of the assessment framework, it is not defined here. The exact definition of the comfort function will be left for deliverable WP1.3. It is important to note here, though, that comfort may need to be calculated for different passengers (not just the driver). The global comfort score will be the average score of all occupants.

Safety is defined as a binary function (1 = safe or 0 = not safe). Several factors affect safety, including air quality air temperature and lack of power due to battery overheating during a highway ride. However, a key aspect of safety that relates to the comfort system is windshield fogging, which is considered in this project. The modelling of safety in terms of windshield fogging will be developed as part of WP1.2 (holistic comfort model) and WP1.3 (3-D thermal model of car cabin). While windshield fogging is a high priority to clear, ordinary car HVAC systems cannot clear the windshield instantaneously. Furthermore, it is not the aim of DOMUS to ensure that they do. Therefore, the weight for safety can be large but finite.

3.4.2 Comparison with traditional methods

In this section, the proposed method is compared with traditional warm-up / cool-down assessment methods.

The proposed method can be seen as somewhat comparable to the traditional approach. Specifically, if:

1. traditional results gave a warm-up time of w and a cool-down of c,
2. weights for energy and safety are set to zero,
3. only two, equally weighted scenarios (warm-up and cool-down) are included in the scenario database with duration of x minutes,
4. the comfort function is set to 0 if the temperature is considered comfortable (e.g., close to 22C) and -1 otherwise,

then, following the proposed framework shown in Figure 2, the proposed method would give an average performance of $-w/x$ for the warm-up and $-c/x$ for the cool-down. Thus, the overall (averaged) summary will then be $-(w+c)/2x$. So therefore, the proposed method result will be a scaled version of the traditional methods.

The proposed method resolves the previously mentioned issues with the traditional method. Specifically:

1. Scenarios can reflect more typical environments and control system behavior. In particular, if the comfort system incorporates a penalty for acoustic noise, systems that use maximum fan levels will be penalized. Furthermore, although both hot and cold tests might be worthwhile, milder temperatures can also be included.
2. By using a comfort function and incorporating the comfort of all passengers, the proposed assessment method better accounts for subjective comfort.
3. Rather than a binary comfort function, the assessment method supports a real-valued comfort function that reflects degrees of discomfort rather than simply comfortable / uncomfortable.
4. To take into account the maintenance of comfort, scenarios can be included that begin from an already comfortable situation.
5. Pre-heating and pre-cooling can be assessed fairly by including scenarios that support a planned drive with an allowed preparation time.
6. The assessment framework supports scenarios that include multiple passengers and a comfort function that can estimate subjective comfort for different passenger locations.

4 Definition of experimental use case – what does influence comfort?

Since the proposed fitness function incorporates energy consumption, safety and holistic comfort, this section details the procedure by which the identification of factors which influence holistic comfort was made. These factors would then be measured and related to the holistic comfort as part of the virtual assessment.

To proceed, an empirical approach was taken to define one general experimental use case (see Section 3.3.4). One prototypical experimental use case consists of different experimental and controlled factors like the in-vehicle thermal and acoustic characteristics. This definition of an experimental use case excludes factors which are too complex to simulate, like real driving conditions with e.g. fast changes of temperature, critical situations, mood or realistic sun-radiation and wind through an open window. The focus of this section therefore lies on factors, which are relevant in an experimental setup and are believed to influence thermal comfort and to be useful for the overall goal of DOMUS. Due to the complexity of human comfort perception and the focus on thermal and acoustic comfort, the identification of relevant factors for the DOMUS-project needed a careful adaptation and clear terminology.

The following terminology was defined during the development process:

Baseline: A basic experimental use case, which serves as a base for every testing and which consists of controlled and experimental factors.

Controlled factors = observed factors: Factors, which need to be considered in every testing in DOMUS. They are more or less controllable, but have to be in a certain range and measured. They can influence the dependent variable, but are not manipulated empirically.

Experimental factors: clear factors that will be experimentally researched by one or more partners.

Independent Variable: Factors, that are manipulated and hypothetically cause systematic variance in the expression of the dependent variable.

Dependent Variable: The expression of the dependent variable hypothetically depends on the manipulation of the independent variable. Factors that are observed and influenced by independent and controlled Variables. The effect of the experiment, mostly a comfort vote due to a perceived comfortable environment (pleasant or unpleasant temperature, noise level etc.)

4.1 Introduction and Background

For a differentiated view on influencing factors and the purpose of understanding thermal comfort better, several partners agreed on adopting an experimental approach. Each participant will test different factors in their facility and should ensure the collected data is comparable and fits the simulated model that will be developed later. The testing conditions should be based on use cases regarding the user's perspective. To achieve this goal, an online-survey and two workshops were conducted and, according to the General Agreement, a list of use cases was defined after defining and prioritizing relevant user scenarios. This list of experimental use cases was further distilled into one detailed, general experimental use case, rather than many undetailed use cases through a three step approach. The presented factors (influences on thermal and acoustic comfort) in Figure 4 are a result of this three steps.

The first step towards defining the experimental use cases was an online-survey to **gather** a broad set of use cases from all partners. The results were compiled into a matrix of categories, which are described in section 4.1.1. This matrix, consisting of categories, which signify a collection of influencing variables, was further specified and **organised** in a second step in a workshop in Brussels, described in section 4.1.2. After this reorganisation and reduction of the number of relevant categories, the final list of experimental use cases was deduced through a **prioritisation** step (see section 4.1.3). In this final workshop, the attendees decided to condense a long list of experimental use cases to one general baseline (see section 5.1.4). Over the course of the chosen interdisciplinary three-step approach, the consortium was encouraged to and did take part in the discussions, so that a diverse development process could be granted. This procedure was chosen to make use of the different expertise prevalent in the consortium and is displayed in Figure 3.

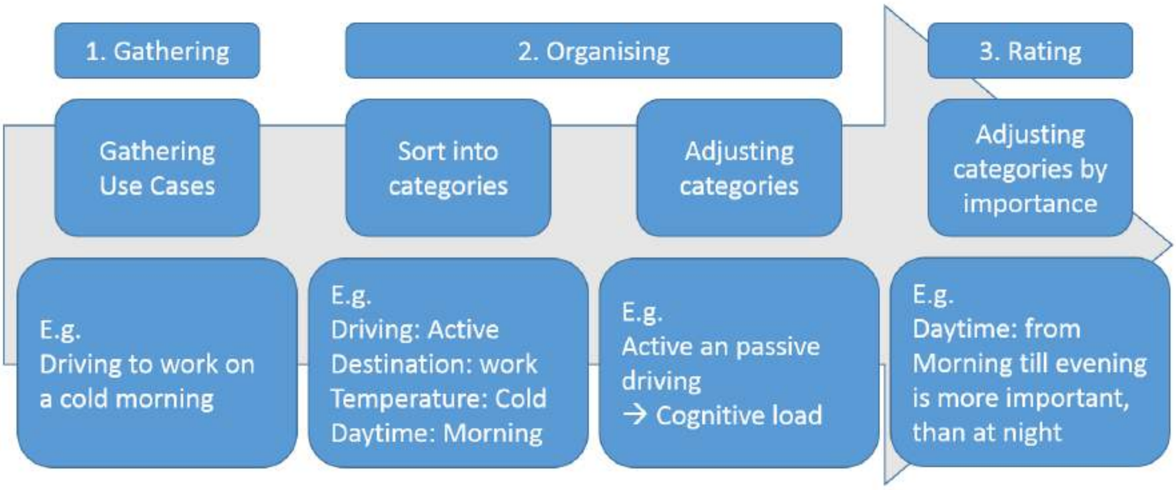


Figure 3: Development of experimental use cases through a three-step approach

4.1.1 1st Step: Online Survey in January 2018 – **Gathering**

To identify relevant use cases for the DOMUS-project, ika set up an online survey with open questions to interview the whole consortium. The consortium was required to phrase suggestions of potential use cases by using everyday terms, in order to make for an easy understandability. A total of 32 uses cases were formulated with a broad diversity. Similarities were sorted out (e.g. below freezing = below 0°C) and keywords were gathered to build categories of environmental conditions (e.g. temperature: freezing, hot, moderate). Those categories were the basis for the subsequent analysis. Clustering those categories into reasons (e.g. season and humidity are external reasons, where age and gender are personal reasons) helped in getting a better overview of the gathered information. The gathered categories and the proposal for organisation were discussed and developed in the next step in Brussels.

4.1.2 2nd Step: Workshop in Brussels in February 2018 – **Organising**

The goal of this workshop was an organisation of the categories gathered earlier to identify relevant influences on thermal and acoustic comfort. The idea was to determine relevant categories and exclude irrelevant influences. The workshop participants organized the categories with respect to how important it was in their opinion that the categories would be relevant for the future simulation and later vehicle concept developed in DOMUS. Every category (e.g. temperature or age) with its expressions (e.g. hot, warm, neutral, cold) was discussed and either accepted, cancelled or adjusted.

During this process, the general term *use case* was discussed and the focus set to *experimental use cases*, which are testable within the DOMUS-project due to technological constrains. During the definition of terms, the attendees decided for fictional *design use cases* and other similar expressions (e.g. *prototype use case*) to be out of focus for this specific development. Experimental use cases should sketch situations and challenges of an EV (e.g. cold environment) and not solve a given situation (e.g. the vehicle is well insulated). This was done in a way so that a list of experimental use cases will be an orientation of what the consortium members can tackle with an empirical study. According to this goal, the present partners committed to aim for categories, which are situational (e.g. temperature or daytime). Categories regarding the car (e.g. insulation or noise level) were excluded, because those are already part of a technical solution. Some personal categories (e.g. mood or number of cars in household) were also excluded, because those are out of focus for the further analysis. The organising of the gathered results could not be finished in this workshop and a final list of experimental use cases was not created. A third step was necessary for prioritising the different categories. Therefore, the result was a preliminary and distilled list of categories, from which experimental use cases can be extracted.

4.1.3 3rd Step: Workshop in Aachen in April 2018 – **Prioritisation**

In order to make for proper empirical testing in DOMUS, this workshop focused on the categories, which can be manipulated or measured in the experiments. The goal was to formulate a list of 1-10 experimental use cases, onto which the experimentation can be based. This was achieved by a prioritisation of the earlier gathered and organised categories. The leading question of the workshop was if one certain experimental use case should be included in DOMUS or abolished, because another one was more important.

Using the distilled list from the second step, the attendees were to formulate experimental use cases and quickly realized that a general prioritisation was not feasible, since the number of possible experimental use cases would be too high and a clear weighing of categories depends on the individual preference. Additionally, many categories are interdependent (e.g. temperature and daytime). Following this, the goal of the workshop was adjusted and the list of categories was split into two groups: Experimental and controlled categories.

Assuming that every category influences the thermal comfort, the categories are from now on called experimental factors (manipulation) and controlled factors (testing environment). Every category from the earlier two steps was discussed one last time and either put into one of the two groups or excluded from further development. The result of this process is displayed in Figure 4. Here, all relevant factors for experimental use cases are displayed and their expressions sketched (e.g. a subject’s sensitivity to temperature from minimum to maximum). If one partner has a valid reason to focus on a certain category and plans to manipulate it empirically, then the category is marked as an experimental factor and promised to research this further.

Through all factors, one general baseline, where every partner can base their experiments on is highlighted. This baseline marks an expression on every factor which is in most cases a neutral value (e.g. wind: almost nothing) or a reasonable distribution (e.g. age: reasonable distribution).

It was decided that one general baseline would be sufficient for the experimental use cases instead of a long list with a high number of different experimental use cases. This decision was due to a better comprehensibility of the baseline instead of a list and a modification of factors. Starting from the baseline, each facility is going to change different variables that are listed as the experimental factors, while at least surveying or controlling each other mentioned (controlled) factor. The aim for the partners is to test the baseline condition and then manipulate certain experimental factors (see figure 4).

The results of the approach described in the present section serves as guideline for the experimental protocol in DOMUS. As Deliverable 1.3 will further specify the experimental setups from the different partners, the results of deliverable 1.2 will serve as basis. With this procedure, each experiment will be enabled to get compared to the baseline condition in order to create a deeper understanding of thermal and acoustic comfort. Concluding the presented development process, every factor is briefly explained in the following subsection.

Figure 4: Baseline experimental use case

4.1.4 Results

In the workshop at ika, every partner agreed upon one general baseline. The factors, which are included in this baseline, were carefully gathered, discussed and changed during the three steps described above.

The following baseline was created:

Baseline = Controlled factors + experimental factors

Controlled factors (in Baseline) = Sensitivity to temperature (can be measured through a questionnaire) + Age (reasonable distribution) + Gender (reasonable distribution) + Clothing (reasonable for temperature) + no history (as much as possible, season, outside weather and temperature needs to be measured) + no purpose (other than participating in an experiment) + no passengers (only one subject is measured at a time) + no preconditioning (not as an experimental condition, only for acclimatisation on indoor air) + daytime (regular work time) + low lighting (light is low for the surrounding) + fan is on, but on a low scale (no airflow at all is impossible, but it should be reasonable few airflow) + reasonable humidity (reasonable for temperature in a certain range) + no traffic (no mental stress) + A, B, or C Segment vehicle (size of cabin should be measured

Experimental factors (in Baseline) = long exposure + quiet environment (reasonable low) + engaged in task + no radiation (reasonable low) + neutral temperature

Starting from the baseline, every facility is going to change different variables that are listed in the experimental factors. All participants agreed that it is crucial to control for demographic data and align this with every facility.

5 Fitness function

As part of the proposed assessment framework, the fitness function assesses the fitness of the state of the car at any point in time.

For any given scenario, therefore, the scenario fitness function is the average of the instantaneous fitness function over all time steps in a given simulation period (Fig. 2), i.e.,

$$F = \frac{1}{T}\int_{0}^{T} f(t)\ dt \qquad (0)$$

where F is the scenario fitness function, $f(t)$ is the instantaneous fitness function at any time t, and T is the simulation period.

The fitness function is a function of three main factors: comfort, energy use and safety. Of these three factors, we desire to reduce the energy use, maintain the comfort perception at an acceptable level, while making sure that the vehicle or its occupant is safe, regardless of the energy consumption and comfort perception.

Therefore, mathematically, the fitness function for a given scenario should be defined such that:

$$\min E \qquad (1)$$

$$\max C \qquad (2)$$

$$\text{subject to:}$$

$$S = 1 \qquad (3)$$

where,

$$E = \frac{1}{T}\int_0^T e(t)\ dt,\ C = \frac{1}{T}\int_0^T c(t)\ dt,\ S = \frac{1}{T}\int_0^T s(t)\ dt \qquad (4)$$

$e(t)$ is the energy consumption at time t, which is given by the instantaneous power multiplied by its duration.
$c(t)$ is the holistic comfort at time t, and
$s(t)$ is a measure of the safety at time t, e.g., in terms of the percentage of an area of the windshield defogged by time t.

Note that $e(t)$, $c(t)$ and $s(t)$ are not meant to be defined in this framework, however they should be defined such that:

1. S gives a binary safety score that indicates whether the safety is acceptable or not acceptable. $S = 1$ indicates that it is safe and $S = 0$ indicates unsafe. For example, the safety $s(t)$ can be defined such that $S = 1$, if a safety standard – such as 90% of vision area A shall be demisted in 10 minutes – is met during the simulation period.

2. C gives a binary comfort score that indicates whether the cabin occupant is comfortable (holistically) or not. $C = 0$ indicates that it is comfortable and $C = -1$ indicates uncomfortable. For example $c(t)$ can be defined such that $C = 0$, if a certain comfort criterion is met during the simulation period – such as comfort should be achieved, say, 70% of the time. The exact definition of what is an acceptable comfort is left to WP1.2.

The equation (3) is the constraint that ensures that the vehicle or its occupant is always safe.

The fitness function commonly has the interpretation of a utility function which we desire to maximize. Therefore, the fitness function should be defined as a single function which, upon maximization, ensures that the expressions in $(1), (2)$ and (3) are all satisfied. To obtain this function, we may first combine (1) and (2) into a single-objective optimization problem by linear scalarization [1].

Mathematically, this can be defined as follows:

$$F^{-} = w_c C - w_e E \qquad (5)$$

where,
F^{-} is the fitness function without the safety consideration, and $w_c, w_e > 0$ are the weights associated with comfort and energy consumption, respectively. The weights w_c, w_e are unknown, and the process of their determination is given in Section 5.4 to 5.6.

By including the safety constraint of the relation (3), the fitness function is defined to ensure that:

$$\begin{aligned} &\max F^{-} = w_c C - w_e E && (6) \\ &\text{subject to:} && \\ &S = 1 && (3). \end{aligned}$$

Thus, the fitness function, defined as F, can be appropriately defined as the Lagrangian [2] of the expressions in (5) and (3), given by:

$$F = w_c C - w_e E + \lambda(S - 1) \qquad (7)$$

where $\lambda > 0$ is the Lagrange multiplier. Notice that, by equation (7), the fitness function is maximized when the comfort is maximized, the energy consumption is minimized and the safety is equal to 1. Minimizing the energy consumption consequently leads to an increase in the driving range.

Given that the three factors have different units (i.e., energy consumption in kWh, safety and comfort being dimensionless), the scenario fitness function also serves to bring the factors to a common unit. In this regard, the fitness function can be thought of in financial terms, and can be expressed in terms of \$. The units of the weights w_c, w_e and λ should therefore be appropriately chosen such that equation (7) is dimensionally correct. We consider now the three factors of energy consumption, comfort, and safety, and what their respective weights signify.

5.1.1 Energy consumption

The nominal energy consumption of a typical vehicle may be quoted in terms of kWh/km, e.g., 17kWh/100km. Therefore, a 17kWh/100km vehicle travelling at an average speed of say, 96km/h, will have on average a power consumption of $17 \times 96/100 = 16.32$kW or 16320 Joules/sec and an average energy consumption $e(t)$ of 16.32kWh in an hour trip. This implies that the weight associated with energy consumption w_e has to have a unit of \$/Joule, or equivalently \$/kWh. Therefore if the fitness function were considered in terms of its monetary value, then the weight w_e has the implicit interpretation as the unit cost of energy.

5.1.2 Holistic comfort

The holistic comfort $c(t)$ may be stated in terms of a numerical scale. The exact mathematical definition is left for deliverable WP1.2 (holistic comfort model) . The holistic comfort is however dimensionless. Thus, the weight associated with comfort w_c may be given in terms of \$, and can be interpreted as the amount (in dollars) required to raise or reduce the holistic comfort vote by one point, if the fitness function were considered in terms of its monetary value.

5.1.3 Safety

A key aspect of safety that relates to the comfort system is windshield fogging. The exact definition of the safety model will be left for WP1.2 and WP1.3 (3-D thermal model of car cabin). While windshield fogging is a high priority to clear, ordinary car HVAC systems cannot clear the windshield instantaneously. For this reason, safety standards are stated as, for example: 90% of vision area A shall be demisted in 10 minutes. This implies that the measure of safety $s(t)$ can be express in terms of the percentage of windshield cleared in vision area X per unit time. Since S is dimensionless (0 or 1), the weight associated with safety, λ, which is the Lagrange multiplier, may be expressed in terms of \$, which is the amount (in dollars) required to clear 90% of a foggy windshield in 10 minutes, if the fitness function is interpreted as a monetary value.

5.2 Normalized fitness function

Without an appropriate choice of the set of weights, the fitness function, as defined in Equation (7), can easily be dominated by either one of the three factors, given that the factors have different ranges of values. For example, for a vehicle whose energy consumption is $E = 16320$ Joules/sec, with an acceptable comfort of $C = 0$, and for which $S = 1$, the energy consumption easily dominates the fitness function evaluation, if all three weights have the same numerical value. Thus, it is important to choose the weights w_e, w_c, λ delicately such that all three factors contribute significantly to the fitness function.

However, unlike the weight w_e, which has the easy interpretation as the unit cost of energy, the weights w_c and λ can be difficult to determine precisely. EV users or experts may not easily define the amount (in dollars) necessary to change the holistic comfort vote by one point, which is w_c, or the cost (in dollars) associated with completely clearing a foggy windshield in a given time interval;, which is w_s. Another objection is that, users are more willing to pay for an extra range as compared to the time to comfort or safety which they consider as a given, due to regulation norms.

An alternative to the fitness function in Equation (7), which eliminates the above problem, is to standardize or normalize each of the factors, so that they are dimensionless, and they have roughly the same range of values. This procedure is known as feature scaling or data normalization. While there are different ways to perform feature scaling, the particular method used in this document is "min-max scaling". The normalized score x_n of any parameter x by min-max scaling is, by definition, given as:

$$x_n = \frac{x - \min(x)}{\max(x) - \min(x)} \qquad (8)$$

The expression in (7) ensures that all possible values of the normalized parameter x_n are constrained in the interval [0,1].

Other feature scaling methods such as “standardization” may also be employed. For the parameter x, the standard score is, by definition, given by:

$$x_s = \frac{x - \mathrm{mean}(x)}{\text{standard deviation } (x)} \qquad (9)$$

One advantage of standardization over min-max scaling is that the latter method tends to lose information regarding outliers in the data, since it constrains all possible values into the interval [0,1], whereas standardization leaves the parameters unbounded. However, for our purposes, the mean and standard deviation of the comfort C, energy consumption E and safety S are not trivially known, and would require detailed experimentation to identify. On the other hand, the minimum and maximum values can be determined by definition, as shown in Section 5.2.3, hence the choice of min-max scaling.

After normalization by min-max scaling, the weights assigned to the factors of comfort and energy consumption, can therefore e interpreted as the *relative importance* the user attaches to the factors. These weights may be obtained through an online survey, focus groups or expert interviews. Here, respondents may simply be presented with several driving conditions, so that they rate each of the factors of energy consumption, thermal and acoustic comfort on a 1 – 10 scale. An exception is the weight assigned to safety, which is the Lagrange multiplier, which should not be based on user preferences, but has to be obtained via the maximization of the fitness function. The implication of this is that the weights could, in fact, be variable depending on the driving scenario. However, an indicative value may be found for each of them as, for example, a sum weighted by the likelihood of the different driving conditions, in order to keep the fitness function simple.

The normalized fitness function is given below as:

$$F_n = w_c C - w_e E_n + \lambda(S - 1) \qquad (10)$$

where,
E_n is the normalized energy consumption.

$$E_n = \frac{1}{T}\int_0^T e_n(t)\ dt \quad and \quad e_n(t) = \frac{e(t) - E_{min}}{E_{max} - E_{min}} \qquad (11)$$

where

$$w_e + w_c = 1, \qquad w_e > 0, \qquad w_c > 0, \qquad \lambda > 0 \qquad (12)$$

Note that the comfort and safety scores do not need to be normalized as they are already in the interval $\{-1, 0\}$ and $\{0, 1\}$. From the above definition of the fitness function, the maximum instantaneous fitness function value would be:

$$F_n^{max} = 0 \qquad (13),$$

whereas the minimum value would be:

$$F_n^{min} = -w_c - w_e - \lambda \qquad (14).$$

Moreover, the following special cases might be of interest:

5.2.1 Case A

A vehicle which maximizes the comfort and minimizes the energy consumption, but is not safe. In this case, the instantaneous fitness function would be $F_n = -\lambda$;

5.2.2 Case B

A vehicle which achieves poor comfort and energy consumption, but is safe nonetheless. This would have a fitness function value of $F_n = -w_c - w_e$.

Given that safety cannot be compromised, Case B might be preferred over Case A; thus, the fitness function should give a higher score to Case B than Case A. This suggests that, by comparing Equations (13) and (14), the following inequality must also hold:

$$-w_c - w_e > -\lambda \qquad (15),$$

Or equivalently,

$$w_c + w_e < \lambda \qquad (16)$$

5.2.3 Maximum and minimum values

E_{min}: the minimum energy consumption E_{min} is zero.

E_{max}: the maximum energy consumption E_{max} may be obtained by multiplying the nominal energy consumption of a test vehicle (given in kWh/km) by the allowable speed limit (130 km/h in Europe).

Since C is defined to be binary: $C \in \{-1, 0\}$,

C_{min}: the minimum comfort score C_{min} is -1

C_{max}: the maximum comfort score C_{max} is 0

Since S is defined to be binary: $C \in \{0, 1\}$,

S_{min}: the minimum safety score S_{min} is 0.

S_{max}: the maximum safety score S_{max} is 1.

The advantage of the normalized fitness function is that EV users or experts only have to determine the relative importance (weights) of energy consumption and comfort, rather than, for example, determine the amount (in dollars) necessary to change the holistic comfort vote by one point in a second, which may not be intuitive. The disadvantage with the standardized fitness function is that it does not have an easy interpretation as, for example, $/sec.

Specifying the maximum and minimum values allow the standardized factors to be defined.

5.3 Fitness function for keeping both safety and comfort at acceptable levels

For the fitness function, as given by equation (10), to be maximized, the energy consumption will have to be minimized, comfort maximized, while maintaining an acceptable safety level. Thus, the choice of the optimal solution to this fitness function, will be one that achieves a certain minimum energy consumption and a maximum comfort at an acceptable safety.

Intuitively, the weights w_c and w_e serve to introduce a tradeoff between comfort and energy, for example, in scenarios where a user might prefer to conserve energy in order to reach their destination even if they are outside the acceptable comfort level.

However, if what is required is not such a tradeoff, but a strict minimization of energy consumption alone (and hence an increase in the driving range), at an acceptable comfort and safety, then the comfort term can be treated as another constraint in the manner in which safety is treated earlier. Thus, the fitness function in this case should be defined such that:

$$\begin{array}{ll} \min E_n & (17) \\ \text{subject to:} & \\ C = 0 & (18) \\ S = 1 & (19) \end{array}$$

where $C = 0$ is the acceptable comfort and $S = 1$ is the acceptable safety, as mentioned in Section 5.0.

Then, employing Lagrangian mulitpliers, the above set of equations ((17) –(19)) implies that the fitness function should be defined as:

$$F_n = -E_n + \lambda_1(C - 0) + \lambda_2(S - 1) \qquad (20)$$

where λ_1 and λ_2 are two Lagrangian multipliers.

Notice that, in equation (20), the unacceptable solutions are those with an unacceptable safety ($S = 0$) and/or unacceptable comfort ($C = -1$).

5.3.1 Case 1: Comfort is not acceptable, but safety standard is met

In this case, the fitness function value becomes $F_{unacceptable} = -E_n - \lambda_1$ or less; this is the case even when the energy consumption is minimized, i.e., $E_n = 0$ in which case the fitness function value becomes $F_{unacceptable} = -\lambda_1$.

5.3.2 Case 2: Safety is not acceptable, but comfort is acceptable

In this case, the fitness function value becomes $F_{unacceptable} = -E_n - \lambda_2$; this is the case even when the energy consumption is minimized, i.e., $E_n = 0$ in which case the fitness function value becomes $F_{unacceptable} = -\lambda_2$.

5.3.3 Case 3: Safety is not acceptable, and comfort is not acceptable

In this case, the fitness function value becomes $F_{unacceptable} = -E_n - \lambda_1 - \lambda_2$; this is the case even when the energy consumption is minimized, i.e., $E_n = 0$ in which case the fitness function value becomes $F_{unacceptable} = -\lambda_1 - \lambda_2$.

5.3.4 Case 4: Safety is acceptable, comfort is acceptable

In this case, the fitness function value becomes $F_{acceptable} = -E_n$; this is the case even when the energy consumption is at its worst, i.e., $E_n = 1$ in which case the fitness function value becomes $F_{acceptable} = -1$.

It follows from the above four cases that the first three unacceptable cases should have fitness function values less than the fitness function value of Case 4, if the aim is to maximize the fitness function. Thus, the following inequalities should apply:

$$-\lambda_1 < -1 \quad \equiv \quad \lambda_1 > 1 \qquad (21)$$

and

$$-\lambda_2 < -1 \quad \equiv \quad \lambda_2 > 1 \qquad (22)$$

The two inequalities of (21) and (22) ensure that the fitness function values of all the acceptable solutions are greater than or equal to -1, while the unacceptable solutions are those whose fitness function values are less than -1.

Therefore, if the inequalities of (21) and (22) are met, the optimization procedure is reduced to selecting acceptable solutions whose fitness function values are greater than or equal to -1, where the optimal value is the maximum value greater than -1.

However, notice further that this formulation of the fitness function in equation (20) is comparable to the original normalized fitness function of equation (10) with the following correspondence:

$$w_e \equiv 1 \qquad (23)$$

$$w_c \equiv \lambda_1 \qquad (24)$$

$$\lambda \equiv \lambda_2 \qquad (25)$$

Thus, while the fitness function of equation (10) aims to maximize comfort, minimize consumption at an acceptable safety level, it can also be interpreted as minimizing the energy consumption while keeping the comfort and safety at acceptable levels, as long as the following inequalities hold:

$$w_c > w_e \qquad (26)$$

and

$$\lambda > w_e \qquad (27)$$

Therefore, the fitness function of equation (10) allows the optimization for the DOMUS project, so long as one chooses solutions whose fitness function values are greater than or equal to $-w_e$, where the optimal value is the maximum value of all the fitness function values greater than $-w_e$.

To conclude this discussion, the fitness function of (10) is a general function which can do either one of the following two things, depending on how the values are interpreted:

1) It provides the optimal tradeoff between energy minimization and holistic comfort maximization at an acceptable safety, **if the methodology is simply to select the largest fitness function values.**

2) It meets the project objectives of minimizing energy consumption at an acceptable comfort and safety levels, **if the largest value is selected from the set of acceptable solutions, i.e., those whose fitness function values are greater than $-w_e$.**

5.4 Driving conditions specifications for questionnaire

In order to properly define the fitness function, the weights chosen should satisfy a number of inequalities, namely (16), (26) and (27) – in order that, upon maximization of the fitness function, the objective of minimizing energy consumption at acceptable comfort and safety levels can be achieved. However, the inequalities do not give us the exact values of the weights. Therefore, to make the weights well-defined, we take a user-centric methodology where the weights are considered as the user's preferences of comfort, energy consumption and safety under various driving conditions. We then analyze these responses in Section 5.6 to come up with a well-defined set of weights which satisfy the inequalities (16), (26) and (27), and hence the project objectives.

If we think of the weights as user preferences, then it is clear that the importance a user attaches to comfort, safety and energy consumption is dependent on the **person** and the **context**. Therefore, the relative importance are intended to be obtained as follows:

Context: obtain a comprehensive list of driving scenarios in which a user most likely would encounter, taking into account distance, temperature, humidity, noise level, time of day, etc.

Person: create a questionnaire with the comprehensive list of driving conditions to be answered by different people whose personal situations, sensitivities and preferences might cause them to attach different levels of importance to the three factors. This would account for the variation that exists in the real population.

Since the relative importance of the factors of comfort and energy consumption are dependent on the specific driving condition a user finds themselves in, it is important to establish a list of relevant driving conditions under which different preferences for comfort and energy consumption may be expected. For example, if a user were driving on a particularly slippery road after a huge snowstorm, they would be most concerned about safety and not much else. Alternatively, a user who is taking a weekend trip of about 4 hours in fair weather would be most concerned about conserving energy.

The driving conditions in this list must be guided by a number of principles. First they must be unique, in that they must capture the variation of weights. They must be relevant, such that they don't correspond mostly to some corner or unlikely cases. The driving conditions must also be generalizable and non-personal, so that they are not based on any one individual's preferences.

In order to identify the relevant driving conditions, it is important to first identify the parameters which influence the three factors of safety, energy consumption and comfort.

5.4.1 Safety

Safety in terms of windshield fogging is mainly influenced by humidity and temperature. Also, it is generally safer to drive in broad day light than at night. Therefore the parameters whose influence on safety are considered are: humidity, temperature and time of day.

5.4.2 Energy consumption

Among other things, the energy consumption of a vehicle depends on the vehicle's energy consumption specification. The distance being travelled, and the speed at which the vehicle travels all have some influence of the energy consumption for a given trip. While charging stations might increase the electric range of EVs, they do not help in assessing the rate at which a given available energy might be consumed, and the importance an EV user attaches to that. Thus, for a given test vehicle which is the DOMUS test vehicle, the parameters that have been considered as influencing the energy consumption include: distance and average speed. However, it can be argued that the average speed correlates with the distance. For example, for an in-city trip of about 10km, regulations might restrict the average speed to around 30kmph, whereas for a 100-km highway trip, the average speed might be around 100kmph.

5.4.3 Comfort

Comfort perception is considered in terms of both its acoustic and thermal aspects. The main contributing factor to the thermal aspects of comfort is the external temperature. For the acoustic aspects, comfort perception may be influenced by the opening or closing of windows, the discomfort may be maximal in open windows at high speeds, and minimal in closed windows. Moreover, the HVAC noise also influences the acoustic comfort perception. However, making changes to the HVAC settings is a user response behavior that would vary from user to user depending on the driving scenario. In other words, an appropriately defined scenario such as an extremely low ambient temperature might cause a user to make changes to the HVAC settings, which would in turn have an influence on their acoustic comfort perception. Thus, it suffices to consider only the status of the window as influencing acoustic comfort, for the purposes of defining the fitness function weights, since the other aspects of acoustics such as HVAC noise would be observed as user response.

5.4.4 Driving conditions matrix

In all, the following five variables are considered in defining the driving conditions for the purpose of determining the fitness function weights: time of day (day or night), humidity (low or high, i.e., snowing or raining), trip distance (long or short), temperature (extreme or temperate), window status (open or closed). Further specifications are included below:

- Vehicle type: DOMUS test vehicle
- Vehicle energy consumption: specified by DOMUS test vehicle
- 100% SOC, no further charging along road trip
- Low humidity: <50%
- Long distance: 120km, with the vehicle travelling at 100kmph
- Short distance: 10km, with the vehicle travelling at 30kmph
- Cold temperature: -10℃ to 10℃
- Hot temperature: 28℃ to 35℃
- Temperate: 18℃ to 23℃

Table 1: Driving conditions matrix

Condition	Time of day	Humidity	Trip distance	Temperature	Window status
1	Day	Snowing	Long	Cold	Close
2	Day	Raining	Long	Hot	Close
3	Day	Raining	Long	Temperate	Close
4	Day	Snowing	Short	Cold	Close
5	Day	Raining	Short	Hot	Close
6	Day	Raining	Short	Temperate	Close
7	Day	Low	Long	Hot	Open
8	Day	Low	Long	Cold	Close
9	Day	Low	Long	Temperate	Open
10	Day	Low	Long	Temperate	Close
11	Day	Low	Short	Hot	Open
12	Day	Low	Short	Cold	Close
13	Day	Low	Short	Temperate	Open
14	Day	Low	Short	Temperate	Close
15	Night	Snowing	Long	Cold	Close
16	Night	Raining	Long	Hot	Close
17	Night	Raining	Long	Temperate	Close
18	Night	Snowing	Short	Cold	Close
19	Night	Raining	Short	Hot	Close
20	Night	Raining	Short	Temperate	Close
21	Night	Low	Long	Hot	Open
22	Night	Low	Long	Cold	Close
23	Night	Low	Long	Temperate	Open
24	Night	Low	Long	Temperate	Close
25	Night	Low	Short	Hot	Open
26	Night	Low	Short	Cold	Close
27	Night	Low	Short	Temperate	Open
28	Night	Low	Short	Temperate	Close

In the list in Table 1, many possible combinations of the five variables that are deemed unlikely have been removed, e.g., opening the window while it is snowing or raining or there is extreme cold – in order to keep the driving conditions relevant.

5.5 Assessment of fitness function weights

Ideally the assessment of fitness function weights would occur through empirical study of driver and passenger behavior over time where human experience driving the vehicle under the various driving conditions. It is difficult enough for human judges to numerically differentiate the importance of comfort, efficiency, and safety based on a large number of driving conditions. Therefore, the judgments must be methodologically supported by a thorough contextualization and experiential embedding of the sought driving conditions such as in a real vehicle or intensive imagination techniques. Such process however, is rather lengthy and resource intensive. Because at this early stage of a research process of developing a new, previously untested procedure, the main focus is to test the general principles of the procedure. Therefore, it cannot be justified to expend a too large portion of project funding on such assessment. To approximate the results of such contextualized study, a questionnaire technique was used. Participants were not actually embedded into the experienced conditions but asked to imagine the conditions. We understand this procedure as a first step: If the overall research process turns out to be successful, as we certainly hope at this point, assessments of the fitness weights are recommended to occur under contextualized experience conditions.

5.5.1 Questionnaire for the determination of fitness function weights

Once the driving conditions were specified, a questionnaire containing a comprehensive list of these conditions was created to be answered by different people whose personal situations, sensitivities and preferences might cause them to rank the three factors of safety, energy consumption and safety differently. Since the objective was to identify a real user’s preferences, and it was deemed important to get more inputs in order for the results to be representative of the target population, inputs to this questionnaire were not sought from experts only, but from all members of WP1 group: COV, TME, iKA, ViF, CRF, IDIADA. Moreover, the questionnaire was also circulated to the National Transport Design Centre (NTDC), part of the Centre for Future Transport and Cities (FTC), at Coventry University, whose expertise include human systems integration and vehicle dynamics. The questionnaire was distributed via Online Surveys, and the responses were anonymized.

The responses were collated and analyzed to identify the most likely set of preferences for any of the driving conditions on the list. The driving conditions themselves can then be weighted in terms of the most likely ones, in order to obtain an indicative set of weights for comfort and energy consumption.

The questionnaire is in the following form:

You are driving a Fiat 500e on a highway in the morning on a long weekend trip. The trip distance is about 120km. Since you’re driving at an average speed of about 100kmph, you expect to arrive in about 1 hour and 12 minutes. It is cold outside the vehicle, with the temperature anywhere between -10C and 10C. It is snowing lightly, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 1 hour and 20 minutes at the speed of 100kmph.

(Note that the battery duration is calculated based on the nominal energy consumption under mild weather respectively for both city travel and highway travel. For the purpose of the questionnaire, differentiation of the nominal energy consumption was not made in terms of other parameters such as the external temperature, since it was desired to solicit users’ preferences in environments that deviated from mild weather, for which reason the mild weather energy consumption figures were used as baseline).

Consider this driving condition, meditate on how you are most likely to react, and answer the following questions:

On a scale of 1 – 10 (1 being the least important and 10 being the most important), of how much importance would **energy consumption** be to you?

1 2 3 4 5 6 7 8 9 10

On a scale of 1 – 10, of how much importance would **thermal comfort** be to you?

1 2 3 4 5 6 7 8 9 10

On a scale of 1 – 10, of how much importance would **acoustic comfort** be to you?

1 2 3 4 5 6 7 8 9 10

On a scale of 1 – 10, how likely is the above **driving condition** to you?

1 2 3 4 5 6 7 8 9 10

A detailed list of the driving conditions, which corresponds to the driving conditions matrix, used in the questionnaire is given below.

To reduce the effect of questionnaire fatigue, the 28 scenarios are compressed into 14, by investigating the time of day variable (day or night) in any given question. Moreover, the resulting 14 conditions were split into two parts: Part A and Part B.

5.5.2 Condition 1

You are driving a Fiat 500e on a highway in the morning on a long weekend trip. The trip distance is about 120km. Since you're driving at an average speed of about 100kmph, you expect to arrive in about 1 hour and 12 minutes. It is cold outside the vehicle, with the temperature anywhere between -10C and 10C. It is snowing lightly, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 1 hour and 15 minutes at the speed of 100kmph. The nominal energy consumption is about 19.3 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving at night, returning from the weekend trip? (Refer to Condition 15 in Table 1.)

5.5.3 Condition 2

You are driving a Fiat 500e on a highway in the morning on a long weekend trip. The trip distance is about 120km. Since you're driving at an average speed of about 100kmph, you expect to arrive in about 1 hour and 12 minutes. It is hot outside the vehicle, with the temperature anywhere between 28C and 35C. It is raining lightly, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 1 hour and 15 minutes at the speed of 100kmph. The nominal energy consumption is about 19.3 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving at night, returning from the weekend trip? (Refer to Condition 16 in Table 1.)

5.5.4 Condition 3

You are driving a Fiat 500e on a highway in the morning on a long weekend trip. The trip distance is about 120km. Since you're driving at an average speed of about 100kmph, you expect to arrive in about 1 hour and 12 minutes. The weather is mild outside the vehicle, with the temperature anywhere between 18C and 23C. It is raining lightly, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 1 hour and 15 minutes at the speed of 100kmph. The nominal energy consumption is about 19.3 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving at night, returning from the weekend trip? (Refer to Condition 17 in Table 1.)

5.5.5 Condition 4

You are driving a Fiat 500e to work in the morning. The trip distance is about 10km. Since you're driving at an average speed of about 30kmph, you expect to arrive in about 20 minutes. It is cold outside the vehicle, with the temperature anywhere between -10C and 10C. It is snowing lightly, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 4 hours and 36 minutes at the speed of 30kmph. The nominal energy consumption is about 17.4 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving home at night, after working late? (Refer to Condition 18 in Table 1.)

5.5.6 Condition 5

You are driving a Fiat 500e to work in the morning. The trip distance is about 10km. Since you're driving at an average speed of about 30kmph, you expect to arrive in about 20 minutes. It is hot outside the vehicle, with the temperature anywhere between 28C and 35C. It is raining lightly, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 4 hours and 36 minutes at the speed of 30kmph. The nominal energy consumption is about 17.4 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving home at night, after working late? (Refer to Condition 19 in Table 1.)

5.5.7 Condition 6

You are driving a Fiat 500e to work in the morning. The trip distance is about 10km. Since you're driving at an average speed of about 30kmph, you expect to arrive in about 20 minutes. The weather is mild outside the vehicle, with the temperature anywhere between 18C and 23C. It is raining lightly, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 4 hours and 36 minutes at the speed of 30kmph. The nominal energy consumption is about 17.4 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving home at night, after working late? (Refer to Condition 20 in Table 1.)

5.5.8 Condition 7

You are driving a Fiat 500e on a highway in the morning on a long weekend trip. The trip distance is about 120km. Since you're driving at an average speed of about 100kmph, you expect to arrive in about 1 hour and 12 minutes. It is hot outside the vehicle, with the temperature anywhere between 28C and 35C. It is not raining, and you have your window open.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 1 hour and 15 minutes at the speed of 100kmph. The nominal energy consumption is about 19.3 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving at night, returning from the weekend trip? (Refer to Condition 21 in Table 1.)

5.5.9 Condition 8

You are driving a Fiat 500e on a highway in the morning on a long weekend trip. The trip distance is about 120km. Since you're driving at an average speed of about 100kmph, you expect to arrive in about 1 hour and 12 minutes. It is cold outside the vehicle, with the temperature anywhere between -10C and 10C. It is not raining or snowing, and you have your window open.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 1 hour and 15 minutes at the speed of 100kmph. The nominal energy consumption is about 19.3 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving at night, returning from the weekend trip? (Refer to Condition 22 in Table 1.)

5.5.10 Condition 9

You are driving a Fiat 500e on a highway in the morning on a long weekend trip. The trip distance is about 120km. Since you're driving at an average speed of about 100kmph, you expect to arrive in about 1 hour and 12 minutes. The weather is mild outside the vehicle, with the temperature anywhere between 18C and 23C. It is not raining, and you have your window open.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 1 hour and 15 minutes at the speed of 100kmph. The nominal energy consumption is about 19.3 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving at night, returning from the weekend trip? (Refer to Condition 23 in Table 1.)

5.5.11 Condition 10

You are driving a Fiat 500e on a highway in the morning on a long weekend trip. The trip distance is about 120km. Since you're driving at an average speed of about 100kmph, you expect to arrive in about 1 hour and 12 minutes. The weather is mild outside the vehicle, with the temperature anywhere between 18C and 23C. It is not raining, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 1 hour and 15 minutes at the speed of 100kmph. The nominal energy consumption is about 19.3 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving at night, returning from the weekend trip? (Refer to Condition 24 in Table 1.)

5.5.12 Condition 11

You are driving a Fiat 500e to work in the morning. The trip distance is about 10km. Since you're driving at an average speed of about 30kmph, you expect to arrive in about 20 minutes. It is hot outside the vehicle, with the temperature anywhere between 28C and 35C. It is not raining, and you have your window open.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 4 hours and 36 minutes at the speed of 30kmph. The nominal energy consumption is about 17.4 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving home at night, after working late? (Refer to Condition 25 in Table 1.)

5.5.13 Condition 12

You are driving a Fiat 500e to work in the morning. The trip distance is about 10km. Since you're driving at an average speed of about 30kmph, you expect to arrive in about 20 minutes. It is cold outside the vehicle, with the temperature anywhere between -10C and 10C. It is not raining or snowing, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 4 hours and 36 minutes at the speed of 30kmph. The nominal energy consumption is about 17.4 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving home at night, after working late? (Refer to Condition 26 in Table 1.)

5.5.14 Condition 13

You are driving a Fiat 500e to work in the morning. The trip distance is about 10km. Since you're driving at an average speed of about 30kmph, you expect to arrive in about 20 minutes. The weather is mild outside the vehicle, with the temperature anywhere between 18C and 23C. It is not raining, and you have your window open.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 4 hours and 36 minutes at the speed of 30kmph. The nominal energy consumption is about 17.4 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving home at night, after working late? (Refer to Condition 27 in Table 1.)

5.5.15 Condition 14

You are driving a Fiat 500e to work in the morning. The trip distance is about 10km. Since you're driving at an average speed of about 30kmph, you expect to arrive in about 20 minutes. The weather is mild outside the vehicle, with the temperature anywhere between 18C and 23C. It is not raining, and you have your window closed.

Assume that the Fiat 500e's nominal energy consumption is such that the battery capacity of about 24kWh will last for approximately 4 hours and 36 minutes at the speed of 30kmph. The nominal energy consumption is about 17.4 kWh/100km but actual energy consumption will depend on external factors for example external temperatures or slope.

How about if you were driving home at night, after working late? (Refer to Condition 28 in Table 1.)

5.5.16 Limitations of questionnaires

The 14 conditions given in the questionnaires cover the 28 scenarios shown in Table 1. For the purposes of the determination of an indicative set of weights for comfort and energy consumption, these conditions are valid, sufficient and robust because:

1. They take into account the possible variations in holistic comfort and energy consumption, as shown in Table 1.
2. The conditions are appropriately weighted by the respondents in terms of their actual likelihood.

However, it is worth noting the following limitations to the questionnaire:

1. Every respondent data is valid. There are no outliers, exclusions and data cleansing is not performed, since the mean values are expected to be robust toward outliers.
2. The questionnaire (and therefore every item) matches the empirical standards (e.g. validity, reliability and objectivity).
3. Questionnaire fatigue does not occur.
4. Every respondent could picture himself in the given situations and rate the items accordingly.
5. Although the objective of the questionnaire was to identify the user's prioritization of their energy requirements and comfort for any vehicle they find appropriate for their purpose, the specified vehicle Fiat 500e may not be the vehicle of choice for some on a long road trip.

5.6 Determination of fitness function weights from questionnaire

The questionnaire had 41 respondents in total. The methodology for obtaining the fitness function weights from the responses of the 41 respondents is given below:

1. For a given respondent,

    a. For each driving condition, the likelihood score assigned by the respondent is rescaled into the interval [0,1] as a probability measure p. This is done by the following equation:

$$p = \frac{\text{Likelihood score} - 1}{9} \qquad (28)$$

The distribution of the average likelihoods over all respondents for all the 28 driving conditions is shown in Fig. 5. The standard deviation values are given in Table

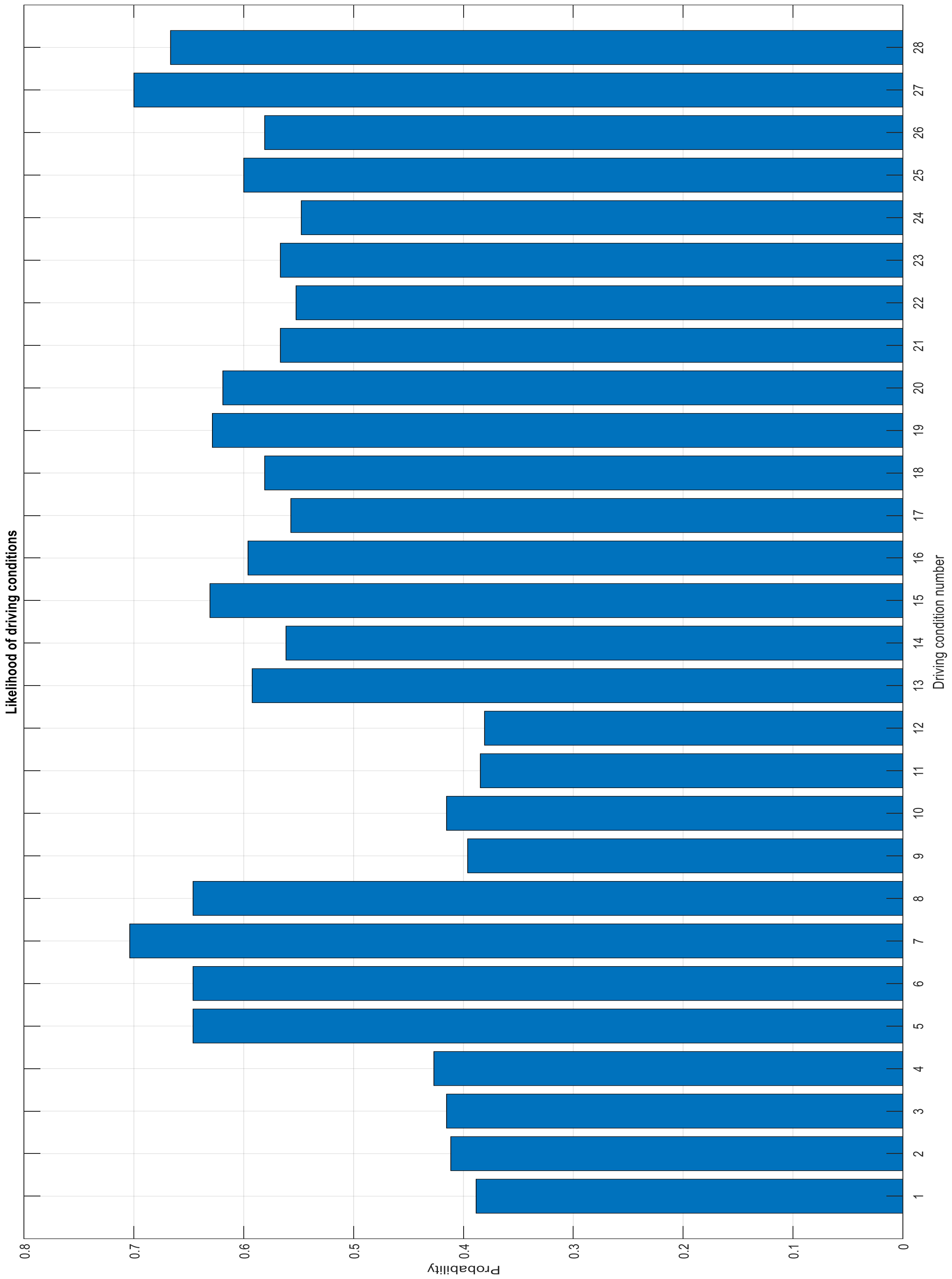


Fig. 5: Likelihood of driving conditions

Table 2: Probability standard deviations for the 28 driving conditions.

Driving condition	Standard deviation
1	0.293021
2	0.294383
3	0.29758
4	0.290596
5	0.237033
6	0.20829
7	0.166086
8	0.20636
9	0.267553
10	0.280987
11	0.328259
12	0.332288
13	0.215264
14	0.236773
15	0.257324
16	0.269044
17	0.198926
18	0.263854
19	0.232686
20	0.208852
21	0.265204
22	0.280391
23	0.210555
24	0.250238
25	0.232379
26	0.260037
27	0.151658
28	0.203306

   b. For each of the driving conditions, the score assigned by the respondent to energy consumption, acoustic and thermal comfort is each multiplied by p.
   c. The weighted average of the scores for energy consumption, thermal and acoustic comfort are then obtained for each respondent. This is obtained by finding the weighted sum (i.e., the scores weighted by p), and dividing by the sum of the probabilities p obtained for the 28 driving conditions.

2. The above procedure (a through c) is repeated for all other respondents. The distribution of the weighted average scores for all the respondents are shown in Figures 6, 7 and 8. The figures represent the probability mass functions where the area under the plots are equal to 1, i.e., for every score, the relative likelihood is given on the y-axis. They are obtained with Matlab using the function ecdfhist.

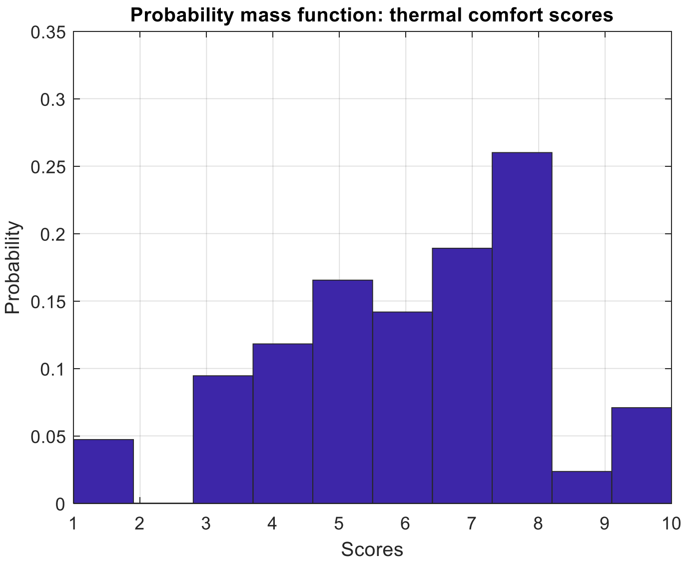


Figure 6: Empirical distribution of thermal comfort scores

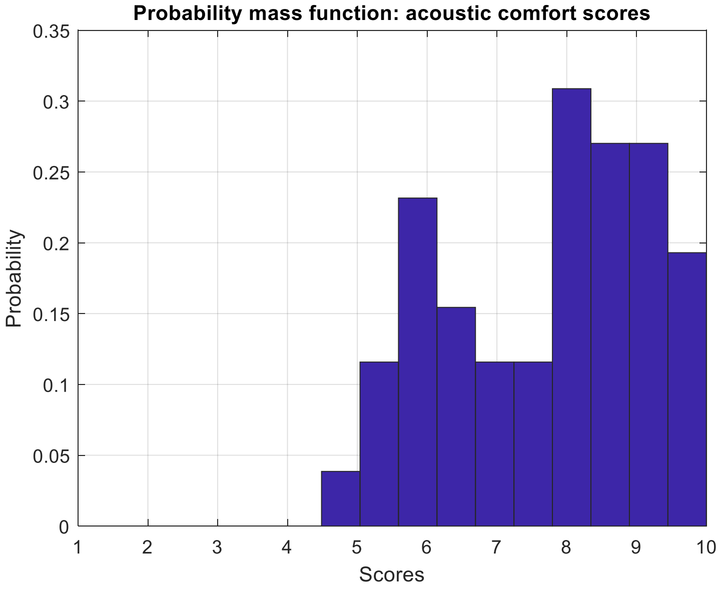


Figure 7: Empirical distribution of acoustic comfort scores

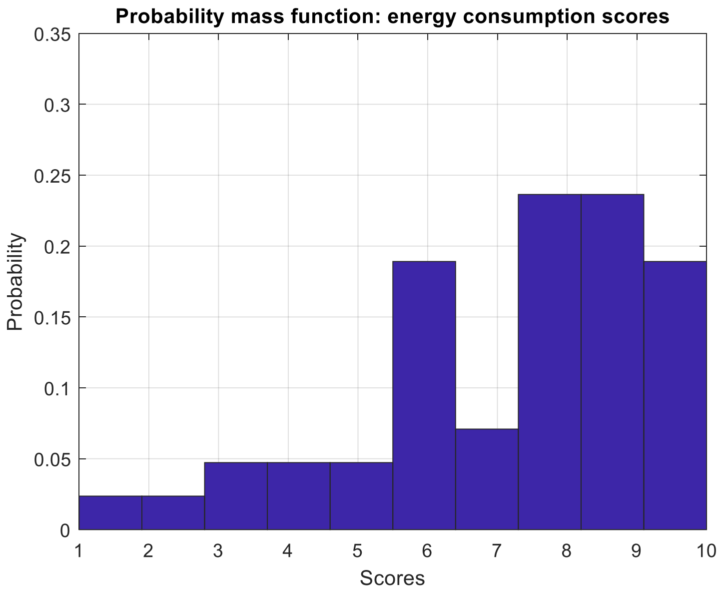


Figure 8: Empirical distribution of energy consumption scores

3. The expected values of the weighted average scores for all the respondents in Step 2 are then obtained for thermal comfort, acoustic comfort and energy consumption. Let these be denoted by $s_{\text{thermal}}, s_{\text{acoustic}}$ and s_{energy} respectively for the thermal comfort, acoustic comfort and energy consumption scores. From the data collected, these are given below as:

$$s_{\text{thermal}} = 7.7066, \qquad s_{\text{acoustic}} = 6.1063, \qquad s_{\text{energy}} = 7.1953 \qquad (29)$$

with the following standard deviations:

$$\sigma_{\text{thermal}} = 1.4577, \qquad \sigma_{\text{acoustic}} = 2.0906, \qquad \sigma_{\text{energy}} = 2.2339 \qquad (30)$$

Note that the maximum likelihood (ML) scores may be taken in place of the expected values. However, since the ML estimates do not take into consideration any prior knowledge or probabilities, the ML estimates could be misleading, and is not considered here.

4. To obtain the holistic comfort score, a soft max of the thermal comfort and acoustic comfort scores is used, i.e.,

$$s_{\text{holistic}} = \ln(e^{s_{\text{thermal}}} + e^{s_{\text{acoustic}}}) \qquad (31)$$

A soft max is used because a lower preference for acoustic comfort should not diminish an occupant's overall comfort preference if the thermal comfort preference is high. Therefore, the comfort preference may be defined as the maximum between the two. The soft max function approximates the maximum function. This gives the following holistic comfort score:

$$s_{\text{holistic}} = 7.8904 \qquad (32)$$

5. With the energy consumption score s_{energy}, and having obtained the holistic comfort score s_{holistic} from Step 6, the weights w_e can be obtained as follows:

$$w_e = \frac{s_{\text{energy}}}{s_{\text{energy}} + s_{\text{holistic}}}, \qquad w_c = \frac{s_{\text{holistic}}}{s_{\text{energy}} + s_{\text{holistic}}} \qquad (33)$$

This procedure yields the following weights:

$$w_e = 0.4770, \qquad w_c = 0.5230 \qquad (34)$$

Therefore, the fitness function from (10) becomes:

$$F_n = 0.523C - 0.4770E_n + \lambda(S - 1) \qquad (35)$$

The Lagrange multiplier in (35) has to satisfy the inequality of (16), namely, $w_c + w_e < \lambda$. Thus, we arbitrarily define λ as:

$$\lambda = w_c + w_e + 1 = 2 \qquad (36)$$

Therefore, the final fitness function is:

$$\boldsymbol{F_n = 0.523C - 0.4770E_n + 2(S - 1) \qquad (37)}$$

Notice that the above selection of weights given by (34) and (36) satisfies the inequalities of (26) and (27) which are required to minimize the energy consumption while keeping comfort and safety at acceptable levels, upon maximization of the fitness function of (38).

We may now express the fitness function as a function of time $f_n(t)$. Recall from equation (4) and (11) that:

$$E_n = \frac{1}{T}\int_0^T e_n(t)\ dt, \qquad C = \frac{1}{T}\int_0^T c(t)\ dt, \qquad S = \frac{1}{T}\int_0^T s(t)\ dt$$

Therefore, (37) can be expressed as:

$$F_n = 0.523\frac{1}{T}\int_0^T c(t)\ dt - 0.4770\frac{1}{T}\int_0^T e(t)\ dt + 2(\frac{1}{T}\int_0^T s(t)\ dt - 1) \qquad (38)$$

which can be simplified as:

$$F_n = \frac{1}{T}\int_0^T (0.523c(t) - 0.4770e(t) + 2(s(t) - 1))\ dt \qquad (39)$$

or equivalently as:

$$F_n = \frac{1}{T}\int_0^T f_n(t)\ dt \qquad (39)$$

where

$$\boldsymbol{f_n(t) = 0.523c(t) - 0.4770e(t) + 2(s(t) - 1) \qquad (40)}$$

5.7 Utility of the fitness function

The final fitness function for a given scenario and duration T is given by equation (37) as

$$\boldsymbol{F_n = 0.523C - 0.4770E_n + 2(S - 1)}$$

Since the maximization of this function ought to yield solutions that minimize the energy consumption at an acceptable comfort and safety, this section recaps the meaning of the variables, details the operating regions of acceptable solutions, and explains how the fitness function values are to be interpreted.

Firstly, the parameters C, S and E_n are the comfort, safety and normalized energy consumption scores respectively. C is a binary and indicates whether the cabin occupant is comfortable (holistically) or not. $C = 0$ indicates that it is comfortable and $C = -1$ indicates uncomfortable. For example, the comfort can be defined as $C = 0$, if a certain comfort criterion is met during the trial period T – such as comfort should be achieved, say, 70% of the time. The exact definition of what is an acceptable comfort is left for the holistic comfort model in WP1.2. S is binary and indicates whether the safety is acceptable or not acceptable. $S = 1$ indicates that it is safe and $S = 0$ indicates unsafe. For example, the safety can be defined as $S = 1$, if a safety standard – such as 90% of vision area A shall be demisted in 10 minutes – is met during the simulation period T.

The optimization procedure for this fitness function, as used in other work packages, is to choose solutions whose fitness function values are greater than $\mathbf{-0.477.}$ Thus, $F_n > -0.477$ forms the region of acceptable solutions, or the feasible region: those solutions which achieve the acceptable comfort and acceptable safety. The optimum solution is the solution that yields the maximum fitness function value in the acceptable or feasible region.

Note, however, that the overall fitness function F_0 evaluates the fitness function for all scenarios in the scenario database (Section 6), i.e.,

$$F_0 = \frac{1}{N} \sum_{i \in Scenarios} w_i \, F_n(scenario\ i) \qquad (41)$$

where N is the sum of all the scenario weights.

Not all solutions may have acceptable fitness function values for all scenarios. Therefore, there may not be any feasible solution if the methodology is to choose an overall fitness function greater than -0.477. A certain tolerance in the feasible region may have to be allowed to account for this fact.

6 Scenario database

In the proposed assessment framework, after the fitness function has been defined, a list of scenarios is required to evaluate their fitness function values in order to obtain the overall fitness of the car.

The scenarios are similar to the driving conditions, only that they contain specific details that define the overall simulation run.

Basic tests in CWTs involve warm-up and cool-down scenarios. Other scenarios involving real drive cycles, in order to assess the energy consumption associated with thermal comfort, will also provide insightful information. Cruising conditions also need to be considered. For cruising, especially for future electrified cars, the trade-off between comfort and energy is really key, as well as maintaining good visibility in very cold conditions.

One of the guiding principles for establishing the scenario database is that, the scenarios must be chosen in such a way to be related to real user's perception of comfort. For example, traditional assessment has considered only time to comfort whereas amount of discomfort experienced was not considered.

The methodology for creating the list of scenarios is as follows:

1) Each scenario is mapped to a specific city or location and a specific date and time. This mapping can be done using the driving conditions matrix as a guide. The advantage of such a mapping is that it ensures that all parameters can be specified precisely. Also, they will map to a real situation in a way that an averaging over all values might not do.
2) From the specific location and specific date and time, the following simulation parameters can be obtained:
    a. The outside temperature (deg. C)
    b. Dew point temperature (deg. C)

c. Precipitation (mm)
d. Relative humidity (%)
e. Wind speed (km/h)
f. Solar irradiance (kWh/m^2)

Although it would be possible to allow these parameters to alter during the trial according to the meteorological record, for simplicity, we assume that they remain fixed for the scenario.

Note that the initial cabin temperature is assumed to be the same as the external temperature (at time $t = 0$). To show the benefit of preconditioning, it is necessary to ensure that not all scenarios (specifically, the first half of the scenarios given in Table 3) involve the driver entering at t=0 but rather enter at some later time, such as $t = 30$ minutes. For preconditioning enabled scenarios, it is assumed that context information is available to the control system - such as there is a regular drive occurring at around t=30 and that the battery is currently being charged.

3) Highly populated cities, such as London, Paris, Athens, or Madrid, are preferred over less populated locations, such as Malta or Lithuania, to ensure that the assessment is as representative of popular human experience as possible.
4) Emphasis is placed on European cities and weather types. For example, tropical locations are not considered.

The scenarios vary in terms of: season, time of day (morning, afternoon, or night), other parameters previously specified (e.g., window
opening, etc.)

With the above methodology, and after specifying a driving duration, the following scenario database is proposed [3][7]:

Table 3: Scenario database

Season	Time of day	Outside Temperature (deg)	Dew point temperature (deg)	Relative humidity (%)	Wind speed (km/h)	Solar irradiance (kWh/m^2)	Number of occupants
Winter	Morning	0	0	100	15	13.4	1
Summer	Afternoon	38	6	14	6	231	2
Summer	Morning	19	12	64	11	136	3
Winter	Morning	3	3	100	6	17.3	1
Summer	Afternoon	29	17	47	22	221	1
Spring	Afternoon	20	8	46	20	182	1
Summer	Morning	26	15	51	11	183	4
Winter	Morning	-3	-3	100	2	69.9	2
Summer	Morning	22	22	100	7	157	4
Summer	Morning	23	20	83	13	155	3
Summer	Afternoon	32	20	49	19	216	1
Winter	Morning	7	5	87	13	29.2	1
Fall	Afternoon	20	15	73	6	166	1
Summer	Morning	23	18	73	11	168	1
Winter	Evening	3	1	87	13	25.5	2
Summer	Evening	28	23	74	6	223	2
Fall	Evening	8	3	71	15	79.3	3

Winter	Evening	3	3	100	6	41.9	1
Summer	Evening	29	22	66	9	225	1
Summer	Evening	19	12	64	9	141	1
Summer	Evening	31	21	55	6	215	1
Winter	Evening	5	2	81	6	204	2
Spring	Evening	13	-5	21	11	167	3
Summer	Evening	19	13	68	6	149	2
Summer	Evening	28	24	79	7	227	1
Winter	Evening	6	0	66	11	32.8	1
Summer	Morning	10	9	94	6	168	1
Spring	Evening	11	4	62	20	158	1

The particular cities, dates, times and current population [4] from which the data in Table 3 are obtained are given below in Table 4:

Table 4: Countries, times and population corresponding to scenario database

City	Season	Date (DD/MM/YYYY)	Time	Population
Helsinki	Winter	01/01/2018	08:20	642045
Madrid	Summer	01/08/2018	17:00	3182981
London	Summer	01/08/2018	08:50	8825001
Stockholm	Winter	01/01/2018	08:50	955000
Lisbon	Summer	01/08/2018	13:00	547733
Seville	Spring	01/04/2018	14:00	689434
Lyon	Summer	01/08/2018	10:00	521098
Sofia	Winter	01/01/2018	09:00	1307376
Berlin	Summer	01/08/2018	07:55	3711930
Copenhagen	Summer	01/08/2018	09:55	602481
Barcelona	Summer	01/08/2018	15:00	1620809
Warsaw	Winter	01/01/2018	07:00	1764615
Athens	Fall	01/10/2018	12:50	655780
Vienna	Summer	01/08/2018	07:20	1889083
Glasgow	Winter	01/01/2018	20:50	615000
Rome	Summer	01/08/2018	20:50	2879215
Brussels	Fall	01/10/2018	19:55	1191604
Budapest	Winter	01/01/2018	17:30	1752704
Naples	Summer	01/08/2018	21:20	970185
Birmingham	Summer	01/08/2018	21:50	1124569
Marseille	Summer	01/08/2018	21:30	869815
Bucharest	Winter	01/08/2018	18:00	2112483
Milan	Spring	01/04/2018	20:50	1370074
Amsterdam	Summer	01/08/2018	22:35	859732

Nice	Summer	01/08/2018	21:30	346055
Prague	Winter	01/01/2018	17:00	1294513
Paris	Summer	01/08/2018	07:00	2206488
Zagreb	Spring	01/04/2018	21:00	803647

The number of occupants (1,2,3,4) shown in Table 3 are broken down below as:

1 – driver alone
2 – driver and one front passenger
3 – driver, one front passenger and one backseat passenger
4 – driver, one front passenger and two backseat passengers

To take into account different driving times in the real user population, the simulation duration is varied for each driving scenario. To do this, we randomly select simulation times from a normal distribution, by considering the most common driving time as 15 minutes and the maximum driving time as 2 hours: we first sample from a normal distribution of 15 minutes and a standard deviation of 105 minutes. We then set all negative values to 15 minutes and all values greater than 120 to 120 minutes. After this, we round all values. These times are matched to each scenario and shown in Table 5.

A key part of the scenario database is the weight assigned to each scenario. To obtain this weight, the population of each city can be appropriately scaled in terms of the total population of all the cities combined.. The results are given in Table 5:

Table 5: Scenario weights and durations

Scenario	Weights	Scenario duration (minutes)
1	0.01417	15
2	0.070247	15
3	0.194763	120
4	0.021076	15
5	0.012088	12
6	0.015215	15
7	0.0115	120
8	0.028853	105
9	0.08192	15
10	0.013296	8
11	0.03577	15
12	0.038944	76
13	0.014473	15
14	0.041691	15
15	0.013573	23
16	0.063543	15
17	0.026298	58
18	0.038681	86
19	0.021411	105
20	0.024819	15
21	0.019196	62

22	0.046621	26
23	0.030237	102
24	0.018974	71
25	0.007637	109
26	0.028569	8
27	0.048696	15
28	0.017736	120

7 Assessment of use-case specific designs

This section details the relationship of the assessment framework with the design framework in WP2.1.

When assessing the new disruptive cabin designs developed in the DOMUS project, special considerations must be taken regarding the selection of simulation test scenarios as well as the definition of weighting coefficients in the corresponding fitness function.

7.1 Two different assessment strategies in DOMUS

Following the concept of two different innovation strategies in DOMUS shown in Table 6 the idea behind the assessment framework of DOMUS is applied differently to different types of investigated vehicle configurations. Depending on whether the focus is on technological driven innovation or on assessing disruptive new designs different scenarios and different weighting of the simulation results will be used.

Table 6:Two innovation strategies in DOMUS, linked with each other

<table>
<tr><th></th><th>Generic approach</th><th>Use case specific approach</th></tr>
<tr><td>Basic idea</td><td>Increased efficiency through innovative technology</td><td>Increased efficiency through strict use-case oriented design</td></tr>
<tr><td rowspan="2">Method</td><td>Integration of advanced components and control strategies in existing multi-purpose vehicles</td><td>Integration of innovative technologies without the limitation of a given multi-purpose vehicle design</td></tr>
<tr><td>Spec optimization → parametric, incremental</td><td>Disruptive new cabin designs</td></tr>
<tr><td rowspan="4">Virtual assessment</td><td colspan="2">Using the same criteria for efficiency, comfort and safety</td></tr>
<tr><td colspan="2">Using the same generic simulation models</td></tr>
<tr><td colspan="2">Using the same simulation framework/methodology</td></tr>
<tr><td>Same complete set of scenarios for each vehicle configuration representing multi-purpose application</td><td>For a selected set of scenarios matching the definition of the design use case of the current vehicle design/configuration</td></tr>
<tr><td rowspan="4">Evaluation</td><td colspan="2">Comparison with the baseline vehicle configuration</td></tr>
<tr><td>Comparison also between different vehicle configurations</td><td>Each design separately with the baseline</td></tr>
<tr><td colspan="2">Using the same fitness function structure</td></tr>
<tr><td>→ applying general fitness weighting coefficients</td><td>→ applying use-case specific fitness weighting</td></tr>
<tr><td>Demonstrator</td><td>→ Result verification through testing</td><td>→ Principle design demonstration (mock-up)</td></tr>
</table>

The differentiation in Table 6 illustrates, why a modification of the developed assessment framework is needed for the assessment of designs developed for specific use cases. Both approaches have a lot in common but there also important differences. On the one hand innovative technology is integrated in an existing design. On the other hand, the design itself is changed in the first line to reach the same goal – increased energy efficiency. Of course, this description is a simplification as new technologies may require changes in the cabin design, too, at least in detail. In the case of design driven innovation of course the potential of technological innovation should be used.

The main difference between the approaches lays in the fact that, for the use case specific approach, the conditions for the evaluation of new vehicle configurations are derived strictly from the use case they are designed for. Therefore, the test scenarios for the evaluation are selected to match the corresponding design use case and a specific weighting for different simulation or test results must be applied.

However, the concept of the virtual assessment is the same for both approaches. The same simulation framework consisting of the same generic simulation models and the same model interfaces will be used to investigate the same quality criteria of vehicle configurations.

The main advantage of the generic assessment framework is the objectivity of its results. Using the result of the same fitness function you can compare various vehicle configurations directly with each other, whereas in case of use case specific assessment a direct comparison of fitness numbers resulting from different design use cases is not valid. In especially a use case optimized vehicle does not have to be a good multi-purpose vehicle even if its fitness value resulting from use case specific evaluation was very good. In the generic approach incremental changes are applied to a baseline configuration, which ensures direct comparability and will support the later derivation of a real demonstrator car.

The main advantage of the use case specific approach is that it has less limitations in the cabin design and therefore has the potential to represent better future scenarios, where shared mobility based on tailored vehicle configurations may play a bigger role. Disruptive design changes can be investigated and compared to the baseline. Instead of a real demonstrator car a mock-up may be built to showcase possible future cabin designs.

In the following sections the derivation of use-case specific scenarios and result weighting is described in more detail.

7.2 Human-Centered EV Cabin Design

Human-centered development aims to make systems usable and useful by focusing on the users, their needs and requirements, and by applying human factors/ergonomics, and usability knowledge and techniques [5]. Such approach should enhance effectiveness and efficiency and represents a critical component of the DOMUS project.

In DOMUS work package 2.1, a human-centered process is used to determine cabin designs that are optimized to meet the needs of drivers and passengers of electric vehicles. The result of applying such process should result in an increased match of comfort expectations and increased user acceptance.

WP 2.1 specifically intends to derive new disruptive cabin designs by using an iterative user-centric approach. The technological innovations from DOMUS work packages three (Cabin Thermal Insulation), four (Cabin low thermal inertia), and five (advanced systems and components and their control) were considered as input into an innovative cabin design process. However, after reviewing the cabin-innovation potential of these technologies, the consortium decided that other considerations needed to be taken to lead toward disruptive, innovative designs. Therefore, innovation sparks were needed and future European mobility situations and constraints were investigated based on ongoing national and international planning activities such as the EU Horizon 2020 project Mobility4EU ([6]). Furthermore, DOMUS consortium partners contributed their expertise in designing novel EV cabins in the context of future mobility as well as critical market relevant constraints and environments were investigated. The DOMUS consortium partners defined their input during two workshops on July 5th and September 18th 2018. Following DOMUS consortium partners were present at this workshop: TME, VOLVO, CRF, IDIADA, IKA, VIF, and COV. At this workshops, several principles of future mobility were identified:

1. European cities will likely restrict access of certain vehicles to urban areas. The rationales for this may be traffic and air pollution requirements. Access to electric vehicles may then become a premium asset to reduce pollution.

2. Car sharing and ride sharing are novel forms of mobility that will increase in size and significance over the next years to reduce the amount of vehicles in the city. Making these offerings attractive to the users becomes paramount and requires novel designs.
3. Seamless integration between multiple modes of urban transportation, for example via portable digital devices will play an important role. These devices will provide trip planning information as well as access to transportation solutions and identification services (e.g. for parking, etc.)
4. The value systems of mobility users will increasingly reflect greater importance on sustainability and smaller vehicles. Individually owned vehicles become less important as primary mobility enablers. Mobility becomes a service with a mix of different transportation modes. Mobility in cities will often be orchestrated following a hub-spoke organization where fast public transport between hubs and sustainable, individual transport options in vicinity of the hubs.
5. Tailoring vehicles to specific user needs becomes an important area.
6. Enabling currently excluded or disadvantaged mobility users (e.g. elderlies, handicapped, children) becomes increasingly important in European transportation systems.
7. Automated driving functionality is an important and increasingly available enabler for mobility as it provides currently excluded users increased accessibility and allows drivers to become passengers and multitask.

7.3 Use case Description

To translate these general future tendencies into a more tangible format, four mobility use cases were created where different personas exhibit their mobility needs within different environments to reflect the use of vehicles in the near to mid-term future. The use cases describe the how car-sharing vehicles could be utilized. The four use case were identified that reflect specific vehicle usage personas that are consistent with the reviewed EU mobility visions and provide examples of how such visions could look like. They reflect different gender, cultural, geographic, economic and professional diversity.

7.3.1 Elvira

Elvira, 28, lives in Rome, she is an entry level lawyer working for a non-profit that helps refugees. She lives on a hill, 25 km from work. The next bus station is 2 km away and the next train station 5 km that can bring her directly to work. Sometimes she needs to get home from the train station and does not want to walk that part of the city by herself. Also, sometimes in Rome it can be very warm.

Elvira is part of a social community actively engaged in creating collaborative solutions that minimize the environmental impact of her life style. She is on a large social network to exchange ideas and actively prepare and engage in sustainable behavior to reduce the environmental impact that humans have.

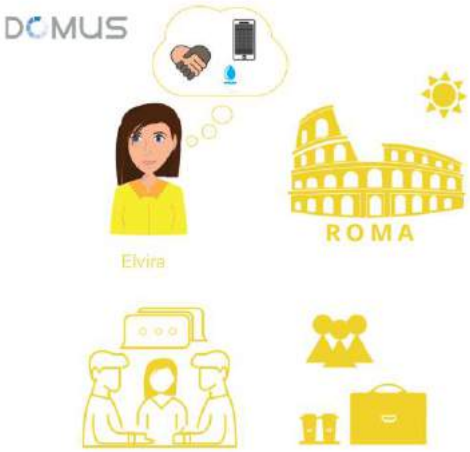


Figure 9: Graphical Summarization of Elvira's Mobility Needs

Elvira is planning her next day: in the morning she will have to go **directly from her home to a business meeting** in the middle of Rome, and then, after that, she continues on to two more clients before arriving at her office which is also in the center of Rome. Because the weather-forecast indicated hot weather, she does not want to use public transportation today. Therefore, in preparation for this trip she has indicated on her app that **she will need a car-sharing vehicle** in the morning for a short trip and without passengers or luggage. **The car-sharing agency works with Elvira's company** and ensures that a **car will be parked next morning close to Elvira's home**.

The next morning, Elvira **uses her cell phone to locate the next DOMUS car**. Using the navigation function on her phone she finds the next car-sharing vehicle just a block away from her. It **is 75% charged** and sufficient for most trips in the city. She can unlock the car with her cell phone and finds the tiny car clean and pleasantly smelling. **The DOMUS car has been cleaned overnight and drove itself automatically to Elviras' neighborhood to wait there**. However, **it is not preconditioned with a lower temperature** which would cost extra and Elvira's company (a non-for profit) did not choose this option. **The interior looks exactly like all the other DOMUS vehicles** and the controls and displays are easy to use. **Elvira wants to work** while she is being driven to her meeting location. The DOMUS car has a slot where she can put her laptop with connectors to display information an in-vehicle display and keyboard to provide inputs. There is a desk that allows her to put papers and has a ridge so that the pen cannot fall down. The keyboard is foldable and can be put away. Elvira sits down and enters the destination. Elvira does only rarely drive and feels insecure about driving herself in Rome, so she picks the automated-driving option. She then folds the steering wheel back and starts working. The car updates her unobtrusively about the travel progress so that Elvira can become aware of her location if she wants to but this is not necessary. The DOMUS car **is able to use bus-lanes** and other streets that are only available for public transport and the DOMUS car sharing vehicles. Elvira **knows that a video camera is observing her** and so she makes sure that she leaves the vehicle as clean as she found it. Elvira is a very clean person anyway but the cameras **motivate other drivers to better care** for the vehicle. Elvira arrives at her destination. The DOMUS car stops driving and Elvira gets out of the car: the car finds automatically **a parking and charging spot where it will recharge itself** and wait for Elvira to come back or until the dynamic planning system sends another car for Elvira who has indicated on her DOMUS planning app **that she will need the next vehicle at around 11:30** (give or take 30 min). After the next meeting, Elvira gets back in the car. Because the meeting was rather exhaustive, she wants to relax now and not work anymore. Therefore, she puts the computer into the storage pouch and enters the next destination. The DOMUS car tells her that the drive will take 25 minutes. Elvira selects the relax mode. The seat allows to be put into a laying position, the windows dim and the interior darkens. She cannot be seen from the outside though she can still see out. A noise cancelling system takes away most of the noises of the city. Elvira closes her eyes and the car drives in comfort mode to the next location. Before arriving at the location, it wakes Elvira to make her aware that they will be soon arriving. After her arrival, Elvira gets out and she continues to use the DOMUS vehicle similarly to before throughout the day, mostly traveling by herself. At one point she **uses a public** bus because it is a direct connection and only short ride away. She can use **the same app that she uses for the DOMUS car sharing** also to use the bus system. In her office she and her colleagues decide to go for dinner and therefore, for her second to last trip she orders a vehicle **for four people** so that she can drive three of her colleagues to a restaurant not far from her home. At the end of the day she gets a **small E-car to drive home**.

7.3.2 Kari

Kari, 29 lives with his family in Helsinki and is the owner of a successful software startup and mostly works from home as do most of the employees in his company. The software startup has also sustainability goals that Kari attempts to exemplify through his lifestyle and the one of his company. Sometimes Kari needs to travel to meetings with his current and prospective clients, he likes to take his e-bike. He also needs a car to buy groceries for his family where they need a lot of food because they often invite friends and family to their house and cook for them.

Figure 10: Graphical Summarization of Kari's Mobility Needs

Kari is the **owner of a successful software company**, he incentivizes his employees and can attract highly talented employees by providing them access to DOMUS E-car sharing vehicles for their private and professional trips. During the times of reduced demand, **these cars are rented out to the local**, car-sharing company of the city for their use and some revenue generation. Kari **has his own large luxury E-car** for longer trips such as camping, fishing, family trips, and to visit customers who live far away. Such luxury vehicle is **still an important status indicator** for Kari to show to demonstrate his success and therefore trustworthiness. However, **for all business and local travel he uses the DOMUS E-Car** sharing fleet of his company that also shows the logo of his company on their side, therefore **providing advertising**. In addition, when travelling locally, he likes to take his **foldable E-bike** with him. He uses a similar planning app as Elvira does. There he indicates the need for an E-vehicle the day prior to the travel and the approximate duration. He would like to **continue to work while using his car-sharing vehicle** and accomplish his emailing, texting, and calling while driving so an automated driving function is helpful for him and he does not like ride sharing because he does not want other people to talk to him while he works. When the car arrives in the **morning it is fully charged** and **was just cleaned** during its overnight stay, also the car is preheated for Kari's comfort. **The car drives itself to Kari** based on Kari's reservation the night before. The car is **intended for just one driver and a passenger and has additional storage for a foldable bike** and luggage or grocery bags. He opens the car door with this phone app and puts his foldable E-bike into the trunk. Then he seats himself in the car that is clean and smells good and enters the destination. The car then starts driving and Kari starts working. As he arrives at the destination, Kari takes out his E-bike and goes to his first meeting, **the car parks itself**. After that meeting he uses the E-bike to travel to the next meeting that is close by. He then calls again one of the DOMUS E-vehicles, stores his bike in the back and drives to the grocery store where he buys 3 big grocery bags full of groceries.

7.3.3 Isabelle & Jean

Isabelle is a teacher and Jean is an artist who, since 2 years, has to use a wheelchair to move around. They have two children, 12 and 15 years old. They live in the suburbs of Nice. They live in a complex of row houses in close connection with especially three other families (with two children each) with whom they are sharing multiple types of electric vehicles. Whereas the parents use mostly public transportation and bicycles for their closer mobility, they could really benefit from a vehicle that can drive their six children to the various after-school activities.
Also, Isabelle and Jean sometimes drive to a private beach that is 23 km away and that is close to their parents in Cannes. There they stay overnight and need to bring along all the things their kids need to have at the beach to be happy.

Figure 11: Graphical Summarization of Isabelle and Jean's Mobility Needs

The three families often use **multiple types** of DOMUS vehicles among them. A large one that **seats 7 people** and a **small one that seats 2**. The vehicles are **automatically delivered to the needed location**. Isabelle has ordered a **large 7-seater for every morning during the school year** by the local car sharing company. The car only needs to **transport some hand-luggage** such as purses, backpacks, and briefcases. She **uses an app** that is similar to the one that Elvira and Kari are using, where she determines the desired pick-up time and the estimated drop-off time as well as the size of the vehicle.

In the morning, the large 7-seater vehicle **comes automatically** to Isabelle's house. She gets in and drives with the 6 children to the same school where she is also teaching. In front of the school they all get out and the **automated driving vehicle drives to the next pick-up location**.

An hour later, **Jean needs to get to a local exhibition hall** with seven of his paintings. Since he has to use a wheel-chair, he orders an automated driving vehicle that allows him to enter easily and the car drives him to the destination. Jean likes to drive the vehicle because it **allows him to use it by just** using his hands. It is easy for him **to fixate the wheel-chair** inside of the vehicle during the drive. After Jean arrives at the destination, he exits the car and the **car drives off automatically** to the next customer.

In the afternoon, after Isabelle has brought all the children home from school, Xanthippe, the 15-year-old daughter of Isabelle and Jean, need to be brought to the **local fencing club** where she is the best fencer in her age group and Xanthippe is highly regarded and motivated. For this, Isabelle has ordered a small **automated driving vehicle with enough cargo room** that can transport Xanthippe. Xanthippe brings her **large fencing back** with her which would be difficult to transport using public transportation. The E-vehicle delivers itself to the door steps of Isabelle's house and Xanthippe gets into the small but safe vehicle to be automatically driven to the fencing club. The destination has been already entered by **Isabelle in the sharing-app**, but the car would allow Xanthippe to also change the route if needed. Xanthippe **likes to use** the automated driving vehicle very much because she is not seen as "**uncool**" being driven around by her mother. The other five children often have similar afternoon activities and can now be brought to their activities without their parents spending large amounts of time to drive them, wait for them, and then bring them home again.

7.3.4 Harold

Harold is 89 years old and lives in the suburbs of Stockholm, it is winter and cold. He had a cabinet making business and is well known in Sweden for his artful designs. He does not drive anymore but needs to sometimes be brought to the doctor and he is teaching a workshop at the local college on cabinet making techniques that he enjoys very much. Taking public transportation can be difficult for him because of getting on and off the buses, waiting in the cold, and walking between stations. His doctor's office is in the center of the city 13 km away. He also often needs to go to a hospital for routine observations which is 8 km away.

Usually his daughter drives him but recently she mentioned that she wants to move away. Harold will miss her since she is the primary contact with her and he is not sure how he will be able to live without her, since she provides him also the emotional comfort he needs.

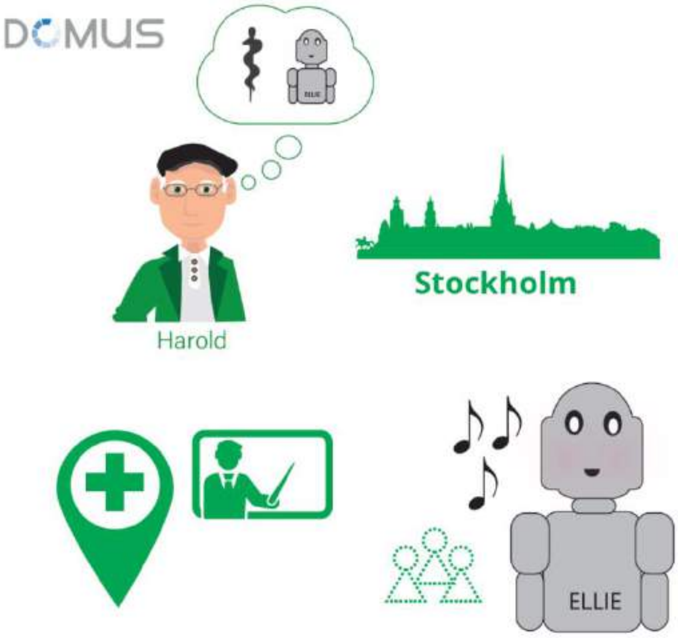


Figure 12: Graphical Summarization of Harold's Mobility Needs

Harold, with the support of his daughter, has ordered a **robot assistant** who can help Harold with many manual tasks at home, cook for him, but also keeps him company. Harold talks to his robot **"Elli" and verbally tells her** where he needs help. **Elli also schedules appointments** for him with the local hospital. Since Harold has tomorrow an appointment, Elli schedules on the website of the local car sharing company where she orders a suitable vehicle to bring Harold to the hospital the next morning. Harold has a subscription for this service that offers **specifically tailored vehicles** that are equipped for elderly people. When Elli orders the vehicle, the website indicates that on the next morning there would be **no other people needing a ride** to the hospital, otherwise, the sharing vehicle would pick up multiple passengers which **Harold likes** because it gives him opportunity to **socialize** with others. The vehicle self-drives and arrives in the morning in front of Harold's house and Elli accompanies him to the car. Elli opens the car via a **wireless key** and helps Harold into the car. The car is **pre-heated** and the **seat is high enough** so that Harold can enter and access it very easily. Also, the **seatbelt comes forward automatically** so that it can easily hold Harold in place. An **electronic key w**ould allow Harold to access the vehicle by himself. The key is contactless and has been programmed when the vehicle was ordered. Elli hands the key to Harold so that he has it when he will use the car to come back in the afternoon. Once in the car, **Elli's personalized software** module (the one that is specific to Harold's needs and preferences) is copied wirelessly into the car so that **she can continue to talk to Harold** without having to be physically located in the vehicle. The **car is self-driving** and drives Harold to the hospital where it delivers Harold right in front of the correct building. **The car plays the music that Harold likes** and Elli talks to him about the news of the day. Once arrived, Harold gets out and the **DOMUS car drives** off to the next suitable parking lot, only to **return when Harold presses on the large key** on his remote key to order the waiting car again. The car then drives Harold home where Elli already waits for him and helps him to get into his apartment again.

7.4 Use case specific fitness assessment

In addition to the generic assessment framework developed in DOMUS work package 1, a design goal fitness assessment is needed to measure the extent to which the novel designs meet their design intent. Does Elvira find the car that was specifically designed to meet her comfort and efficiency needs indeed comfortable and efficient? And does this car indeed better meet her needs than the car that was, for example, designed for Kari? The assessment function as described in DOMUS deliverable D1.2 only assesses the vehicle on a set of overall conditions but not whether it is suitable for the conditions and users it was designed for.

Therefore, a design goal fitness assessment determines whether the vehicle that has been designed for the specific use context and user population is actually able to meet its purpose and if so, how. For this purpose, for each of the use cases, the comfort and efficiency weights were determined by the workshop participants after they spent a day of contextualizing the personas, their scenarios, vehicles, and mobility environments to approximate realistic weights. How important is comfort, both acoustically and thermal, how important is efficiency, and how important are safety considerations? These values will then be used to virtually assess the qualities of different designs in WP 2.2. Whereas ideally, these weights would be assessed by observing the decisions and actions of real drivers (i.e., Elvira and Kari) who experience these conditions in their vehicles, these values were approximated by the workshop participants after completing their scenario descriptions. The workshop participants were asked to answer following nine questions and provide ratings to each of them:

	Not important					**Very Important**					
Question	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**NA***
1. How important is it that the vehicle reaches a comfortable temperature as fast as possible?											
2. How important is it that the vehicle is acoustically well insulated?											
3. How important is the overall crash safety of the vehicle?											
4. How important is overall (thermal and acoustic) comfort?											
5. How important is a large range of the vehicle (i.e. > 300 km)?											
6. How important is it that the vehicle purchase price is low?											
7. How important is it that the vehicle's cabin size is large?											
8. How important is it that the vehicle is overall small?											
9. How important is the ease of using the vehicle?											

In addition, participants were asked to respond to following two questions:

10. What would be the minimum range of the vehicle that you would find acceptable?	
11. What would be the maximum acceptable new vehicle purchase price?	

The design specific factor weights are graphically summarized below, they reflect the averages of the collected data from six representatives of the participating organizations VIF, IDIADA, CRF, VOLVO, and TME:

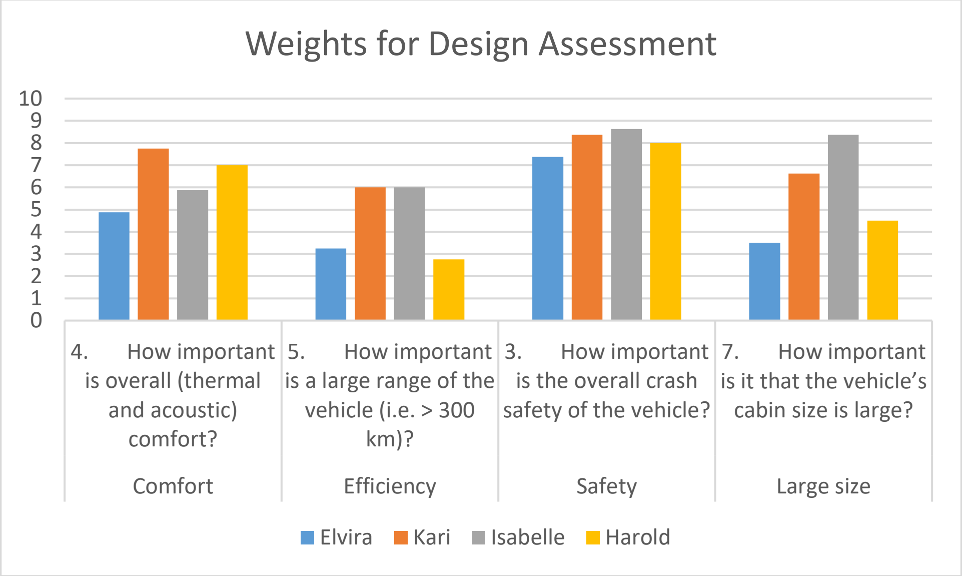


Figure 13: Factor Weights for Design Assessment

The complete results are depicted the table below:

Table 7: Weights for each of the questions

	Elvira	*Kari*	*Isabelle*	*Harold*
1. How important is it that the vehicle reaches a comfortable temperature as fast as possible?	5,13	7,75	6,13	7,75
2. How important is it that the vehicle is acoustically well insulated?	3,75	7,25	5,13	5,75
3. How important is the overall crash safety of the vehicle?	7,38	8,38	8,63	8,00
4. How important is overall (thermal and acoustic) comfort?	4,88	7,75	5,88	7,00
5. How important is a large range of the vehicle (i.e. > 300 km)?	3,25	6,00	6,00	2,75
6. How important is it that the vehicle purchase price is low?	6,50	3,25	6,25	3,38
7. How important is it that the vehicle's cabin size is large?	3,50	6,63	8,38	4,50
8. How important is it that the vehicle is overall small?	6,13	2,75	3,00	3,50
9. How important is the ease of using the vehicle?	6,25	5,63	7,00	6,88
10. What would be the minimum range of the vehicle that you would find acceptable?	122,50km	281,25km	247,50km	135,71km
11.a. Highest new vehicle purchase price	15 KEuro	150 KEuro	50 KEuro	40 KEuro
11.b. Lowest new vehicle purchase price	7 KEuro	15 KEuro	18 KEuro	15 KEuro

For each of the use cases, the user needs were derived and listed. These user needs form the starting point for the cabin design process that creates cabin solutions that meet these needs. This forms a basic component of the human centered design process. Whereas the technological innovations of DOMUS will be considered in the overall assessment of the vehicle performance, the cabin designs are primarily oriented toward addressing the user needs in the specified use cases. The DOMUS innovations are then added to transform the initial design solutions into more practical, efficient, safe, and comfortable ones, still as part of WP 2.1. The baseline for these different designs is the Fiat 500E in the sense that the chassis and cabin form the basis for the needed transformations. The baseline designs are then modified to meet the user needs, for example by modifying the height of the cabin, the size and use of glass, the seating arrangement, etc. The first version of these novel cabin designs will be hand drawings. The hand-drawn cabin designs are then transformed into 3D CAD models for use in WP 2.2. The number of novel cabin designs that will be evaluated in WP 2.2 will be between two and three. The definition and selection of designs will be influenced by multiple criteria, for example, how well DOMUS innovations will be able to be integrated into the novel cabins to virtually assess an impact on the efficiency and comfort impact of the designs.

8 Discussion and Conclusions

This deliverable proposes a multi-objective assessment framework for the virtual assessment of car cabin comfort systems. The central goal of the assessment framework is to assess the comfort control system and the associated cabin environment in a user-centric way. To support this, it considers not simply the temperature of the cabin but rather the thermal and acoustic comfort (which will be developed in Wp1.2), the energy cost, and safety of the user. While safety is primary, each of the other aspects must be normalized and balanced.

The approach to forming the framework has involved a mixed methodology that included expert interviews, expert surveys, and end-user surveys.

The instantiation of the framework may have some flaws. Specific weaknesses include:

- Only a limited set of experts were interviewed or surveyed. A larger population of experts might yield a more robust result. On the other hand, the total world population of experts in this specific area is small and thus even the sample here could be considered to be a large enough sub-sample.
- Only a limited end-user population (41 respondents from COV, TME, iKA, CRF, IDIADA and ViF) responded to the questionnaire. A larger sample may change the values obtained for the fitness function weights.
- The preferences that users express here may change when they come to use the car. Again, this suggests that the results for the fitness function weights may not be the last word.
- Climate change is tending to increase observed temperatures over time. The choices made for the scenario database may thus not be representative of typical temperatures in the future. For this reason, we have chosen recent time points (within the last two years). If needed, new time points can be selected, in response to climate change, to ensure that the scenario database is more representative.
- Real experience with systems developed in this way may cause the users to uncover a rationale for increasing the weight of one element or decreasing the weight of another. For example, energy cost may become more or less important over time due to energy price changes or improved battery technology.
- The selection of cities for the scenario database is intended to match the distribution of populations and vehicles over different climate regions. Naturally, this matching may be imperfect.
-

Notwithstanding these restrictions, we believe that this framework addresses the key shortcomings of past approaches and mean that the framework is *user-centric*. Specifically, it focuses on user experience over time rather than time to target temperature. This focus includes:

- a holistic view of comfort (considered in task 1.2, which is provided in forthcoming deliverable D1.3).

- a scenario database with selected scenarios preferring highly populated areas.
- a fitness function that balances the weights for comfort, and energy according to end-user responses.

Finally, it is important to note that this approach opens the way to optimization. In doing so, we note that opportunities may exist for improvement based on, for example:

- Considering a different strategy for when the windows are open and / or suggesting, via the HMI, that the user open or close windows.
- Pre-conditioning the car prior to the user entering the car.
- Using radiant panels or heated seats to heat specific regions of the car rather than only using blown air.
- Blowing air faster where that heats more efficiently and doesn’t cause reduced acoustic comfort.

9 Recommendation

1. We recommend that the consortium adopt this framework for virtual (simulation-based) assessment of the car cabin and associated control algorithms related to provision of thermal comfort.
2. We recommend that the framework be left open to revision as improvements to aspects of the framework are discovered.

9.1 Key equations

The normalized fitness function per time is given below as:

$$\boldsymbol{f_n(t) = 0.523c(t) - 0.4770e(t) + 2(s(t) - 1)}$$

The normalized fitness function for a given scenario is given as:

$$\boldsymbol{F_n = 0.523C - 0.4770E_n + 2(S - 1)}$$

The overall fitness function evaluated for all scenarios is given as:

$$\boldsymbol{F_0 = \frac{1}{N} \sum_{i \in \text{Scenarios}} w_i \, F_n(\text{scenario } i)}$$

where N is the sum of all the scenario weights.

Due to the limitations to the questionnaires indicated in Section 5.5.16, value judgements against the fitness function would be required.

10 Risk register

Risk No.	What is the risk	Probability of risk occurrence1	Effect of risk2	Solutions to overcome the risk
1	Only a limited set of experts were interviewed or surveyed (Section 3.4.1, Appendix B). A larger population of experts might yield a more robust result. On the other hand, the total world population of experts in this specific area is small and thus even the sample here could be considered to be a large enough sub-sample.	0.5		The framework may need to be adjusted when used in practice to reflect real user needs.
2	Limitations to questionnaire design and responses might affect fitness function weights (Section 5.4.16).	0.5		The fitness function may need to be adjusted when used in practice to reflect real user needs.
3	The list of scenarios used is not exhaustive. This might affect the overall fitness function	0.5		The scenario database may need to be updated to reflect real user needs.

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1 Probability risk will occur: 1 = high, 2 = medium, 3 = Low
2 Effect when risk occurs: 1 = high, 2 = medium, 3 = Low

11 References

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Project partners:

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1	IDIADA	IDIADA AUTOMOTIVE TECHNOLOGY SA
2	CRF	CENTRO RICERCHE FIAT SCPA
3	TME	TOYOTA MOTOR EUROPE
4	Volvo Cars	VOLVO PERSONVAGNAR AB
5	AGC	AGC GLASS EUROPE SA
6	DNTS	DENSO Thermal Systems S.p.A.
7	Faurecia	Faurecia Sièges d'Automobile
8	HUTCH	HUTCHINSON SA
9	IEE	IEE International Electronics & Engineering S.A.
10	LIST	LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY
11	COV	COVENTRY UNIVERSITY
12	Fraunhofer	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.
13	IKA	RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN
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16	UNR	UNIRESEARCH BV

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13 Appendix A – Interview transcripts

13.1 Interview 1 (Oral)

Expert: My role and background has been to work on developing a heating ventilation and air-conditioning system for passenger vehicles for 10 years now.

JB: Do you have a specific role within the team or is it just you've done lots of different things – now you're managing that team?

Expert: I'm actually the only expert in TME on this topic

JB: ok, wow - you're the man

Expert: yes – actually there have been some Japanese staff that come and go but I've been the only member who's been there for the last 10 years.

JB: ok, brilliant, ok.

JB: so, given that I've given a summary of what the assessment framework is, do you think you already have, in your working practice, something that is equivalent, that you have an assessment framework – a way that you say, ok, this is how we assess cars, whatever that might be. Ok, I know that I'm not supposed to ask you detailed questions about what that is, but do you think you have an idea of what that assessment framework consists of?

Expert: we have several assessment frameworks for, definitely, for each items of the car and we definitely have assessment methods and framework for thermal comfort, for demisting performance, which relates to safety, and for fuel consumption. We try and combine the different performance and trade-off considering overall energy management. We don't have an assessment framework which is holistic, and which considers all these items over a fitness function

JB: ok, so, you are saying that a holistic approach might be a very good thing in comparison to …

Expert: it's interesting

JB: ok, great, so, which leads onto the next question – what makes a good assessment framework? If someone comes to you and says here is an assessment framework that I'm dying to try out, what would you say to them? Would you say "oh, make sure you do these three things"

Expert: I think a good assessment framework must, in the end, reflect the user perception. Also, if it is a holistic assessment framework, it needs to match the holistic user perception. That means user has a perception of what is fuel consumption good or bad. What is safety acceptable or not. What is comfortable, acceptable or not. And so a user might take decisions and adjust different systems of the car based on the user's own perception of these different areas. A good assessment framework would reflect as much as possible a wide variety of users. That would be my image of a good assessment framework especially a holistic one.

JB: So it should take into account the variation that exists in the real population?

Expert: Indeed. At least if it can capture part of the population well it's already a good achievement.

JB: Alright

Expert: As a counter example, a bad assessment framework would be an assessment framework which attributes a good fitness result to a car and in the end the user might be dissatisfied and try to operate the car in a different way because actually the assessment, the fitness didn't correspond to a fitness judgement that would have been given by the user.

JB: Do you find that you go through this process where you have an assessment framework and then you realize that people are reacting poorly to it or poorly to the result and then say "Ah, this means we need to change the assessment framework". Do you have a feedback mechanism?

Expert: Yes, this is how the industry has been evolving over the past decades basically by adjusting to customer voice. So the feedback in the process is the user feedback through customer surveys, various sorts of customer voice through different channels.

JB: ok, so, my fundamental challenge here is that having come in in a sort of, maybe seeing this as more of an academic issue, um, is it even conceivable that I'll be able to do a reasonable job of building an assessment framework given that I don't have the background that you have. I'm just wondering whether or not … is it … what process would you recommend that we go through within the DOMUS consortium. Do we need to come back to you?

Expert: Not necessarily. I would recommend to keep some flexibility in the … the biggest challenge I think is the holistic approach. I think you might be successful, even for the holistic but doing it with assessment for each of the performance items: comfort, safety, energy; might be not too difficult individually because you might do some correlation and try to validate one by one but then the weighting might be a challenge. so maybe a good approach would be to propose different fitness functions or something like this for example, now I have a priority for comfort; a fitness function with priority for energy management; and another one with a priority for safety although safety is a kind of must requirement but just as a hypothesis and actually have examples of implementation of it concretely – many cars have some kind of selection; drive mode selection or something like this where the user can select comfort mode or eco mode so actually the industry already came up with this kind of approach so at first you might try to implement it in your fitness so you might not have only one but you have one if we give priority to eco, one if we give priority to comfort and some room for adjusting in future

JB: yes

Expert: considering future adjustment

JB: I think this is exactly how we were thinking about the problem … or at least going towards thinking about it because I think it is a big challenge to put a single number, any single number on any of those weights. ok, um, so we have, I have some notes on the fitness function later. so, yeah, um, do you think this evaluation framework could also, because it is intended as simulation only, but do you think it could also apply to existing in-car evaluations, say within a climatic wind tunnel.

Expert: why not?

JB: right.

Expert: just as you said, in the end the simulation would provide what the sensor would provide. sometimes by testing some heat fluxes or some physical values are difficult to measure by testing, especially in a non-intrusive way. That would be one benefit of the simulation. The simulation has many difficulties. um for example, related to accuracy, because it depends on your model; accuracy, your ability to collect all the material properties and many things. these are some of the challenges of simulation, which you don't have in the testing. so both have pros and cons and both approach coexist and could benefit to each other.

JB: yes – for me I would want to head towards a process of alignment. What differences exist specifically between this proposal and the current methods that you feel might affect the quality of the evaluation?

Expert: I would say it wouldn't affect the quality of evaluation as much as it would affect the decision making. This is a key point. Because I would say here, one of the novelty and the key point is to try to have an overall fitness and holistic approach. This is one of the biggest challenges and very often the answering trade-off is one of the difficult point in the decision making beside the constraints, of course. And maybe one more comment is that in general this is an advantage of the simulation-based assessment method. With the acceleration of the modelling and the computing capabilities you might do different types of design of experiments and multi objective design space exploration and identify the Pareto frontier for multi objective optimization, which is very difficult by testing due to resources, time. Even though there is a trade-off, I believe that by simulation, you can find the optimum, or the pareto front, multi objective optimization. This is also part of the DOMUS project, I think.

JB: Yes, although I'm not completely convinced that we are going to have the simulation power to be able to do the full Pareto front, but we'll try. I want to ask some questions about past issues. Thinking about past experiences, I know there are a lot of things you can't reveal, but I was wondering if there is anything that you can tell me about in terms of the thermal comfort system, the issues that arose previously. To give an example, I think with JLR they found that they had particular user groups that they put their systems in to. Say the Japanese market for example, who preferred the system to be very quiet whereas the US market they found that actually that if it wasn't making a lot of noise that the user didn't think that it was actually working properly. So, is there any things like that that you can …

Expert: Yes there are several challenges of course. Probably all OEM must have found out that there seems to be some regional preferences. There is a lot of theories behind it but my personal experience is that it is mostly cultural related rather than some physiological. It is more due to the environment and habits of people. You get used to something so that you are searching for this kind of performance because in your environment in your house heating. There is differences so somehow it might be included, it might be considered. On the other hand I would not focus too much on it (regional differences). Because for example, some OEM went into very very complex heating ventilation and system where the user could customize many adjustments like temperature balance between upper, lower, ventilation and everything but they seem to have gone back a little bit and my experience looking at my relatives and friends and everything is that people like a system that keeps pretty much simple

JB: So are there any other past corner cases or special circumstances?

Expert: In general, the noise. Indeed, for the ventilation system there are some main targets. like achieving comfort means pleasantly warm heat or something keyword is pleasant in winter and ability to cool, and pleasantly cool and humid environment and of course demisting of … securing of visibility and all this at acceptable noise level. And the trade-off between comfort and noise is very interesting because depending on the segment of the car usually this trade-off is better or worse. higher segment cars usually achieve better performance to noise ratio than lower segment cars. And on lower segment cars you might find that, kind of based on our thinking or criteria, the car is noisy, but the performance is good. then if we look at customer feedback, they don't complain about the noise, but they complain about the performance, which would mean that they would reduce for example the blower from what we have considered because actually for them the noise was the priority. just we didn't consider this multi performance assessment. we didn't consider noise and we treated that separately. so, in the end the user would reduce the blower for example and the user wouldn't complain about the noise but complain about the performance. So this … My experience with my US colleagues is that people wouldn't want so much the noise but want the so-called "punch feeling" – they need to feel the airflow like a punch in your face. Punch feeling is appreciated.

JB: In terms of pre-heating of the cabin prior to entry, can you give me an idea of what a fair assessment of this would need to take account of. An example might be it would need to take care of the energy cost, the effectiveness of the heater, the reliability of the information about when heating is required.

Expert: Pre-heating its quite challenging. At the moment not so many cars have pre-heating. Two groups of cars have pre-heating: It's either electrified with a charging capability. PHEVs and EVs. and then the pre-heating function is usually associated with charging situations. The other group of cars are cars which have a fuel fired heater. For example, diesel cars, after market or manufactured device, where a stove heater, basically, is heating the cabin. In both cases, actually, the charging situation or the conventional heater, range or fuel consumption is not the priority; the priority is performance. So I would say that here … the one that can bring the cabin as fast as possible to the highest comfort level based on the selected comfort without priority to the energy.

JB: Presumably then you would need to have scenarios for pre-heating with it being plugged in, in which case there is essentially no energy cost, but also you need to make sure that the system doesn't try to pre-heat when it is not plugged in or that if it does, it does so in an efficient way.

Expert: But if you do it – if you go for the non-plugged-in, it's going to be difficult to do a fitness function without considering the range of the car, because actually if we are thinking about electrified, so really the direction is electrified, the key point will be the range. I take the example of a PHEV. Most PHEV have a battery of around 10 kWh, which allow you to drive 50 km when the stars are aligned, or 20 km in a more realistic condition. If you do pre-heating your range will go down to zero very quickly. So, and if you have a car like a very famous Californian manufacturer, with a pretty huge battery where you can hundreds of kilometers, then even if you spend the equivalent of 100 km, it's ok because you still reach your destination. So then to say whether it's acceptable or not would really depend on how much the range reduction affects, how much the energy affects your range reduction. Maybe if you consider it as a percentage or something but then it should be linked to the range and it should be per vehicle. Or you need to think about it in your assessment method.

JB: You should possibly not think just in terms of energy cost but you should think in terms of percentage range reduction?

Expert: Yes and finally, as I said in the beginning, it's impact to the customer. To the customer, 1 kW, or 2 kW is it 1 euro or 2 euro, but the top priority should be can I reach this destination or not or will it match my needs of the car – I reach destination but I have another trip, can I recharge? So it is really try to think whether it will meet the user needs. If the user say no I would not something, ok then sacrifice comfort. first priority will be mobility. so try to really always think link the assessment method to the user impact.

JB: Presumably at the same time avoid making the whole thing so complicated that nobody can understand?

Expert: Yes and keeping some flexibility. Room to adjust in the future. Still pick up many things are changing so …

JB: Another novel feature that's been proposed with the DOMUS project is to use PCMs. So same question again – how do we make sure we have an assessment framework or a scenario that appropriately rewards or penalizes a good or bad PCM introduction?

Expert: Phase change material is tricky. You need to identify use cases and scenario and aim for most frequent as most PCMs have target temperature depending on the type of melting point depending on the type of material. You will size your system based on the parking duration or something like this. If we're thinking about keeping heat, there are also PCMs for battery terminal management but maybe not what you are thinking about – it's more for cabin comfort?

JB: More for cabin comfort

Expert: So here it is about trying to identify the most frequent the most relevant situation and design it – select the system that will …

JB: Generally, about the scenarios, I mentioned the warm up and cool down almost certainly to be included. What other scenarios are likely to provide insightful information.

Expert: Cool down, warm up, but of course also cruising conditions. For cruising, especially for future electrified cars, really the trade-off between comfort and energy is one of the key and I want to say also keeping good visibility both initial defrost but maintaining visibility when cruising in very cold condition, for example, in minus 20 or something like this or minus 10. Or imagine when you have sometimes this freezing rain, actually temperature is freezing and it’s raining. The condition on the windshield is very severe. Consider a selective approach.

JB: That’s a very good guide. So field trials also might be helpful to provide information about real world behavior but what sort of problems tend to be identified in field trials as opposed to laboratory trials

Expert: In low temperature, the misting issues, they’re much better identified in field trials because of the difficulty to get realistic humidity condition in testing environment for several reasons. One is that the car is not preconditioned with the right humidity. All the plastics they absorb release humidity. In the real environment you drive the car and the floor mats, carpets, plastics, everything will be soaked with humidity due to the usage which is difficult to represent in the test. Another one is that many wind tunnels work with super-cold evaporator and desiccant wheel. It’s very very much dry so the air is very dry in the wind tunnel. It’s difficult to control the humidity to the level of real world conditions… although from absolute level, humidity is very low in these low temperatures, but from relative it’s also very low. You cannot reach 80, 90 close to 100 % humidity in cold conditions in a wind tunnel. So demisting is really one of the points in field trials. And realistic radiation conditions. So radiation plays a huge part in the perceived comfort and interior. Radiation from the glazing walls in hot and cold condition. In winter you drive and actually your glass surface temperature might be at 2 degree with a relatively high emissivity and relatively close to your upper body. So even if it’s 24 degrees in the cabin you might feel like it’s 15 degrees because of this glass. In the wind tunnel you don’t have the sky, the radiative environment is different. Also it doesn’t match exactly. But this could somehow be considered in a proper simulation. Radiation and humidity is very interesting.

JB: I have lots of questions regarding fitness function that you have already have answered somewhat.

JB: How much does it cost or how much are users willing to pay for a kWh of energy? I think that’s really not the question – I think you’ve answered it.

Expert: You can refer to the commercial value of different battery packs. Some OEMs offer different battery packs so you can see the price difference. So it gives you an image of how much the customer is willing to pay for range.

JB: What about how they are willing to pay for comfort in comparison?

Expert: You might also find some OEMs that provide a heat pump as an option and then you could estimate the price of this option with regards to other options. Some OEM have heat pump as an option. So efficiency is being charged at the moment to the customers.

JB: And I suppose the other question is, is there going to be a similar thing about windshield fogging. Do you think there are cases where OEMs provide special facilities for windshield fogging?

Expert: Yeah certainly so. For many years there has been wire type heater in the windshield used by many OEMs. More recently there has been the development of coated silver layer on the windshield which has a double benefit of heating in winter and reflecting the infrared in summer. You can find those in mass production in several cars. And everybody is looking at polycarbonate glazing. I think there is a working group to define some new regulation to allow use of polycarbonate for the windshield in Europe because current regulation only allows glass. It is defined in such a way that only glass can be applied on the windshield. Other windows you could already have polycarbonate. But there is more progress to be made to get polycarbonate on the windshield.

JB: In terms of the overall – I can't remember what car we are looking at in terms of – is it mainly the small

Expert: A-segment

Expert: Testing is going to be done; final demonstration is going to be done on A-segment Fiat.

JB: I think you've already answered this – I'll go through the transcript to get the answer – it is the nominal range and nominal battery capacity in terms of kWhs. Perhaps I can ask you supplementary questions when I get confused?

JB: I think that covers all the questions. Any other advice for this process?

Expert: Maybe also would be to consider separately the plugin and the electric cars because for the electric cars if you have 60 kWh – huge – battery pack, losing a bit of range, you don't care. It's ok, you already paid for a huge battery. If you have a PHEV car with a range which goes between 20 and 50 depending on the driving condition, some device which can make your 20 km become 30 or 40, that will be interesting. For electric cars, from 450 to 500 kilometers.

JB: It's a selling point but other than that, not much more.

Expert: So really for the kind of efficiency, it should really be looked at with respect to the range of the car and impact to the customer. This is a key point.

JB: I don't know if we are going to completely get there with this project but we're going to try.

Expert: I think it would be worth thinking about it and leaving some room for it.

JB: Yes, I think we are going towards flexibility. In terms of the fitness function weights it is not about saying these are the weights, it's about saying these are maybe example weights you could start with but we really don't know.

Expert: I would modify the weights to reflect some different situation.

JB: Yes – good point.

JB: Thank you so much for sharing. It's been great to talk with you.

Expert: I'm very interested in this project. I don't have much time to work on it but I'm keeping an eye on it.

JB: We hope to have good results to show you.

Expert: I will be watching it.

JB: OK. Feel free to tell us when things go wrong.

Expert: I will tell to A.

Both: Thank you.

13.2 Interview 2 (Written)

13.2.1 About the framework

1. Can you tell me something about your role in the development of the thermal comfort system?
   The department I work for is focused on developing innovative systems, components and methodologies related to Engine Cooling, Exhaust and HVAC systems, with the aim to achieve the best tradeoff among thermal management targets of the different systems, vehicle performance, fuel economy, product flexibility, cost and weight, environmental friendliness, perceived comfort and well-being.
2. In your opinion, what makes a good assessment framework?
   A good combination of numerical and experimental analyses, where experiments are useful to validate and tune numerical models. Moreover, the scenarios must be chosen in such a way to be related to real user's perception of comfort. For example, it is better to choose a "light" cool down rather than a standard cool-down, which is used to assess the system maximum performance.
3. Having seen the framework:
   a. Does it make sense to evaluate this way in simulation? Why or why not?
      Yes, but models need to be adjusted with experimental data.
   b. Could this evaluation framework also apply to existing in-car evaluation within the climatic wind tunnel?
      Normally in climatic wind tunnel thermal comfort measurements are carried out only, but other measurements related to energy consumption may be added in case of a full electric vehicle, using electric current sensors.
   c. What differences exist between the proposed assessment framework and current methods that might affect evaluation?
      Currently the energy assessment related to thermal comfort is not carried out as a standard process. Cool-down and warm-up tests are performed with procedures and testing environment that are different from fuel economy ones.

13.2.2 About past issues

4. Reflecting on past experiences with developing a thermal comfort system, what issues arose previously?
   One of the main issues consists in retrieving data for numerical models about thermal loads, materials, HVAC control strategy, especially in the early design concept phase. It is necessary to rely on experimental characterization of the previous vehicle belonging to the same segment. Moreover, many parameters need to be considered and optimized in different use cases.
5. Are there known corner cases or special circumstances that need to be catered for in a particular way?
   Comfort models are designed to evaluate thermal comfort near optimal condition, which means that there aren't metrics for transient case far from such optimum: you can only assess if you are in a discomfort situation but cannot give a score. This happens in extreme conditions (very cold or very hot), that are the ones that are more energy demanding.

13.2.3 About novel features

1. Given a system that does pre-heating of the cabin prior to entry, what would a fair assessment of this approach need to take account of? (e.g., energy cost, effectiveness of heat-up, reliability of information about when heating is required)
   It depends whether the vehicle is connected to the charging station or not. In case it is connected, the energy cost maybe less important. The time available to heat-up the cabin is also to be considered: if a short time is available and energy is available, you need to target the heat-up effectiveness. The information about when heating is required can trigger both the system effectiveness and the energy saving.

2. Given the use of Phase Change Materials (PCMs) within the cabin to smooth the change of temperature over time, what sort of test scenario would best demonstrate or test this feature?
   The scenario can be a stop/start cycle after a pre-conditioning phase in which the PCM has time to be "charged". The stationary conditions when the PCM is all solid or all liquid must also be tested, in order to understand how the material behaves in terms of thermal conductivity.

13.2.4 About scenarios

1. Basic tests in CWTs involve warm-up and cool-down scenarios. What other scenarios are likely to provide insightful information?
   Other scenarios should involve real drive cycles, in order to assess the energy consumption associated with thermal comfort.
2. Field trials help to provide information about real-world behavior. What sort of problems tend to be identified by field trials?
   Field trials should identify problems that may arise from the integration and interaction of the subsystems and from the ways they are used by the driver in a real context (e.g. different air vent position, blower speed).
3. How might field trial style problems also be identified in a virtual way?
   In the real use all the parameters (ambient temperature, external wind, solar radiation intensity and direction, …) varies increasing the difficult to reach stationary thermal conditions. It is very time consuming to simulate all the possible transient conditions.

13.2.5 About fitness function

For a specified driving scenario and test vehicle:

1. How much does it cost (or are users willing to pay) for 1 kWh of energy?
   I don't know, maybe users are willing to pay for extra range in EVs.
2. Depending on an EV user's initial thermal comfort perception, how much does it cost (or are users willing to pay) to get thermally comfortable within the shortest possible time during a defined driving scenario? How much time is necessary to achieve this thermal comfort?
   It depends on the ambient conditions: more severe they are, more time is needed. In plugged vehicle with preconditioning system the time to comfort may be close to zero. In my opinion users are willing to pay for extra range rather than to reduce time to comfort, which is considered a "given".
3. Depending on an EV user's initial acoustic comfort perception, how much does it cost (or are users willing to pay) to achieve acoustic comfort within the shortest possible time during a defined driving scenario? How much time is necessary to achieve this acoustic comfort?
   Though the acoustic interior level of an EV vehicle is surely lower with respect to ICE vehicle, the unpleasant sound due to the electromagnetic sources or gear whine can be disappointing, resulting in a drive that is not assessed as comfortable even if the overall levels are not high. Noise from auxiliaries also assume particular importance as it can be a cause of unpleasant sound.
   The capacity of human hearing apparatus to detect selective frequencies in a broadband signal is the source of the annoying effect.
   Nevertheless, the end user of an EV vehicle can be disappointed by resonances or orders and therefore they can pay some euros to avoid this spoiling effect.
   Anyway, the tradeoff between range (and therefore weight) and comfort is highly devoted to range as it is the main problem of EV vehicle and the tradeoff between mass and insulation/absorption has to consider this ratio.
4. Depending on the initial windshield fogging, how much does it cost (or are users willing to pay) to completely clear a foggy windshield within the shortest possible time during a defined driving scenario?

Also, in this case, even more than in previous ones, users are not willing to pay to reduce defogging time, it is a "must" for safety reason, regulated by specific vehicle homologation norms.

13.3 Interview 3 (Written)

13.3.1 About the framework

6. Can you tell me something about your role in the development of the thermal comfort system?
   Expert 1 – Climate Architecture Team. Working with the architecture and more specifically the energy use of the climate system.
   Expert 2 – Technical Expert Climate Systems. Working with all areas related to climate comfort.
7. In your opinion, what makes a good assessment framework?
   Too large open ended question…
8. Having seen the framework:
   a. Does it make sense to evaluate this way in simulation? Why or why not
      Yes. In many ways this would be a really good way to evaluate systems in simulation. However, creating the weights for different attributes is very difficult. Furthermore, the accuracy of the model to be able to answer in absolute values (which would be important for comparing/weighting different attributes) must be (very) high. For evaluation of new concepts this is a very good method. For a first step relative results are acceptable (and of course better than nothing).
   b. Could this evaluation framework also apply to existing in-car evaluation within the climatic wind tunnel?
      Yes and no. Many systems and solutions are already decided when a vehicle is available for evaluation. Vehicles tests are done more for verification and climate software calibration. (and concept evaluations/advanced engineering projects are done separately). Large modifications on a complete vehicle is complicated.
   c. What differences exist between the proposed assessment framework and current methods that might affect evaluation?
      The described traditional method is very simplified, many more steps are included in current development.
      The largest differences are that for a traditional system there are a lot of knowledge available before the development. For example how different cabin temperatures during a cool down corresponds to customer satisfaction. Furthermore, there is knowledge about the outlet temperatures and airflow that are required to achieve the cabin temperatures and AC-system setup to achieve the cooling power for that flow and temperature. In other words, for traditional systems (and relatively small system changes) many trade-offs are done earlier based on simulations and/or engineering judgements.
      Road tests are a common method to develop and verify the complete climate systems. I.e. subjective comfort evaluation by different people such as calibration engineers, attribute leaders and test engineers.

13.3.2 About past issues

9. Reflecting on past experiences with developing a thermal comfort system, what issues arose previously?
   There are many, many specific technical issues that arise in almost all development of new vehicles. However, the work consists mainly of balancing styling, cost, packaging and performance.
   Another aspect is that many issues are not technical, instead cooperation with departments developing related systems are often can cause problems.

10. Are there known corner cases or special circumstances that need to be catered for in a particular way?
    There are countless cases and circumstances that can be very difficult to foresee. Often these types are found and handled on one platform, pre-empted on the next platform and resurfaces

on the third platform. Competences move around in the company and everything cannot be (or aren't) handled with requirements.

13.3.3 About novel features

3. Given a system that does pre-heating of the cabin prior to entry, what would a fair assessment of this approach need to take account of? (e.g., energy cost, effectiveness of heat-up, reliability of information about when heating is required)
   Most important is to do what the customer wants the system to do. I.e. do the customer want a preconditioning that's what he should get (even if the range is impaired (until limp-home-functionality)). For a predictive preheating the accuracy of must be high. Customer will not be satisfied if they do not understand why the car is preconditioned sometimes and sometimes not.
4. Given the use of Phase Change Materials (PCMs) within the cabin to smooth the change of temperature over time, what sort of test scenario would best demonstrate or test this feature?
   Not convinced that this will help. The PCM is required to be preconditioned before start; otherwise, the system will use more energy during driving than compared with a system without. Note that a cabin has higher set temperature in winter compared to summer (to compensate for radiation effects), i.e. different comfort temperatures. This affects a what temperature the PCM should change phase.

13.3.4 About scenarios

5. Basic tests in CWTs involve warm-up and cool-down scenarios. What other scenarios are likely to provide insightful information?
   There are many, many tests possible depending on what type of information is needed. Fog / mist susceptibility and defroster performance, i.e. wet cabin in cold conditions. Calibration of the climate control software for all temperatures is probably the most time consuming tunnel test during development.
6. Field trials help to provide information about real-world behavior. What sort of problems tend to be identified by field trials?
   Control software debugging. NVH (blower, ac-compressor noise). Special cases. Unforeseen complications when all thermal systems finally are integrated, i.e. lot of interaction between different control software's.
7. How might field trial style problems also be identified in a virtual way?
   Simulation of complete systems… Integrating NVH and thermal systems (and control). However, trying to replace late vehicle verification with simulation has a low output/input ratio, especially compared to doing early work with simulation. Best use of simulation is to increase knowledge about systems early before real vehicles are built. And increase the performance of these systems.

13.3.5 About fitness function

For a specified driving scenario and test vehicle:

1. How much does it cost (or are users willing to pay) for 1 kWh of energy?
   Do not know.
2. Depending on an EV user's initial thermal comfort perception, how much does it cost (or are users willing to pay) to get thermally comfortable within the shortest possible time during a defined driving scenario? How much time is necessary to achieve this thermal comfort?
   Cannot answer
3. Depending on an EV user's initial acoustic comfort perception, how much does it cost (or are users willing to pay) to achieve acoustic comfort within the shortest possible time during a defined driving scenario? How much time is necessary to achieve this acoustic comfort?
   Cannot answer
4. Depending on the initial windshield fogging, how much does it cost (or are users willing to pay) to completely clear a foggy windshield within the shortest possible time during a defined driving

scenario?

Cannot answer