A Taxonomy of Vulnerable Road Users for HCI Based On A Systematic Literature Review

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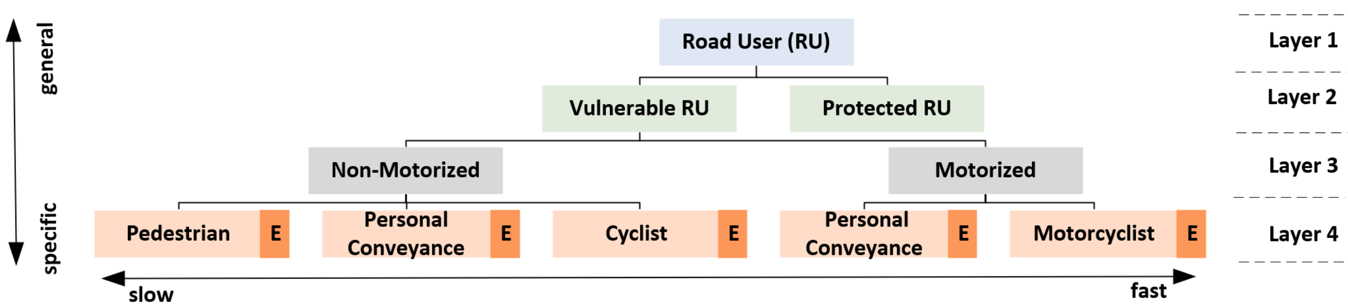

Figure 1: Hierarchical four-layer taxonomy of *vulnerable road users*.

ABSTRACT

Recent automotive research often focuses on automated driving, including the interaction between automated vehicles (AVs) and so-called "vulnerable road users" (VRUs). While road safety statistics and traffic psychology at least define VRUs as pedestrians, cyclists, and motorcyclists, many publications on human-vehicle interaction use the term without even defining it. The actual target group remains unclear. Since each group already poses a broad spectrum of research challenges, a one-fits-all solution seems unrealistic and inappropriate, and a much clearer differentiation is required. To foster clarity and comprehensibility, we propose a literature-based taxonomy providing a structured separation of (vulnerable) road users, designed to particularly (but not exclusively) support research on the communication between VRUs and AVs. It consists of two conceptual hierarchies and will help practitioners and researchers by providing a uniform and comparable set of terms needed for the design, implementation, and description of HCI applications.

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CCS CONCEPTS

• **Human-centered computing** → **HCI theory, concepts and models**.

KEYWORDS

Automated vehicles; external communication; taxonomy; vulnerable road users; eHMIs

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1 INTRODUCTION

Academic and industrial research investigates the design of fully automated vehicles (AVs) [135]. The increasing level of automation will change how people interact with vehicles [19, 77, 200]. This change leads to novel design considerations which will reshape human-machine interfaces (HMIs) on the inside and the outside of vehicles [77, 137, 180, 209, 246]. Depending on the level of automation, the role of passengers inside a car might evolve into active collaborators rather than designated "drivers" [239–241]. In SAE Automation Level 5, humans will not intervene in vehicle control at all [205]. In a transitional phase, however, there will be mixed traffic with varying automation levels and modes of operation, which might become a source of confusion. Eventually, the complete spectrum of road users (e.g., scooter, car, truck and bus drivers, cyclists, pedestrians, motorcyclists, robots or animals such as guide dogs) will interact with AVs from an outside perspective [172]. In contrast to manual driving, no human signals will be available for right of way negotiations, warnings, or further cues in fully automated driving [180]. This will create potentially complex and dangerous interaction scenarios, such as pedestrians crossing in front of (multiple) AVs, cyclists on dense urban roads, or scooters navigating through traffic with vehicles of mixed automation levels and modes. Not fully understanding the intentions of every relevant road user will invariably lead to accidents. One solution to overcome the lack of communication with potentially absent human drivers in AVs and to raise awareness of VRUs could be external human-machine interfaces (eHMIs) [39, 40, 42, 61, 112, 155, 174]. External cues of AVs on these eHMIs could reduce misunderstandings and unclear situations and thereby enhance traffic safety. To foster traffic safety and the acceptance of AVs, eHMIs should be especially targeted at VRUs [42, 110]. However, the definition of VRUs originates from traffic safety observations and is not adequate for the design and implementation of human-vehicle (HCI) communication systems.

The World Health Organization (WHO) defines vulnerable road users as pedestrians, cyclists, and drivers of motorized two-wheelers [184]. VRUs are mainly unprotected in case of a collision and account for more than half of all fatalities in road accidents worldwide [46]. However, it seems that there is no common understanding of VRUs in the human-computer interaction research domain. Some publications refer to VRUs in line with the WHO definition [82, 164], others use VRUs as a synonym for pedestrians [2, 16, 217] or do not define the term at all [117]. Some authors distinguish certain aspects of VRUs such as age [65, 91, 166] and gender [91, 166], police-reported alcohol involvement [65], location, and action [166]. The WHO definition of VRUs (pedestrians, cyclists and motorcyclists [184]) is too broad to be targeted completely by a single human-computer interaction (HCI) concept or application. For example, designing (two-way) external automotive user interfaces for cyclists might not result in useful outcomes for pedestrians and vice-versa. Additionally, an eHMI validated with healthy middle-aged adults might not prove effective for children or pedestrians with visual impairments. Due to the complexity and fundamental differences within the VRU subgroups, a more specific separation seems necessary. Especially pedestrians are diverse, e.g., in age, vision, physical or mental capabilities [55]. In addition to eHMIs, there is also numerous HCI work focusing on (vulnerable) road users, for example, aiding cardiac patients in cycling [90] or warning distracted pedestrians before walking onto a street [120]. Thus, through the lens of HCI design, a more fine-grained differentiation between different types of road users in the context of HCI systems seems necessary.

A common understanding of target groups could benefit the development, classification, and comparison of prototypes. It could also help to uncover research gaps and to foster inclusion as well as accessibility for the future of automated driving. To this end, we present a taxonomy regarding VRUs for HCI researchers and practitioners. To our knowledge, there is no established taxonomy for this context yet. We conducted a exhaustive literature research in the domains of HCI and especially automotive user interface research, as well as a basic literature analysis in traffic psychology and traffic safety research. The resulting taxonomy consists of seven layers ordered in two separate conceptual hierarchies and is visualized as tree diagrams, see Figure 1 and Figure 3.

This taxonomy will help to categorize existing work and to indicate research gaps. Furthermore, publications using terms from this taxonomy can be reviewed, compared, and expanded according to the presented structure.

Contribution Statement: This work contributes a literature-derived taxonomy for designers of HCI solutions for VRUs. We present (1) an analysis of current work in the field of external communication between AVs and VRUs and (2) derive a detailed taxonomy of VRUs for HCI research and practice.

2 BACKGROUND

We started our analysis by looking at how traffic safety institutions define road users (RUs) and VRUs. While these categorizations fit the purpose of classifying road safety data, we found that they are too broad for HCI design. A literature research in related HCI publications showed that the term is used inconsistently. Furthermore, we include an overview on how to design for people with different abilities and show how our taxonomy supports these findings.

2.1 Definitions of Road Users in the Context of Road Safety

The Collins Dictionary defines RUs as "anyone who uses a road, such as a pedestrian, cyclist or motorist"[194][p. 1]. Other definitions vary between three to five subcategories always including pedestrians, motorcyclists, and additionally either "car occupants" [156], "motorised four-wheeler occupants" [171] or "vehicle occupants" [172]. Bicyclists (sometimes referred to as "pedal cyclists") are commonly defined as a unique subgroup [171, 172] and unspecified road users [172]. The WHO groups road safety incidents by the five subcategories: "Drivers/passengers of 4-wheeled vehicles","Drivers/passengers of motorized 2- or 3-wheelers","Cyclists", "Pedestrians", and "Other/unspecified road users" [184]. The National Highway Traffic Safety Administration (NHTSA) provides a query tool [6] to subset data in their traffic safety reporting systems [4, 5, 7] with seven main categories: "Crashes", "Vehicles", "People", "Drivers", "Occupants", "Pedestrians","Pedalcyclists". In the project SARTRE (Social Attitudes to Road Traffic Risk in Europe), road users were distinguished between car drivers, motorcyclists, and "other road users", which consists of "pedestrians, cyclists, and users of public transport" [12].

2.2 Vulnerable Road Users

VRUs are mainly described as pedestrians, cyclists, and motorcyclists [185] as this group accounts for more than 50% of traffic fatalities [184]. Other definitions refer to VRUs as road users who are not protected by an outside shield [46, 245]. Furthermore, there are specific user groups that require further considerations, for example, pedestrians with limited mobility. Therefore, some definitions additionally include individual capabilities [72, 176]. The European Commission defines VRUs as "non-motorized road users, such as pedestrians and cyclists as well as motorcyclists and persons with disabilities or reduced mobility and orientation" [190]. In line with the European Commission for Mobility and Transport, we argue that a classification of VRUs should consider VRUs with further special needs. Today, there are ≈ 1.3 billion people with some and 217 million people with moderate to severe vision impairment [26]. About 36 million people are blind [182]; 466 million people suffer from a loss of hearing [183]. Furthermore, there are strong indications that age-related abilities and cognitive skills should be considered [224]. For example, children only begin to fluently read at the age of ≈ 7 and have largely disparate skill sets [30, 100].

2.3 Designing for People with Different Abilities

HCI prototypes can benefit from a customized user-centered design approach [42, 109]. Universal Design aims at creating products to be accessed, understood, and used in a natural manner, without needing adaptation, modification, assistive devices, or specialized solutions [45]. This should be possible universally, independent of individual physical, sensory, mental, or intellectual limitations [178]. However, due to the variety of abilities and skills, this is not always possible [71]. People with special needs are therefore included in the design and evaluation in approaches such as user-sensitive inclusive design [173] or ability-based design [248]. With such methods, the skills of people with impairments can be accounted for [247]. Kraus [134] reports disability prevalence in the USA in 2015 and distinguishes between hearing, vision, cognitive, ambulatory, self-care, and independent living disabilities. *The International Classification of Functioning, Disability and Health* (ICF) [227], distinguishes Mobility and Physical Impairments, Head Injuries - Brain Disability, Vision, Hearing, and Spinal Cord Disability, Cognitive or Learning Disabilities, Psychological Disorders, and Invisible Disabilities.

We envision a more precise definition of a target population for HCI solutions to support inclusion. To this end, we propose a taxonomy including RUs, VRUs, and especially vulnerable road users (EVRUs) with individual limitations. In the context of eHMIs, there is a taxonomy regarding relevant traffic situations for the communication between AVs and Human Road Users [85], a design space for eHMIs [41], a review of empirical work on eHMIs [203] and a classification of the mainly used approaches [149]. However, we have not found any work on the classification of RUs with a focus on the stakeholders of eHMIs nor have we found such work in a broader HCI context.

3 METHODOLOGY

In order to learn about the meaning of VRUs in related HCI Work, we retrieved relevant literature in a structured way: We queried the proceedings of the six most cited HCI venues according to Google scholar[147]. Due to their contents regarding HCI research on future mobility, we additionally retrieved publications from the venues named in Table 1. Our exclusion criteria were:

- workshop publications that are not peer-reviewed
- publications which don't define a specific user target group at all or only name VRUs without further specification
- if VRU is used as another acronym than "Vulnerable Road User(s)", e.g., "Voice response unit"
- if VRU or "Vulnerable Road User(s)" only appear in references
- if VRU or "Vulnerable Road User(s)" only appear as an example or exclusively in the outlook
- if only VRUs inside of vehicles are regarded
- if VRUs are not named at all or not relevant in the presented research work. For example, if the focus of work is not on traffic interaction but on other aspects of mobility, such as driven speeds in manual driving

We considered publications from the last 20 years for all ten conferences and the journal, hence the time span 01/2000 - 09/2020. Our literature search was carried out by two researchers together in several steps. We identified and screened 251 publications and excluded 83 of them. The remaining total of 168 papers provides the basis for our taxonomy. Process details are shown in Figure 2.

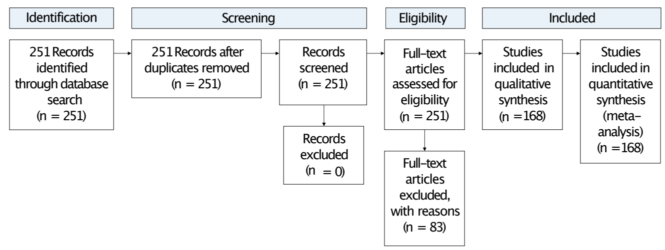

Figure 2: PRISMA Flow Diagram [167] illustrating our paper selection process.

The search query for each conference or venue in the respective digital library (*ACM DL*, *IEEE Xplore*, *Elsevier* or Google Scholar) was: `"query": AllField:("vulnerable road user" OR "vulnerable road users" OR "VRU") "filter": Conference Collections: [Conference / Venue]`). This query resulted in a sample of 251 publications (in September 2020), as shown in Table 1. We clustered eligible work depending on what the actual research topic of the publication was (see Table 2 and Table 3). Our literature search led to the following results:

We found that almost all publications give examples for VRUs, e.g., "such as pedestrians" [150, p.2] or "like children and eldery" [252, p. 1]. Others mention a rather vague level of vulnerability for RUs: "most vulnerable road users" [42, p.1], or differentiate between vulnerable road users (e.g., an elderly lady) and less vulnerable road users (e.g., a woman with a phone making a phone call) [212]. Almost half (44.6% or 75 of 168) of the publications we reviewed use the term VRUs but consider pedestrians as the only target group. Cyclists were the second most addressed group (42 of 168; 25%).

We believe that a uniform separation and classification of terms should be introduced to provide a clear and comparable meaning. An additional challenge, however, is that even pedestrians as a subgroup of VRUs are still too diverse for inclusive HCI design. Bengler et al. [18, p.6] explicitly state that "personal factors of the passenger and the surrounding HRU [Human Road User] affect the communication process". This includes long-term (e.g., gender, age) and short-term (e.g., attention) personal characteristics.

4 CONSTRUCTING A TAXONOMY OF (VULNERABLE) ROAD USERS FOR HCI

Based on the literature analysis described above, we constructed our taxonomy for (vulnerable) road users in two parts. The first part of the proposed taxonomy indicates how to proceed from general applications to specific user groups or users (see Figure 1) with four layers. The subgroups are ordered from the left (slow) to the right

Conference / Venue	**Number of publications**
ACM Conference on Human Factors in Computing Systems (*CHI*)	**13**
ACM Conference on Computer-Supported Cooperative Work & Social Computing (*CSCW*)	**0**
ACM/IEEE International Conference on Human Robot Interaction (*HRI*)	**2**
ACM Symposium on User Interface Software and Technology (*UIST*)	**0**
ACM Conference on Pervasive and Ubiquitous Computing (*UbiComp*)	**1**
ACM International Conference on Human-Computer Interaction with Mobile Devices and Services (*MobileHCI*)	**1**
IEEE Transactions on Affective Computing	**0**
ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (*AutoUI*)	**20**
The ACM Symposium on User Interface Software and Technology	**0**
IEEE Transactions on Intelligent Transportation Systems (*ITS*)	**62**
Transportation Research Part F: Traffic Psychology and Behaviour	**152**
Combined	**251**

Table 1: Retrieved venues and number of publications.

Usage of term VRU	**Number of eligible publications** with references
Pedestrians only	**35**: [3, 17, 22, 24, 28, 36, 58, 62, 67, 68, 80, 83, 87, 92, 93, 98, 102, 113, 123, 124, 130, 131, 145, 148, 150, 160, 165, 168, 181, 197, 206, 236, 242, 244, 254]
Motorcyclists only	**1**: [75]
Cyclists only	**7**: [32, 69, 114, 122, 146, 237, 238]
Children & elderly	**1**: [252]
Children & cyclists	**1**: [158]
Pedestrians & cyclists	**8**: [15, 78, 89, 95, 97, 143, 214, 218]
Pedestrians & cyclists & elderly	**1**: [61]
Pedestrians & cyclists & elderly & children & scooter	**1**: [212]
Pedestrians with vision impairment	**1**: [42]
Pedestrians with mobility impairment	**1**: [14]
Pedestrians with vision, hearing & mobility impairment	**1**: [43]
Combined	**58**

Table 2: Categorization of publications based on usage of the term 'vulnerable road users (VRUs)' in CHI, UIST, AutoUI, CSCW, UbiComp, MobileHCI, HRI, IEEE Transactions on Affective Computing and ITS from 2000 — 2020.

Usage of term VRU	**Number of eligible publications** with references
Pedestrians only	**40**: [1, 9, 11, 13, 29, 31, 37, 50, 56, 60, 84, 88, 96, 104, 105, 107, 125–127, 141, 162, 175, 186, 188, 189, 195, 202, 204, 207, 208, 210, 213, 216, 225, 228, 232, 233, 249, 250, 255]
Cyclists only	**35**: [25, 51, 52, 54, 66, 70, 73, 74, 79, 81, 108, 115, 116, 119, 121, 128, 136, 138–140, 142, 153, 177, 179, 191–193, 219, 221, 222, 226, 230, 231, 235, 243]
Motorcyclists only	**11**: [8, 27, 35, 48, 49, 63, 76, 94, 99, 118, 132]
Pedestrians & children	**3**: [21, 159, 169]
Pedestrians & elderly	**3**: [20, 64, 196]
Cyclists & children	**1**: [220]
Pedestrians & cyclists	**10**: [10, 86, 106, 129, 163, 170, 199, 229, 234, 251]
Pedestrians & motorcyclists	**1**: [201]
Pedestrians & cyclists & elderly	**1**: [20]
Pedestrians & cyclists & motorcyclists	**5**: [101, 152, 161, 187, 223]
Combined	**110**

Table 3: Categorization of publications based on usage of the term 'vulnerable road users (VRUs)' in Transportation Research Part F: Traffic Psychology and Behaviour from 2000 — 2020.

(fast) according to their estimated maximum speed. Since the speed range is a spectrum without clear categories, there are no cut-off sections on the horizontal axis.

The second part describes specific attributes of *Especially Vulnerable Road Users* (EVRUs) with three layers, see Figure 3). The attribute *EVRU* can be assigned to any of the VRUs from layer four (orange) of Figure 1 and supports a precise specification of VRU subgroups. In an iterative process, we included, adapted, and merged groups on the defined criteria *outside protection*, *motorization*, *age*, and *impairment*. Protected RUs (drivers of cars, trucks, and busses) are **not** part of the scope of this taxonomy. Still, the dimension of the EVRUs also could also be applied to such road users.

Figure 1 layer 1: Road users *(RUs)* are the most general classification and thus the first (top) category of the tree visualization. RUs include every being and vehicle participating in traffic, see section Definitions of Road Users in the Context of Road Safety.

Figure 1 layer 2: Prophylaxis and safety features of RUs are the main concern of this layer. Therefore, there is a distinction between vulnerable (*VRUs*) and protected road users (*PRUs*).

- **VRUs** remain basically unprotected against collisions with other RUs. VRUs generally have less mass and slower maximum speeds than PRUs. A detailed categorization of VRUs is described in the layers below.
- **PRUs** include all occupants of vehicles that provide some degree of protection in case of a collision, e.g., through a crumple zone, airbag, roll bar, driver cabin, vehicle mass, or an outside shell. Thus, PRUs consist of occupants of cars, trucks, busses, vans, tramways, agricultural machinery, and delivery, construction, or military vehicles. A more fine-grained definition of PRUs is not part of this taxonomy.

Figure 1 layer 3: The separation of the motorization originates from traffic safety reports and should be considered when developing HCI prototypes for the traffic context. For example, due to different speeds (i.e., time to recognize displayed information) and degrees of severity in case of collisions.

- **Non-Motorized** RUs move exclusively or at least partially by muscle power (e.g., bicycles but also e-bikes).
- **Motorized** RUs move completely by an engine. For example, cars and hybrid powertrains such as mopeds.

Figure 1 layer 4: Definition of specific target groups. This is the first layer that features a meaningful level of detail for the design and description of HCI (or especially eHMI) solutions.

- **Pedestrians** are people who are walking or running, i.e., those who move on foot.
- **Personal Conveyances** include smaller transport equipment and sports devices, such as skateboards or roller skates and assisting devices, such as strollers or wheelchairs. Entities of this subgroup can be non-motorized or motorized (see Figure 1 layer 3). This does not include protected road users.
- **Cyclists** are people who ride a uni-, bi- or tricycle, recumbent bike, tandem or a velomobile.
- **Motorcyclists** include drivers and passengers of mopeds, scooters, and motorcycles (either engine-assisted or fully motorized).

Figure 3 layer 5: The attribute *especially vulnerable road user* (EVRU) can be applied to any category of layer 4 (this is why all subgroups in layer 4 of Figure 1 are marked with an "E"). Thus, EVRUs can be attached to any leaf nodes of the graph in Figure 1. This additional classification of vulnerabilities provides a crucial benefit to a detailed description of potential target groups. For EVRUs, specific circumstances for each subgroup should be considered to formulate meaningful requirements and specifications. For example, when designing concepts for people with macular degeneration (blurred seeing in the center of the vision), other aspects should be accounted for than when designing for EVRUs with limited hearing. Furthermore, a precise naming of target groups eases comparison and searches for eligible related work.

Figure 3 layer 6: EVRUs are divided into age-related and impairment-related limitations. This distinction is inspired by the *International ACM SIGACCESS Conference on Computers and Accessibility*[211]. Although Hanson et al. state that any such categorization may "suggest bias or reflect negative, disparaging, or patronizing attitudes toward individuals or groups of individuals" [103, p. 62], they provide guidelines on how to write about disabilities. Our categorization is based on their work, which also distinguishes between cognitive, vision, hearing, mobility impairments, and age-related symptoms.

- **Age**: All age-related restrictions of the entire spectrum from children to the elderly. Examples include the ability to read, which children may not have, or a potential lack of understanding of new technologies by senior citizens.
- **Impairment**: Specific manifestations of being especially vulnerable are defined based on various special needs that are not necessarily age-related.

Figure 3 layer 7: The categories of layer 7 can be useful to define the scope of a specific problem concerning an EVRU-subgroup. Additionally, the subgroups can be expanded by specific disorders, such as cataracts or tinnitus.

- **Child**: People in the age group of 0 to $\approx$ 17 years. Cognitive [215] and motor skill [47] vary with age, hence, a specific definition of the investigated age group should be done in each project.
- **Elderly**: People with an age of 60 years or over, a specific definition of the age group should be done in each project.
- **Cognitive**: All limitations which affect the mental process, including knowing, learning, and understanding.
- **Vision**: Individual visual perception and the ability to sense light with the visual system (eyes).
- **Hearing**: Capabilities of auditory perception, i.e., the ability to perceive and understand sounds.
- **Mobility**: Limitations related to the human locomotor (musculoskeletal) system and movements of the body.
- **Other**: This subcategory includes limitations that could be considered when designing eHMIs or other tools for EVRUs with special needs that are not covered by previous classifiers.

5 DISCUSSION, LIMITATIONS, & OUTLOOK

In our analysis of publications related to the communication beween AVs and VRUs, we found that the term VRU is often used as a fuzzy synonym for pedestrians. As a result, readers of HCI publications referring to VRUs might become confused about the precise target group of the respective work. A comparison based on keyword searches or related index terms (e.g., "VRU(s)") leads to diverse outcomes. We also found work addressing vehicle communication towards specific subgroups of VRUs without explicitly using the term 'VRU' [23, 33, 34, 38, 53, 57, 85, 110, 133, 144, 151, 154, 155, 157, 174, 198, 253, 256]. These publications were not selected in our structured process in Figure 2 thus we did not include them in the results. However, this indicates that there are publications which do not account for the variety of target groups or do not embed their work in the context of other road users, although they actually address vulnerable road users. In our opinion, this is a long overdue discussion, since VRUs and eHMIs are a trending topic of the last years and we expect many more publications to follow in this domain in the near future. Our focus on eHMIs is due to the research background of the authors, and therefore part of the genesis of this work. Eventually, we argue that our taxonomy is a useful tool for HCI. Considering eHMIs as a concrete application example (interplay of (fully) automated vehicles and VRUs), we

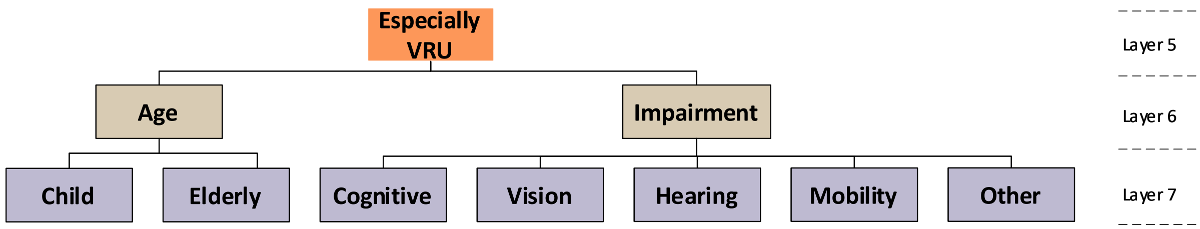

Figure 3: Hierarchical three-layer representation of specific attributes for *especially vulnerable road users.*

believe that eHMIs will be the essence of human-vehicle interaction in the future.

HCI researchers and practitioners in the automotive and traffic domain will benefit from a clear and structured definition of VRUs. To this end, we propose such a taxonomy with numbered layers (see Figure 1 and Figure 3) including named groups and subgroups.

We assume that the main application area for our taxonomy will be research in the context of eHMIs, however, it is targeted towards the broader field of HCI. A side effect of our taxonomy could be that researchers consider further limitations of EVRUs. Hence, ideally, our work could support inclusion by more clearly indicating the potential scope of EVRUs. A precise naming of target groups will also help to increase the efficiency of novel HCI prototypes as it limits the design space around the selected VRU or EVRU group.

An ideal outcome of our taxonomy in the context of eHMIs could be the following: researchers and practitioners may adjust their research endeavors, argumentation, and wording in future publications according to this taxonomy. Furthermore, in the HCI community, designs of inclusive eHMIs could be categorized and evaluated within this taxonomy. As a result, development gaps of eHMIs targeting specific impairments or mobility limitations of EVRUs could be identified. Eventually, involved developers might recognize that no eHMI prototypes are aiming at EVRUs with, for example, hearing impairments, present such findings to their management board, and develop corresponding prototypes. More realistically, we hope to provide a solid starting point for some of these processes and plan to structure our own future work accordingly.

5.1 (No) Directionality of the Taxonomy

The tree diagram structure indicates that deeper levels pose more demanding and specific requirements. Solutions for children or people in their later years could also be valuable for other pedestrians. Solutions for motorcyclists could be viable for both bicyclists and motorcyclists. However, this has to be proven by case-specific investigations and cannot be concluded through this taxonomy. We consider our taxonomy directionless. A solution targeted at one specific group does not allow the deduction that this solution is viable for any other group, layer, or category. For example, in the work of Colley et al. [42], EVRUs with vision impairments gained perceived safety by an auditory feature of an eHMI, while the more general group of unhindered pedestrians claimed to benefit more from visual feedback of the prototype.

5.2 Granularity vs. Precision of the Taxonomy

We derived our categorization to the best of our knowledge and beliefs from the existing literature. However, in some cases, any categorization may be generally debatable. One such example are e-bikes or e-scooters: While they technically are motorized and hence could also be in the same category as motorcycles, their riders typically would consider themselves much closer to bicyclists and also share more characteristics with the latter (e.g., speed range, absence of a helmet requirement, usage of bike lanes). The corresponding eHMI concepts thus are also likely to be closer to those for bicyclists. We are aware that there might be more such potentially debatable cases but argue that our taxonomy stops at a useful granularity to be still widely applicable, also to future forms of mobility.

5.3 Practical Implications for eHMIs

Today, human drivers have only few possibilities to interact with VRUs. They can use gestures, eye-contact, implicit communication, and honking. Therefore, we can assume that communication between human drivers and different subgroups of VRUs does not vary much. AVs, on the other side, have the potential to use connectivity and other modalities, such as mobile devices [111] to communicate. These possibilities should be employed to create safer traffic for everyone. It can, however, be difficult to detect to which category a VRU belongs. For example, people with hearing impairments are not obviously identifiable. However, this population has to be kept in mind when designing eHMIs. Our proposed taxonomy aids in reminding practitioners and researchers of this. Future work should focus on the implications of this taxonomy and demonstrate how it can help cluster related work in a meaningful way. Additionally, the taxonomy could help to systematically question whether eHMIs targeted towards a specific VRU subgroup might also be applicable to other groups, at least to some degree.

5.4 Limitations

This taxonomy focuses on persistent characteristics of RUs. Thus, vision impairments that are caused by environmental conditions such as the weather are therefore not considered. Similarly, vulnerabilities which change by group size (e.g., pedestrians in large groups [197]) or varying distances between vehicles and VRUs [44, 59] are not part of this taxonomy.

Although the root node of the tree diagram in Figure 1 is labeled "Road Users", the focus of this work is on the VRU branch. General RUs could also be clustered in categories, layers, and subgroups similar to VRUs. However, we were motivated by research in the domain of eHMIs combined with their stakeholders, which is why this work mainly considers VRUs. Further possible separation criteria could have been: a more detailed age group (e.g., "younger adults"), cultural differences, gender, or the perspective (from inside a vehicle or from the outside of vehicles). We decided to exclude those parameters because we were not convinced of their benefit for a wider HCI audience in relation to eHMIs.

The proposed dimensions of EVRUs are based on a thorough literature review. However, the definition of EVRUs was especially difficult regarding which impairments should be included. While we believe that our differentiation makes sense, at least for eHMIs (and possibly for many other use cases), a more granular approach could be necessary for others. While we focus on HCI and especially eHMI research, this work aims to support researchers and practitioners in a wide field of applications. For example, industry, traffic psychology, statistical categorization, and city planning.

6 SUMMARY AND CONCLUSION

We analyzed 251 publications regarding VRUs and found that there is a need for a much more precise and comparable definition of VRUs in the context of HCI research. Therefore, this work's primary goal is to establish a common understanding of VRUs to support future developments regarding AVs' external communication with other road users. Based on previous definitions and the usage of terms in the literature, we presented a taxonomy of road users focused around VRUs with two tree diagrams, one with four and one with three layers. Furthermore, we discussed some possible exemplary applications of this taxonomy. Overall, this work highlights the need to precisely specify target groups for prototype development and inclusion in the automotive domain. The introduced taxonomy provides a basis for precise use of keywords and could improve the comparability of prototypes, the understanding of the scope of investigations, and the description of target groups in automotive research and practice.

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