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Reconfiguring Vehicles for Drivers with Disability: A Knowledge-Based Decision Support System

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Abstract: Driving a car is pivotal to supporting Persons with Disabilities (PwDs) independence and quality of life. The problem of reconfiguring a vehicle to meet both the PwD's needs and the (local or supranational) regulations is far from trivial since it requires the identification of the appropriate modifications and adaptations to be installed on the driver's car. However, PwDs may not be acquainted with the mechanical modification, aids, and devices installed on their cars to allow them to drive, nor may they be aware of the possible configurations available. In the Italian context, this knowledge is strictly regulated by local and European regulations, which—according to the type(s) of impairments a driver has—indicate the possible configurations for the vehicles and the aids and mechanical modifications that need to be implemented. Therefore, to support PwDs in understanding the possible modification(s) their cars could undergo, a novel knowledge-based Decision Support System (DSS) was developed with the support of the Italian National Institute for Insurance against Accidents at Work (INAIL). The DSS exploits ontological engineering to formalize the relevant information on cars' modifications, PwDs' impairments, and a rule engine to match candidate drivers with the (sets of) car configurations that can be installed on their vehicles. Thus, the proposed DSS can enable the drivers to acquire more insights on the types and functionalities of the driving aids they will use. It also supports INAIL in administering the "special driving license".

Keywords: ontology engineering; ontology-based decision support system; car configuration; drivers with disabilities; decision support system

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1. Introduction

Disabilities and impairments significantly impact a person's ability to perform several activities. Among these activities, the ability to drive a vehicle is fundamental to fostering persons with disabilities (PwDs)' independence [1]. However, disabilities and impairments can hinder driving abilities, especially when they result in a loss of capacity in the upper or lower limbs. Permanent impairments to upper and lower limbs often result in the inability to drive a "standard" vehicle—i.e., any vehicle designed and manufactured for persons not characterized by any disability or impairment.

PwDs with permanent limitations or impairments to upper and lower limbs may experience difficulties in maneuvering a car using the steering wheel, shifting gears with the stick shift, or breaking and accelerating using pedals. In other words, "regular cars" may not be equipped to ensure PwDs' driving. Moreover, a PwD's personal aids—such as a prosthesis or orthosis—cannot ensure safe driving since they enable only a portion of the functions of the limb they replace. Therefore, cars need to be adapted to meet PwDs' physical needs for driving safely. The adaptations may involve the vehicle mechanics and the provision of user-specific aids, depending on the driver's health condition and impairments.

Disabilities and impairments can also appear as a consequence of accidents or conditions that affect an individual after he or she has learned how to drive a regular vehicle. Thus, the modification of a vehicle implies the drivers (with disability) relearn how to drive a car with the mechanical modifications and aids that characterize its new configuration. Before that, drivers need to become acquainted with the aids and modifications that could characterize their cars.

Nonetheless, it is possible to reconfigure a vehicle in different ways to meet a PwD's needs. The selection of the modifications depends mainly on two factors:

1. The driver's health condition dictates the types of aids, devices, and mechanical modifications that can be adopted for a vehicle.
2. The regulations characterizing the country in which the modifications on the vehicle are executed.

Vehicular modifications constitute a legal requirement for driving a car when disabilities or impairments characterize a driver. Moreover, it is also required that drivers with disabilities regain access to a driving license (named "special driving license" in Italy). This type of driving license is granted by a medical committee, which analyzes the candidate driver's health status and specifies the driving aids and mechanical modifications of the vehicle; in some cases, they can also specify restrictions to the use of the vehicle, depending on the severity of the impairments.

The knowledge necessary to indicate the modifications and driving aids to be provided is codified in a set of local and European laws. The aim of this paper is to introduce a Decision Support System (DSS) leveraging such knowledge to support drivers with disability in understanding the possible modification(s) their cars could undergo; in this way, the driver can be enabled as an active part of the decision and can acquire more insights of the types and functionalities of the driving aids he or she is going to use. The knowledge relevant to the DSS is formalized relying on domain ontologies—i.e., shared and formal conceptualizations of a domain of knowledge–, developed leveraging the support of the Italian National Institute for Insurance against Accidents at Work (INAIL). In Italy, INAIL is the institution that supports PwDs in obtaining the special driving license, providing candidate drivers with essential information about the regulations, evaluating the driving skills, guiding in the selection of car configurations that support candidate drivers, and making candidate drivers test some reconfigured vehicles. The DSS can be accessed via a prototypical application, which can serve both the medical committee and the candidate drivers in understanding and selecting the modifications to be applied to the PwD's vehicle. In principle, candidate drivers and clinical personnel should use Rip@rto DSS to discuss together the modifications proposed, understanding the set(s) best suiting the driver's preferences, and providing PwD with more information regarding specific aids.

The remainder of this paper is organized as follows: Section 2 reviews scientific literature to identify works related to the reconfiguration of vehicles for PwDs, with the aim of identifying the main trends in such a topic. Section 3 briefly illustrates the laws and regulations characterizing the framework for the adaptation of vehicles for drivers with disabilities, focusing on the European and Italian perspectives. Section 4 describes the architecture of the DSS, with particular attention to the ontological layer, its engineering phase, and its reasoning capabilities. In the same section, the prototypical desktop application of the DSS, aimed at illustrating the general features expected from the definitive version of the DSS application, is introduced. Section 6 discusses the proposed DSS and its functionalities, highlights some limitations of the proposed approach, and underlines some research directions. Finally, the Conclusions summarize the main outcomes of this work.

2. Related Work

The problem of the reconfiguration or modification of vehicles for PwDs has been addressed in the literature mostly from the rehabilitation and design [2,3], psychological and social [4], and user experience [5] perspectives. Moreover, especially during the past three decades, many studies were dedicated to the design of driving aids for PwDs. Although these works are prior to the European Framework (see Section 3), they investigated fundamental aspects of driving and PwDs, such as driving for wheelchair users [6], the development and deployment of aids and accessories for PwDs [7], and the preliminary definitions of aids prescription guidelines [8] and drivers' safety [9].

While these perspectives are fundamental in underlying drivers with disabilities' needs in several fields (including the acquisition of knowledge pertaining to aids and vehicle modifications), very little is said regarding the adoption of computer-based systems to foster the satisfaction of such needs. In this section, we reviewed the scientific literature to identify works addressing the topic of DSSs in the fields of vehicular modifications for PwDs by adopting a Systematic Literature Review approach. The review methods and its results are presented and briefly discussed in the following subsection.

2.1. PRISMA Literature Review

The methodology adopted for the literature review is the Preferred Reporting Items for Systematic Reviews (PRISMA) [10]. The approach consists of three steps (article retrieval, screening, and inclusion). Thus, the research question investigated was searched in the Elsevier Scopus and Web of Science databases translated into the following query:

((vehicle modif) AND disab*))*
OR
(driver AND disab*)*
OR
(((vehicle config) OR (car config*) OR (vehicle reconfig*) OR (car reconfig*)) AND disab*)*

The databases were searched for journal articles, book chapters, and conference proceedings in English, and they were limited to the subject areas of Computer Science, Engineering, and Decision Sciences. No time constraints were set for this search, and articles "in press" were also considered—since they are included in the databases.

Figure 1 schematizes the PRISMA review process and its quantitative results.

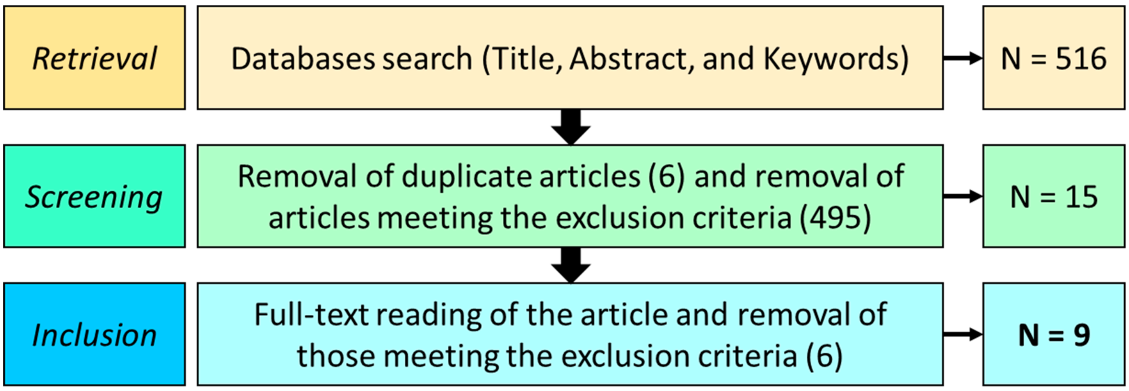

Figure 1. A diagram representing the PRISMA flow and the quantitative results.

The search in the databases retrieved 516 records, which were reduced during the screening phase to 15. The screening phase (and the inclusion phase) were conducted under the following exclusion criteria:

- The paper addresses autonomous vehicles, public transportations, or any other system for a PwD mobility other than his/her car
- The paper investigates wheelchairs outside of their role in driving activities
- The paper concerns accident prevention or vehicle traffic monitoring

The exclusion criteria allowed us to focus on identifying solutions for PwDs devoted to assisting them in driving, adapting their vehicle, and acquiring (or re-acquiring) driving skills after an impairment or disability.

The 15 works included were reduced to 9 during the inclusion phase, in which all the articles were read.

2.2. Results

The amount of included works includes three journal articles and six conference proceedings. The selected work span from 1989 to 2024. The majority of the works is concentrated in 2023 (four papers). The full-text reading conducted in the inclusion phase allows us to classify the topic(s) addressed by each work (Table 1).

Table 1. The list of included works with the illustration of their main topics.

	Year	Type	Topic	Description
[11]	1989	Conference	DSS	Clinical DSS for the identification of equipment
[12]	2021	Journal article	Equipment	Study of a feature for equipment
[13]	2022	Journal article	Simulator	Training and assessment
[14]	2022	Conference	DSS	PwD-dedicated DSS for the selection of equipment
[15]	2023	Conference	Equipment	Equipment to support coping
[16]	2023	Journal article	Equipment	Design of a piece of equipment
[17]	2023	Conference	Simulator	Training and assessment
[18]	2023	Conference	DSS	PwD-dedicated DSS for the selection of equipment
[19]	2024	Conference	Simulator	Training and assessment

Among the included works, two conference papers ([14,18]) describe specific and preliminary aspects of the DSS proposed in this work.

2.3. Discussion on the Findings of the Literature Review

The papers are equally distributed among the three main topics: three works discuss DSSs, three papers investigate the design and development of equipment to help drivers with disability cope with a specific aspect of their disabilities, and three works illustrate simulators for training PwDs for driving and to assess their progress or residual driving abilities.

The first example of DSS dedicated to suggesting adaptive equipment for drivers with disabilities among the included works is dated 1989. Wheeler et al. [11] intended to develop a tool to assist rehabilitation professionals in determining the suitable equipment for the personalization of vehicles for persons with a physical disability. The result—Knowledge-based Adaptive Driving Equipment Tool (KADET)—consists of a prototype application evaluated by experts; however, it is not specified what types of equipment KADET can suggest. In [14], the development of a domain ontology for a DSS aimed at supporting car reconfiguration for PwDs is addressed; this work is also completed by its front-end application [18], a mixed-reality application developed to support PwDs in acquiring knowledge about the equipment (as mentioned above, these two works constitute the basis of the DSS proposed here).

Regarding the studies that address the design, development, or discussion of equipment for drivers with disabilities, the topics addressed span significantly. In [12], a particular aspect of the EU Directive 2015/653 [20] is investigated. The Directive stresses that the maximum force a PwD could exert on the vehicle's primary controls could be adjusted; in other words, the force required to operate with the brakes and steering wheel can vary. Thus, the authors defined the steering and braking operative forces in driving as necessary for the physical assessment before in-car on-road driving assessment of drivers with physical disabilities. Salem and Boutaba [15] proposed a system to convert auditory cues into displayed alerts: the system consists of a piece of equipment thought for drivers with auditory disabilities; the system adopts data-driven techniques to enable sound recognition and then compares acquired sounds' spectrograms to properly classify the auditory cues and convert them into visual alerts. In [16], the design of a combined brake and accelerator pedal for drivers with disabilities (affecting lower limbs) is presented. The design process results consist of a pedal capable of reducing braking and accelerating activities interference and, thus, makes it easier for a PwD to drive.

In the area of simulators for the (re-)acquisition of driving abilities, Ricci et al. [13] described an open-source simulator for training and assessment of a PwD's driving abilities (ADRIS). ADRIS allows for setting customized features (such as adaptable driving controllers) and testing in different virtual environments and conditions, enabling physiological data acquisition. Arlati and colleagues [17] introduced VRoADS, a virtual reality-based simulator, to support clinical assessors in evaluating a PwD's driving-related abilities. VRoADS was developed as an "upgrade proposal" of the existing simulator in INAIL, reproducing the same assessing tests (steering wheel rotation, braking, peripheral view, acoustic reactions, etc.) in a more ecological and immersive environment. To grant access to driving training and acquire data on a PwD's progress, Jones and colleagues [19] proposed a virtual reality-based simulator prototype (DriVR). Although the aims are similar to those addressed by the other two simulators proposed, DriVR adopts different technologies.

Three main directives seem to guide researchers on this matter: the development of DSSs, the provision of a simulator capable of supporting training and assessment of PwDs, and the design and development of specific pieces of equipment that should support drivers with disability in coping with the limitations imposed by their physical conditions.

While the simulators insist on the same aims (supporting the (re-)acquisition of driving abilities and assessing them in their progress or in their residual abilities), the DSSs retrieved also share similar purposes (identify and recommend equipment, or aids, or car configurations) but for different audiences. KADET [11] is thought for clinical personnel involved in the rehabilitation of drivers with disabilities, while the other DSS ([14,18]) are devoted to PwDs. The difference between the two systems could be explained in the light of their publishing years: KADET is dated 1989, while the other is dated 2022. This could mean that at the time of developing KADET, there was no consolidated (and European) regulatory framework capable of supporting clinicians in identifying the appropriate equipment; on the contrary, after 2016, a European Directive provided supranational guidance in this regard. Differently from the two previous directives, the design and development of pieces of equipment present variegated outcomes; although the aim remains the same for all the works (support drivers in coping with their physical limitations), the impairments and necessities addressed are considerably different; thus, this makes the outcome likewise different.

The very few papers included allow us to underline a significant phenomenon. The retrieved simulators and equipment devoted to PwDs and driving, as well as the works pertaining to the DSSs, point towards the adoption of the European regulatory framework as a "standard de facto" on the topics of vehicle adaptations ([12,14,17,18]).

The temporal distribution of the paper and the case of one relevant work "older" than the others indicates that the researcher's attention on such a topic has only started to rise recently. Nevertheless, Wheeler et al.'s work [11] clearly suggests that the issue pertaining to the identification of the equipment and devices that could be used to reconfigure a PwD car is not new. Considering the year of publication of most of the works, it may be plausible that the possibility of relying on a consolidated regulatory framework could have played a pivotal role in developing this research area. The pervasiveness of the European normative is not limited to the field of DSSs, but it also guides research on equipment and simulators. Therefore, it is safe to conclude that this regulatory framework marked a milestone for the European countries in the area of car reconfiguration for PwDs. Nonetheless, it is evident that the European laws are far from perfect, as underlined in [12]. Yet, they provide a fundamental perspective for the topic addressed.

Another noticeable fact pertaining to the DSSs in the investigated research area is the lack of data-driven solutions. This may indicate that there are no exhaustive datasets on car reconfigurations for PwDs and that the knowledge-based approach may be (so far) the only feasible way to arrive to a DSS. This would also imply that knowledge-based solutions would require reliable sources of knowledge.

2.4. Findings and Remarks

The literature review underlines that PwDs and driving is a very recent topic. However, there exists a variety of solutions to such a complex problem, and this phenomenon is reflected in the results of the review (Table 1). The very few papers related to the development of DSSs are dated 1989 and, more recently, 2022 and 2023. The latter two studies are preliminary works of the DSS described here and, thus, leaves KADET [11] as the only DSS to compare our solution with. Differently from KADET, the Rip@rto DSS leverages EU and Italian norms to formalize a semantic knowledge base; moreover, Rip@rto is devoted to the collaborative selection of aids and devices by PwDs and clinical personnel.

The review process has some limitations: the query is focused on car reconfiguration, so to elicit those works that specifically cover these particular aspects. However, it is worth observing that the evolution of research towards unmanned and autonomous vehicles may support driver with disabilities in a different way [21,22].

3. Regulatory Framework for Drivers with Disabilities and Vehicle Modifications

This section provides a few coordinates on the laws and regulations characterizing the situations of driving for PwDs and modifications of vehicles following a permanent impairment or disability. This section will focus on the case of the European Union since—as highlighted in the previous section—it seems to cover a pivotal role in the field of car reconfiguration; this is true also for the Italian context, in which INAIL operates as the institution in charge of providing PwDs with suitable car modifications.

During the past ten years, the EU has made an effort to standardize access to the special driving license, which was previously managed by single countries with different local regulations. The first effort of this homogenization effort is the EU Directive 2015/653 [20], which was adopted in all EU countries, including Italy, in the following two years. In particular, Italy incorporated this Directive in the national "Codice della strada" (a set of laws and regulations to discipline local traffic) [23].

The identification of a driver's disabilities and impairments and the consequent selection of mechanical modifications, devices, and aids follow a strictly regulated process: the driver's physical and cognitive abilities are assessed by specialized health professionals (a medical committee), who are in charge of identifying a person's impairments and their magnitude and, thus, assesses his or her residual abilities for driving. The process may also result in limiting the driver's possibility to drive under certain circumstances: for instance, a driver may be required to drive within the limits of a specified radius from his or her city, or she/he may be prevented from driving on highways, or she/he may be restricted from driving during night hours or for a time longer than a specified amount, or she/he is required to always have a passenger accompanying her/him. These specifics are coded in EU Directive 2015/653 (and in its updated version dated 2020), which provides a set of codes to identify aids to be given to drivers for medical reasons, vehicle adaptations, and administrative conditions that may characterize the driver's license (Table 2). Italian law received these prescriptions, updating the 148/1991 Ministry of Transport circular.

Once the health condition is assessed, the regulatory framework provides a set of rules describing different modifications that can occur to a vehicle depending on its driver's condition and impairment(s). Therefore, it is possible that one or more "car configurations" are available for a specific condition. Each configuration is composed of a set of aids and mechanical modifications to the vehicle, thought to support the PwD in coping with her/his impairments while driving. Figure 2 provides an example of the combination of impairments and possible car configurations.

Table 2. An excerpt of the codes foreseen by the EU Directive 2015/653.

Specific	Code	Name
Driver (medical reason)	01	Sight correction and/or protection
	02	Hearing aid/communication aid
	03	Prosthesis/orthosis for the limbs
	05	Limited use (subcode use obligatory, driving subject to restrictions for medical reasons)
Vehicle adaptations	10	Modified transmission
	15	Modified clutch
	20	Modified braking system
	25	Modified accelerator system
	31	Pedal adaptations and pedal safeguards
	32	Combined service brake and accelerator systems
	33	Combined service brake, accelerator and steering systems
	35	Modified control layouts (Lights switches, windscreen wiper/washer, horn, direction indicators, etc.)
	40	Modified steering
	42	Modified rearview mirror(s)
	43	Driver seating position
	44	Modifications to motorcycles (subcode use obligatory)
	45	Motorcycle with sidecar only
	46	Tricycles only
	47	Restricted to vehicles of more than two wheels not requiring balance by the driver for starting, stopping and standing
	50	Restricted to a specific vehicle/chassis number (vehicle identification number, VIN)
	51	Restricted to a specific vehicle/chassis number (vehicle identification number, VIN)
Limited use codes	61	Limited to daytime journeys (for example: one hour after sunrise and one hour before sunset)
	62	Limited to journeys within a radius of. . .km from holder's place of residence or only inside city/region
	63	Driving without passengers
	64	Limited to journeys with a speed not greater than. . .km/h
	65	Driving authorized solely when accompanied by a holder of a driving license of at least the equivalent category
	66	Without trailer
	67	No driving on motorways
	68	No alcohol
	69	Restricted to driving vehicles equipped with an alcohol interlock in accordance with EN 50436

The figure provides two examples of impairments that imply vehicular adaptations according to the side of the disability. The possible impairments are coded by the law (as explained in the following section) and their combinations (double impairments).

The example coded as "1PM + 1C" indicates that the PwD is characterized by one arm being replaced by a myoelectric prosthesis (1PM); in contrast, the other arm, although impaired, is still capable of performing driving-related functions.

Different is the case for impairment code "3", which—depending on the side where the disability is located—requires the PwD to make a choice about the different options available (Figure 3).

Impairment		**Configuration**
4	Anatomical loss of a lower limb due to amputation at a higher level than eight centimeters from the knee joint spacing; Or amputation at a lower level but not compensated with a tolerated and efficient prosthesis; Or functional limitation due to stabilized outcomes from injuries which do not allow the regular and timely use of accelerator and brake pedals (for impairment on the right) or regular and continuous use of clutch pedal even in the more severe traffic conditions (e.g., impairment on the left).	*Impairment on the right side:* • Accelerator and brake pedals operated by the left limb with accelerator on the left of the brake (25.07) • Enlarged brake pedal operated by the left lower limb (20.03) • Frizione manuale (15.02) oppure frizione automatica (15.03) oppure cambio automatico (10.02) *Impairment on the left side:* • Manual clutch (15.02) or automatic clutch (15.03) or automatic transmission (10.02)
1PM + 1C	*(Double impairment)* **1PM**: Anatomical loss or agenesis of one of the upper limbs at a higher level of the elbow joint and with conservation of the scapulohumeral joint, compensated with a tolerated and efficient myoelectric prosthesis that allows fine hand and elbow's movements necessary for driving. **1C**: Functional limitation of an upper limb for stabilized outcomes of injuries which nevertheless allows to grip the steering wheel with autonomous movement and secure grip, to operate control devices of all types placed on the corresponding part of the steering wheel and on the dashboard, and to operate the gear lever in all its positions (if the disability is a right) and the parking brake lever (if the disability is on the right).	*More severe impairment on the right side:* • Right upper limb myoelectric prosthesis (03.01) (only holding the steering wheel function, not gripping) • Left side steering wheel knob (40.11) • Automatic transmission (10.02) • Power steering (40.01) • Control devices that can be used without adversely affecting driving and maneuvering (35.01) *More severe impairment on the left side:* • Left upper limb myoelectric prosthesis (03.01) (only holding the steering wheel function, not gripping) • Right side steering wheel knob (40.11) • Automatic transmission (10.02) • Power steering (40.01) • Control devices that can be used without releasing the steering wheel and knob with the right hand (35.04) (for example, control unit integrated with the knob)

Figure 2. An example of the impairments (a single impairment and a double impairment) and the possible configurations foreseen by the Italian law.

Impairment		**Configuration**
3	Agenesis or partial anatomical loss of a upper limb with functional integrity (for the purposes of driving) of the scapulohumeral joint and elbow, and with preservation of at least two thirds of the forearm, which allows the holding of the steering wheel during the operation of control devices and the operating of the gear shift with possible adaptation.	*Impairment on the right side:* ***Option I*** • Automatic transmission (10.02) • Left side steering wheel knob (40.11) • Power steering (40.01) • Control devices that can be used without negatively influencing driving and maneuvering (35.01) ***Option II*** • Adaptation of the gear lever to allow its operation (10.04) • Left side steering wheel knob (40.11) • Power steering (40.01) • Adaptation of the parking brake (20.09) *Impairment on the left side:* ***Option I*** • Automatic transmission (10.02) • Right side steering wheel knob (40.11) • Power steering (40.01) • Control devices that can be used without negatively influencing driving and maneuvering (35.01) ***Option II*** • Right side steering wheel knob (40.11) • Power steering (40.01) • Control devices that can be used without negatively influencing driving and maneuvering (35.01)

Figure 3. An example of optional vehicle modifications depending on the type of disability and its location within the body.

While the process is transparent from a normative and clinical perspective, the PwDs do not necessarily have knowledge about the different configurations and the devices that may be installed in their cars. Moreover, the availability of more configurations for some conditions may require the drivers with a disability to decide which adaptations she/he may want to set up on the vehicle [5]. Therefore, it would be advisable that the PwD is familiar with the most common driving aids (and car configurations) since they significantly impact her/his driving experience.

4. Developing the Rip@rto DSS

To support drivers with disabilities in understanding the modifications their vehicles may undergo, a DSS has been developed and presented in this section. The DSS is one of the results of the "Rip@rto" research project financed by INAIL. The DSS comprises two main components: the ontology and the application acting as a Graphical User Interface (GUI) (as schematized in Figure 4).

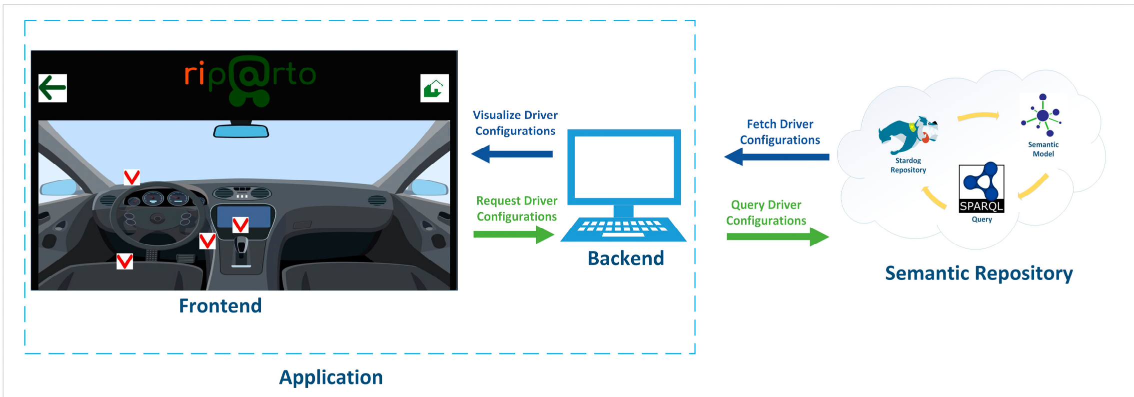

Figure 4. Conceptual architecture of the Rip@rto DSS, including the application and ontology.

In the following subsection, the development of the two components is described.

4.1. Ontological Layer of Rip@rto

As highlighted in Section 2, the lack of suitable datasets and the existence of regulations and norms suggested the formalization Rip@rto's knowledge in the form of an ontology. In this way, a purely kowledge-based DSS may also foster the application acceptance, considering that "black-box" data-driven DSS may not be well tolerated by the clinicians composing the medical committee [24,25], who are ultimately legally responsible for the choices related to a PwD's car reconfiguration. Ontological reasoning enables a transparent and human-friendly reasoning process [26], which resembles the reasoning activities performed by a human assessor [27]. For these reasons, ontologies are widely adopted in DSSs in a variety of fields [28–30]—particularly, in healthcare and clinical domains [31–34].

The Rip@rto ontology needs to "translate" the regulations, their codes, the possible configurations, and the combinations of configurations and impairments in formal, explicit, and shared conceptualization [35]. According to the findings of this discipline in the healthcare domain [36,37], the ontology engineering process takes advantage of both regulations and domain experts. For the development of Rip@rto, the authors had access to INAIL personnel, whose expertise in the field of vehicular modifications for PwD is precious and pivotal. Three domain experts were interviewed to gather insights on the regulations and their functioning in a real setting, and real-world scenarios were developed to validate the results of the ontology reasoning process.

The rigorous normative framework depicting aids, devices, their configurations, and the possible combinations between disabilities and configurations were analyzed within a custom waterfall ontology engineering methodology, in which the expertise of INAIL personnel was fundamental to disentangle the implications of the laws and, thus, clarifying the domain. The engineering process is composed of three main steps: domain analysis and conceptualization, prototype development, and testing.

Due to its "persistent" aspect, the knowledge related to the PwD's health condition and the legal vehicle modifications are not subject to frequent changes; therefore, the DSS—and its underlying ontology—do not need to manage real-time data. On the contrary, the knowledge related to a PwD's health is obtained by consulting clinical personnel, who are the only stakeholders in charge of compiling the PwD's health condition profile (adopting the formalisms described in the following paragraphs).

4.1.1. Domain Analysis and Conceptualization

The activities conducted in this step are paramount in any ontology engineering process since they enable the discovery of the relevant knowledge and its implications and provide it with a conceptual form [36,38]. Since, as detailed in the previous section, the European and Italian regulations discipline the domain of vehicular modifications for PwDs, the efforts were related to the identification of the norms, their structure, and the combinatory rules. The regulations considered explicitly indicate that a driver can be affected by *a single impairment* or *a double impairment*, i.e., a disability affecting two limbs (whether they are both superior or lower limbs). The total number of *single impairment* conditions foreseen by the Italian norm is 14, while the number of *double impairment* conditions amounts to 130. The impairment codes are named with an integer number from 1 to 5, with numbers from 1 to 3 devoted to the description of upper limb conditions and numbers 4 and 5 dedicated to lower limb conditions. Each integer can then be further specified with a capital letter (or a couple of capital letters) to specify the impairment and its severity further. Table 3 provides an example of the use of integer numbers combined with letters to describe the conditions.

Table 3. Examples of the impairment codes, their names, and their description.

Code	Name	Description
1	No functionality in the mutilated or impaired limb	Total loss or agenesis of one of the upper limbs OR functional limitation of one of the upper limbs that does not allow the use of any driving control.
1A	Impaired limb capable of grip on the steering wheel only	Functional limitation to one of the upper limbs (due to stabilized outcomes of an injury) which nevertheless allows to grip the steering wheel with autonomous movement and secure grip, but without the possibility of using the gearshift (manual transmission) and without the possibility to operate controls on the side of the impaired limb.
1B	Impaired limb capable of grip on the steering wheel and to operate controls	Functional limitation to one of the upper limbs (due to stabilized outcomes of an injury) which nevertheless allows to grip the steering wheel with autonomous movement and secure grip AND to operate controls on the side of the impairment, but without the possibility of using the gearshift (manual transmission).
1C	Impaired limb but capable of all functions required for driving	Functional limitation to one of the upper limbs (due to stabilized outcomes of an injury) which nevertheless allows to grip the steering wheel with autonomous movement and secure grip, AND to operate controls on the side of the impairment, AND to use the gearshift (manual transmission, if the impairment is on the right), AND to use the parking brake lever (if the impairment is on the right).
1PM	Limb with myoelectric prosthesis	Anatomical loss or agenesis of one of the upper limbs at a higher level of the elbow joint and with conservation of the scapulohumeral joint, compensated with a tolerated and efficient myoelectric prosthesis that allows fine hand and elbow's movements necessary for driving.

Table 3 illustrates the conditions related to the impairment affecting one arm, with letters A, B, and C further characterizing the type and residual functionalities resulting from the disability. In addition to the above-mentioned capital letters, codes 2 and 3 (devoted to arm and hand impairments descriptions) can also be characterized using the PE capital letters (standing for "aesthetic prosthesis"). Codes 4 and 5 describe, respectively, the loss or complete lack of functionality of a lower limb and a partial anatomical loss or partial lack of functionality of a lower limb; these codes do not require to be characterized with capital letters (except for 5SF, indicating that the loss of functionality of the lower limb does not compromise the possibility to use brake and accelerator pedals correctly).

The set of *double impairment* codes combines all the possibilities expressed by the *single impairment* codes in couples for a total of 130 *double impairment* codes. Thus, these codes can be used to describe impairments characterizing both arms, both legs, or one arm and one leg and to specify the severity of the anatomical or functional loss for each limb.

Regarding the aids and devices that could be adopted in car configurations, according to the norms (see Table 2) it is possible to divide them into three broad categories: *aids for the drivers*, *vehicle adaptations*, and *restrictions on vehicle use*. The first category encompasses the codes from 01 to 05, which correspond to medically prescribed devices (such as glasses, hearing aids, prostheses, etc.); the second category includes all the codes related to the devices, aids, and modifications that could potentially be adopted in car configurations for PwDs (codes from 10 to 51 and all the included subcodes). Finally, the third category includes the codes from 61 to 69, which detail specific limitations to the use of the vehicle (prescribed by a medical committee). In this sense, the European norm is rigid and is a source of knowledge that is not open to any particular interpretation.

Similarly, the configurations are also rigidly normed by the 148/1991 Ministry of Transport circular. The vehicular configurations can be divided into *left-side* and *right-side* configurations, since (as highlighted in Figures 2 and 3), the configurations vary considerably depending on the side where the impairment is located.

Taking into account all the above-mentioned considerations, the ontology must be able to provide an answer to the following Competency Questions (CQs) [39]:

- CQ1: What are the impaired conditions foreseen by the norms for which a car configuration can be suggested?
- CQ2: What configurations can be suggested for a PwD, according to his/her health condition?
- CQ3: What devices or aids compose a car configuration?
- CQ4: On which side of the car should the devices composing the configuration be located?

4.1.2. Development

Following the domain analysis and conceptualization phase, the conceptualization acquired enabled the development of the ontology. To model the knowledge base, the W3C-endorsed languages Resource Description Framework (RDF) [40] and Ontology Web Language (OWL) [41], together with the Semantic Web Rule Language (SWRL) [42] and the query language SPARQL Protocol and RDF Query Language (SPARQL) [43] were used.

These languages are adopted in a variety of ontology-based DSSs and enable ontological reasoning [26], which resembles human inferential abilities. In detail, the OWL profile selected for the Rip@rto ontology is OWL 2 DL, which provides a fair tradeoff between knowledge representation and reasoning capabilities [44]. The possibility of exploiting ontological reasoning capabilities is pivotal in health-related research fields (as pointed out in current literature reviews [45] and in recent works [32–34,46]).

The structure of the ontology (prefixed with `r:`) is based on the knowledge acquired and described in the previous section; therefore, the knowledge base is articulated in four main classes: `r:Candidate_driver`, which groups all the PwDs whose condition needs to be evaluated for vehicular modification; `r:Impaired_condition` and its subclasses, which list all the single and double impairments foreseen by the regulations; the `r:Driving_aids` class and its subclasses, composed of the full list of devices, aids, and mechanical modifications underlined in the European norm; and `r:Car_configuration`, a class to collect all the sets of vehicular modifications foreseen by the norms. The number of classes composing the Rip@rto ontology amounts to, and a graphical representation of them is provided in Figure 5.

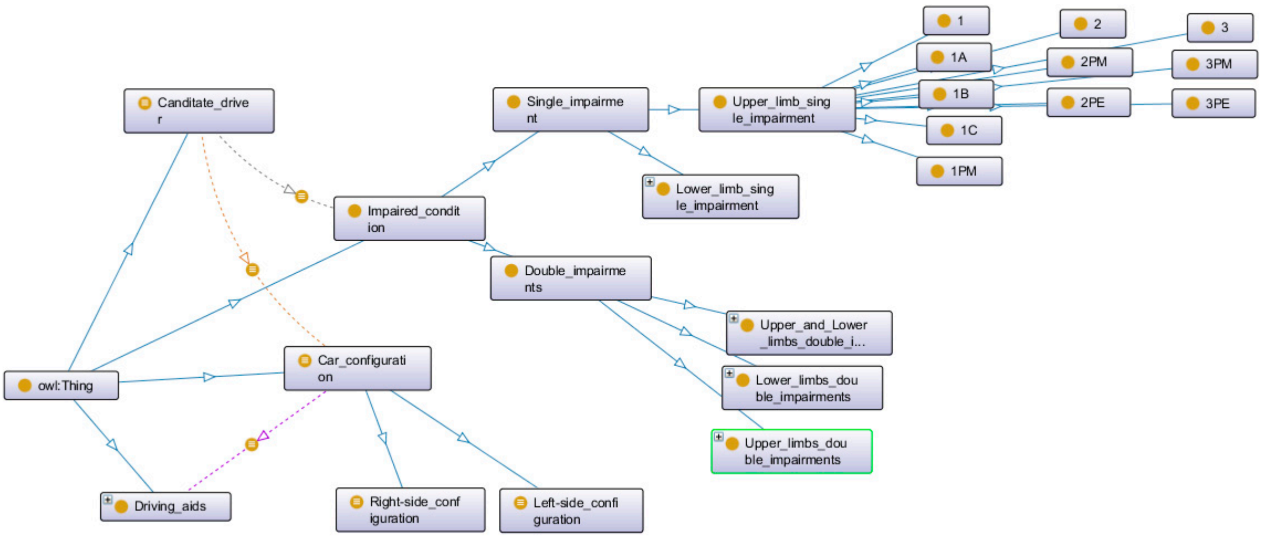

Figure 5. An excerpt of the TBox composing the Rip@rto ontology.

As highlighted in Figure 5, the class `r:Candidate_driver` is described via `owl:restrictions`, which indicate that each candidate driver `r:hasImpairedCondition` at least one health `r:Impaired_condition` and is `r:suggestedSetUp` at least one `r:Car_configuration` to be suggested.

Similarly, the class `r:Car_configuration` is also restricted, using the object property `r:involvesAids` and the class `r:Driving_aids`. Figure 5 illustrates some examples of the subclasses of `r:Impaired_condition`—limited to `r:Upper_limb_single_impairments`.

The `r:Driving_Aids` that compose the `r:Car_configurations` are listed as foreseen by the EU Directive 2015/653, expanding the codes presented in Table 2. Every code is represented as a class, and each class contains one `owl:Individual`, which is linked (via the property `r:involvesAids`) to the `r:Car_configurations` in which the aid is foreseen (Figure 6).

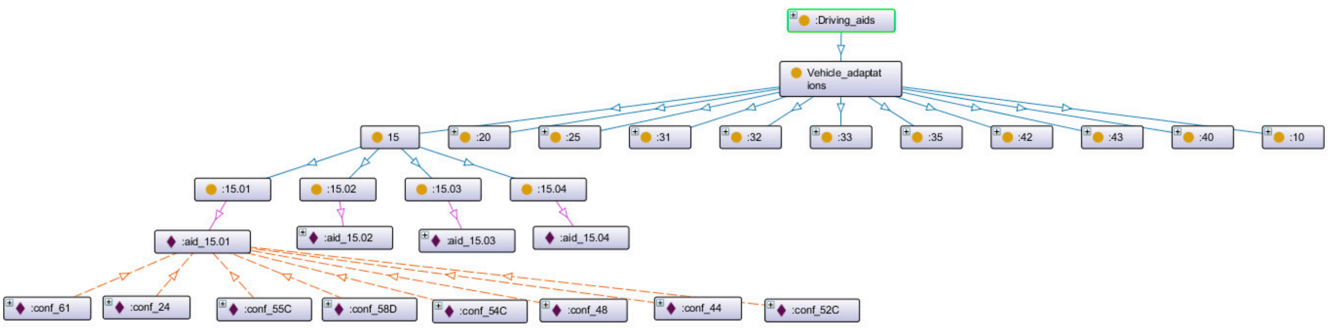

Figure 6. A portion of the ABox and TBox of the Rip@rto ontology; in the example, the class `r:15.01` (Adapted clutch pedal) and its corresponding individual are shown: the individual is linked to the configurations' individuals in which it is foreseen.

For each subclass belonging to `r:Driving_Aids` (and also the subclass of `r:Impaired_conditions`), the `rdfs:label` property was used to provide a human-readable name (corresponding to the Italian translation of the norms and codes involved).

As illustrated above and in Figure 6, each class was instantiated, including the `r:Candidate_drivers` class, as discussed in the following subsection. In particular, analyzing the norms, it was possible to further subclassify the individuals belonging to r:Car_configuration into `r:Left-side_configuration` and `r:Right-side_configuration`. As seen in Figures 2 and 3, depending on the localization of the impairment, the configuration can significantly change; therefore, the adaptations that need to take place to support the PwD vary according to the localization of the disability in the body.

Finally, the development is completed with a set of SWRL rules, which allows for an indication on which condition(s) a car configuration should be suggested to a PwD. For example, the rule:

[1] `Candidate_driver(?d) ∧ hasImpairmentCondition(?d, ?hc) ∧ 1Bs + 5d(?hc) → suggestedSetUp(?d, conf_45B) ∧ suggestedSetUp(?d, conf_46)`

allows one to link together a specific impairment (a double impairment to the left arm (1Bs) and to the right leg (5d)) to the two possible configurations allowed by the norms.

Similarly, the rule:

[2] `Candidate_driver(?d) ∧ hasImpairmentCondition(?d, ?hc) ∧ 4s + 5d(?hc) → suggestedSetUp(?d, conf_57A) ∧ suggestedSetUp(?d, conf_57B) ∧ suggestedSetUp (?d, conf_57C)`

shows the three possible configurations for a user with impairments to both the lower limbs.

The development of SWRL rules relies on domain experts and legislative decrees' knowledge: the matching between specific health conditions and the possible configurations a vehicle can assume is detailed in updating the 148/1991 Ministry of Transport circular. Thus, the Rip@rto ontology "translates" the portions of the law into SWRL rules; the process is eased by the tables depicted within the Italian circular, which are very similar to those illustrated in Figures 2 and 3. The role of domain experts and the cooperation with ontology engineers is pivotal to support the correct interpretation of the regulations and to enable correct SWRL rules definition [37,38,47].

Moreover, rules and `owl:restrictions` also indicate to a PwD on which side of the car the aids should be deployed. Taking into account a person with a 1PM impairment to the left arm, the `r:conf_08` is suggested to be suitable, and it is specified by the fact that `r:aidsLocateOnSide ''Left''`, which is an inference deriving from the classification of `r:conf_08` as an individual belonging to the class `r:Left-side_configuration`.

More than 165 rules are developed to cover all matchings between a PWD's health condition (represented by the `r:Impaired_condition`) and the configurations available. Although "simple", these rules enable the translation from an informal text (the norm) to a logic-based representation, so that it can be used to reason and draw inferences.

The ontology is published online (accessible on: https://www.stiima.cnr.it/progetti-ricerca/riprto/ (last checked 17 October 2024)) and can be downloaded in its Turtle (Terse RDF Triple Language) serialization [48].

4.1.3. Test

The Rip@rto ontology described above is then populated with instances representing some PwDs and their `r:Impaired_condition`. The PwDs' health conditions were provided by INAIL personnel and were received in an anonymous form (i.e., a PwD ID and the related health condition). Since the system and the regulation do not differentiate reconfiguration solutions based on the PwD's gender or age, this approach is considered satisfactory to develop test individuals; thus, 4 test individuals were added to the ontology.

The aim of developing individuals was the test of the ontological prototype (and its set of rules). Also, the test needs to verify whether the developed Rip@rto ontology can answer the CQs presented in the previous subsection. The four users are characterized as follows:

- TestUser_01: impairment condition 1Bs + 5d (left impaired arm capable of gripping the steering wheel and operating controls and a partial loss of functionality of the right leg)
- TestUser_02: impairment condition 4s + 5d (a complete loss of functionality on the left leg and a partial loss of functionality on the right leg)

- TestUser_03: impairment condition 1PM (loss of an arm, specified to be on the right side and equipped with myoelectric prosthesis)
- TestUser_04: impairment condition 1Cd + 4d (functional limitations to the right arm with enough abilities for driving and a total loss of functionality on the right leg).

The CQs presented above were formulated with SPARQL as follows (Table 4):

Table 4. The SPARQL queries "translating" the CQ.

CQ	Question	SPARQL

CQ1	What are the impaired conditions foreseen by the norms for which a car configuration can be suggested?	SELECT DISTINCT ?impCond ?subcl ?lab WHERE {
		?impCond a ?subcl .
		?subcl rdfs:subClassOf r:Impaired_condition .
		OPTIONAL {?subcl rdfs:label ?lab}
		}
		ORDER BY ?lab

CQ2, CQ3	What configurations can be suggested for a PwD, according to his/her health condition
	
	What devices or aids compose a car configuration?
		SELECT DISTINCT ?pwd ?id ?cond ?side ?type ?conf ?aids ?n WHERE
		{
		?pwd a r:Canditate_driver ;
		r:hasImpairmentCondition ?cond ;
		r:driverID ?id ;
		r:suggestedSetUp ?conf .
		?conf r:involvesAids ?aids ;
		a ?type .
		OPTIONAL {?conf r:confNotes ?n} .
		?type rdfs:subClassOf r:Car_configuration .
		?cond a r:Impaired_condition .
		OPTIONAL {?cond r:impairedSide ?side} .
		OPTIONAL {?cond r:moreSevereImpairmentSide ?side }.
		}
		ORDER BY ?conf

CQ4	On which side of the car should the devices composing the configuration be located?	SELECT DISTINCT ?conf ?side WHERE {
		?conf a r:Car_configuration ;
		r:aidsLocatedOnSide ?side .
		}
		ORDER BY ?conf

The CQs 2 and 3 could be conveniently grouped into one SPARQL query (although CQ4 could have also been grouped in the same query, it was presented separately to underline that the information pertaining to the side on which aids are located is independent from a PwD's health condition).

The SPARQL queries illustrated allow us to show the configurations inferred for each of the four test users, the aids and their location, and the candidate drivers with disabilities with the impairment(s) characterizing them. The inferences drawn were considered correct and adequate by INAIL personnel. Similarly to other existing knowledge-based DSSs in the healthcare field [33,34,49], we decided to ask experts to check, validate, and integrate the results of the inference process. No modifications to the inferred information were required. Therefore, the test phase is completed, and the Rip@rto ontology is published.

4.2. Rip@rto Application

In order to help drivers with disabilities better visualize the configurations and required car modifications, a simple application is designed and implemented as a GUI. The application is developed with Unity 3D engine and C# scripting language for cross-platform support. The application not only helps with visualization but also serves as a middleware between the GUI and the semantic repository to dynamically communicate and exchange data. The application needs to access the ontology where the drivers' health conditions and disabilities are defined to receive the inference results about each driver's health condition, disabilities, and limitations. The reasoned and inferred results about the explicit list of car configurations and driving aids for each driver can then be visualized within the application. Additionally, the application must be capable of modifying the ontology in case a driver's health condition has changed or a new driver must be inserted into the ontology.

However, modifying the ontology on the server is not a trivial task because of the Open-World Assumption (OWA) of the monotonic nature of Description Logic (DL) [50]. Reasoning in the OWA means that the statements about knowledge that are not included in or inferred from the knowledge explicitly modeled in the ontology may be considered unknown rather than wrong or false. This makes it impossible for the deductive reasoner to infer the existence of a new instance unless it is already modeled in the knowledge base. Therefore, the application needs to be able to dynamically connect to the semantic database where the ontology is stored, retrieve data from the ontology, and insert new pieces of information into the ontology when needed.

The domain ontologies are stored on the Stardog server, which is a semantic repository that enables semantic reasoning with OWL, capable of managing rules in the SWRL format, and it can export inferred data in various formats.

The application generates a proper SPARQL query 'INSERT' and runs the query on the Stardog reasoner to upload the ontology on the Stardog semantic repository. It can generate the same query later again in case the ontology needs to be updated with a new driver or modified information. It then proceeds to run the reasoner to materialize the most recent inferences based on the SWRL rules that have been defined and stored on the Stardog server with the ontology.

When the ontology is successfully uploaded and reasoned on the Stardog repository, the application is ready to be used by the users (with the support of INAIL personnel). The application displays a list of candidate drivers fetched from the ontology so the user can choose the driver they want to analyze. After choosing the driver on the application, the next page is going to list all the configurations that would work properly for the candidate driver chosen (Figure 7). This list is generated as a result of the application generating and running the proper SPARQL query 'SELECT' in the background to fetch the configuration data regarding the chosen candidate driver. Once the user chooses the configuration, the application displays all the necessary driving aids and car modifications together with an image of the installed aids on the car to better visualize how their car will look with the final result (Figure 8).

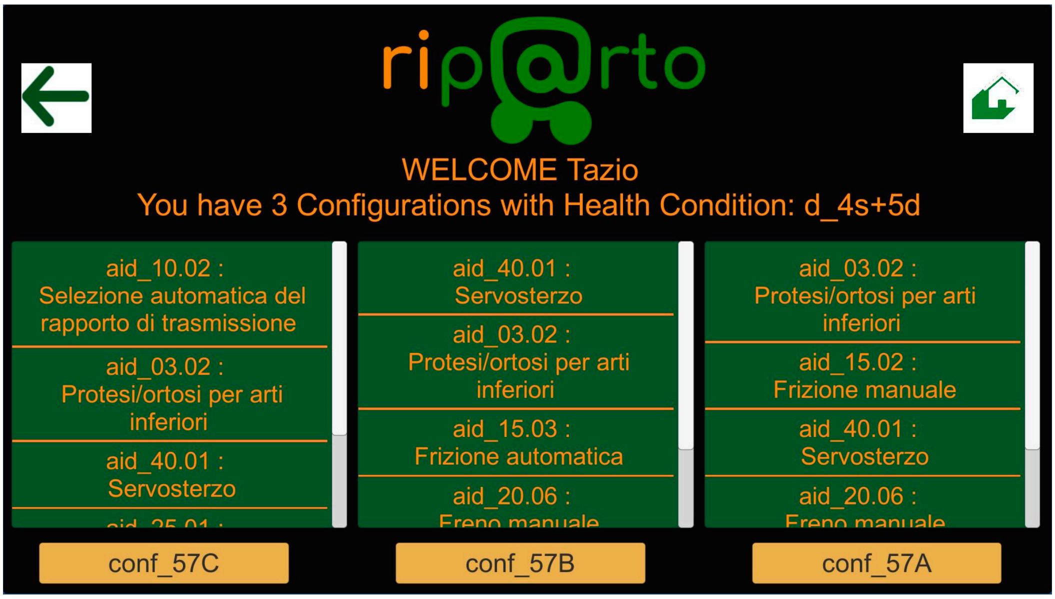

Figure 7. A screenshot of the application illustrating the three possible car configurations (conf_57A, conf_57B, and conf_57C) displaying all the aids necessary for each configuration for the candidate driver "Tazio".

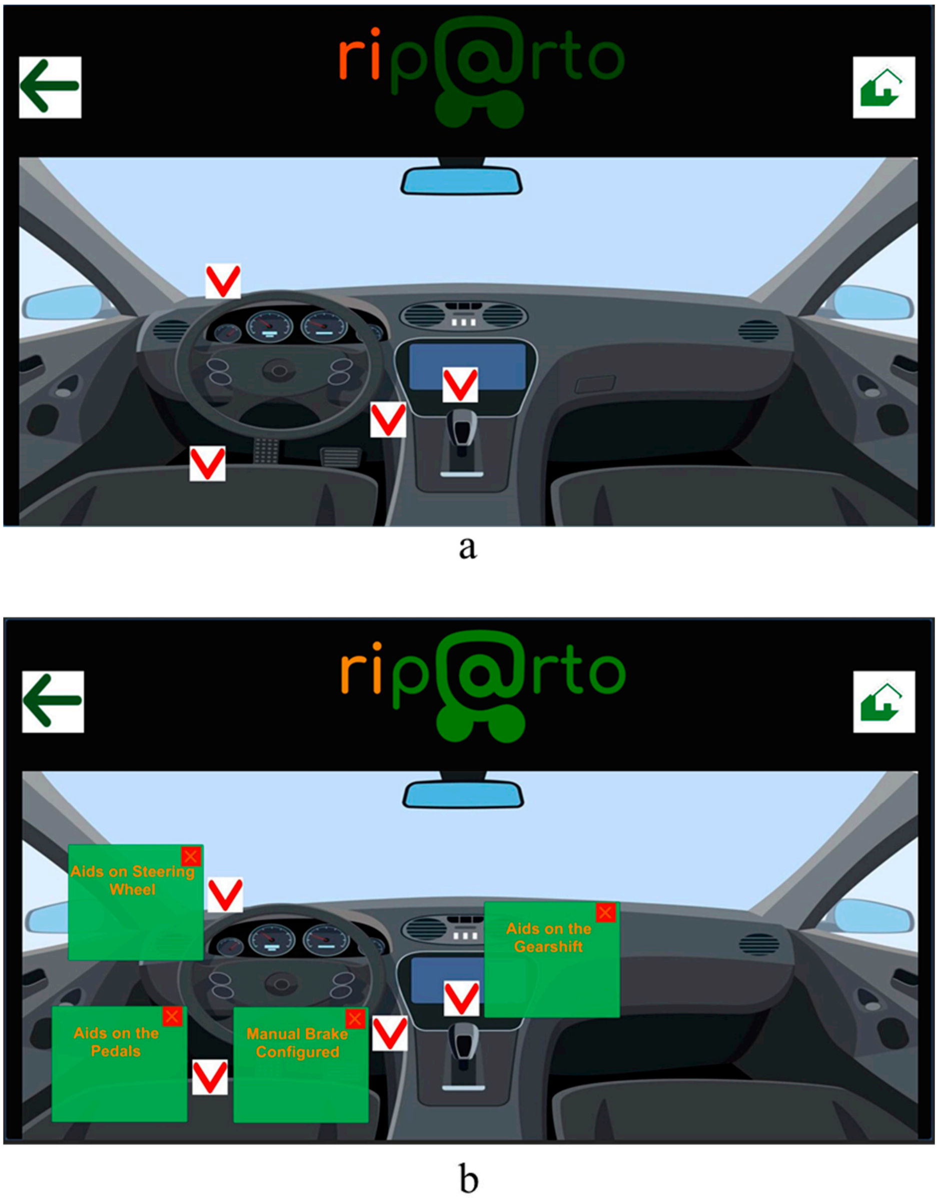

Figure 8. A screenshot of the application visualizing the position of the car modifications and driving aids for the chosen configuration (**a**); each device available can be further detailed to illustrate its description (**b**).

5. Discussion

The proposed DSS is developed with the aim of supporting drivers with disabilities in identifying the possible aids, modifications, and devices that could characterize their vehicles. Such devices and modifications are thought to support PwD in driving by helping them in coping with their impairments while leveraging on their residual abilities.

The system is developed starting from the existing regulatory framework, which indicates the possible disabilities (and their combinations) and classifies the available modifications, devices, and aids. Since this knowledge is strictly regulated, the DSS adopted ontology as a way to formalize the necessary information; its fruition is exerted with an application, here presented as a prototype. This prototypical application helps the users communicate with the semantic repository and exchange information in real time without having prior knowledge of ontologies. It provides a simple GUI in which all the reasoned and inferred data from the ontology can be translated into human-readable information together with graphical representations of the vehicle for better visual understanding.

Regarding the Rip@rto knowledge base, it is worth noting some interesting effects pertaining to the choice of adopting an ontology. First, the semantic representation is suited to represent classifications, particularly those characterized by elements and sub-elements (the characterization of the European and Italian norms). The devices, aids, and mechanical modifications foreseen by the EU Directive 2015/653 enable the classification of any device that could be employed to modify a PwD's vehicle. In this way, this portion of the ontology reflects the regulatory framework: each new device would be necessarily classified according to the existing classification; hence, the classes represented in the ontology will be more than adequate for this purpose. A similar consideration can be drawn for the classification of impairments. The set of the single and double impairments foreseen by the regulatory framework is unlikely to change, unless the basic physical requirements necessary for drivers with disabilities to drive safely are discussed again. Therefore, the description of the impairments the ontology provides is exhaustive and can be easily adapted for any European context.

However, the Rip@rto ontology—although pretty static—is far from immune from the necessity of being updated. For example, if we consider the development of new devices with different functionalities from the existing ones, they would require the amendment of the classification of the EU Directive 2015/653; thus, the Rip@rto ontology would also require an update. As a consequence, the set of configurations could also vary since new devices may combine the functionalities of one or more existing ones. Nonetheless, the Rip@rto ontology can be updated and tested (limited to the modifications generated).

A relevant aspect in which the DSS could support the clinical personnel is the identification of restrictions on use codes. The Rip@rto DSS does not indicate any of these codes, which are not devices, so they do not fall under the scope of the DSS. However, it is not infrequent that these codes are used in daily life to limit the use of cars for those individuals whose abilities are somehow limited. In this regard, the ontological layer could take advantage of the results of driving simulators for PwDs (in particular, the one that is being developed in the Rip@rto project [17]) to suggest clinicians with a set of "restriction on use" codes. This can potentially be achieved by acquiring and processing simulations' data related to assessment and training and by adding to the ontology a second layer of SWRL rules.

6. Conclusions

This work introduced the Rip@rto DSS, a prototypical ontology-based application to support PwDs in identifying and becoming accustomed to the aids, mechanical modifications, and devices that could characterize their vehicles. The ontology underlying the DSS is based on European (and Italian) norms and was developed in close collaboration with the Italian National Institute for Insurance against Accidents at Work (INAIL). By relying on ontological reasoning, the DSS is capable of providing drivers with disabilities with the possible sets of modifications their vehicles could mount and, thus, enabling them to make a conscious choice among the different possibilities. For each possible configuration, the DSS also illustrates the side of the vehicle where the aids are going to be placed.

A prototypical application demonstrates the potential of this approach, indicating different possible car configurations for each driver and illustrating within the vehicle cabin where the devices are going to be deployed for each configuration.

This work falls under the category of systems devoted to supporting PwDs in re-acquiring their ability to drive and, thus, regaining their autonomy in life. Nonetheless, it is necessary to mention that while a DSS such as Rip@rto may support PwDs and clinicians in the short and medium term, the rapid development of assisted driving systems may serve as a long-term solution (not limited to PwDs) [51–53].

Future works on Rip@rto foresee the possibility of further expanding the ontological knowledge base to support the identification of restrictions on the use codes. In this sense, the ontological layer could serve as part of a more complex (and, possibly, automated [54]) system devoted to assessing candidate drivers and suggesting vehicular modifications.

Nevertheless, before modifying the application, it is necessary to assess Rip@rto's acceptance among clinicians composing the medical committees and candidate drivers. To this aim, a set of validation tests will be set in place, exploiting the Technology Acceptance Model (TAM3) [55] and interviews to gather feedback from the end users of the DSS. Also, the application will be improved to match the expanded ontology and provide faster data exchange and better visualization.

Finally, the prototype will be tested with both candidate drivers (PwDs) and professionals from the medical committees. The aims of the tests will be: (a) to acquire the usability scores of the prototype and (b) to acquire feedback to further enhance both the ontological layer and the interface. The tests will involve the administration of the System Usability Scale (SUS) [56] and the Technology Acceptance Model [55] to assess the DSS's general usability an to further investigates those aspects pertaining to the possible adoption of such a system in the real world by clinicians.

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