IEEE SA
STANDARDS ASSOCIATION

IEEE SA LITERATURE REVIEW



IEEE 2846

LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATED DRIVING SYSTEMS

Authored by

IEEE VT/ITS/AV Decision Making Working Group

IEEE

Documents
Document Sharing Hub

Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

TRADEMARKS AND DISCLAIMERS

IEEE believes the information in this publication is accurate as of its publication date; such information is subject to change without notice. IEEE is not responsible for any inadvertent errors.

The ideas and proposals in this specification are the respective author's views and do not represent the views of the affiliated organization.

ACKNOWLEDGEMENTS

Special thanks are given to the following contributors of this paper:

Maria Soledad Elli, *Intel Corporation*

Ignacio Alvarez, *Intel Corporation*

Cristhian Lizarazo, *Motional Inc.*

Patricia Derler, *Kontrol GmbH*

Mark Costin, *Nvidia Corporation*

Francesca Favaro, *Waymo LLC.*

Qiming Zhao, Denso Corporation

Constantine Mastory, *Stellantis N.V.*

Qi Hommes, *Zoox Inc.*

Christopher Becker, *Zoox Inc.*

Beth Osyk, *Edge Case Research*

Brett Pennington, *Rivian*

Rafael Eisener, *Valeo S.A.*

Sarah Thornton, *Nuro Inc.*

The Institute of Electrical and Electronics Engineers, Inc. 3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2022 by The Institute of Electrical and Electronics Engineers, Inc.

All rights reserved. 28 April 2022. Printed in the United States of America.

PDF: STDVA25369 978-1-5044-8642-2

IEEE is a registered trademark in the U. S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated. All other trademarks are the property of the respective trademark owners.

IEEE prohibits discrimination, harassment, and bullying. For more information, visit http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html.

No part of this publication may be reproduced in any form, in an electronic retrieval system, or otherwise, without the prior written permission of the publisher.

Find IEEE standards and standards-related product listings at: http://standards.ieee.org.

Copyright © 2022 IEEE. All rights reserved.

Documents
Document Sharing Hub

Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

NOTICE AND DISCLAIMER OF LIABILITY CONCERNING THE USE OF IEEE SA DOCUMENTS

This IEEE Standards Association ("IEEE SA") publication ("Work") is not a consensus standard document. Specifically, this document is NOT AN IEEE STANDARD. Information contained in this Work has been created by, or obtained from, sources believed to be reliable, and reviewed by members of the activity that produced this Work. IEEE and the IEEE VT/ITS/AV Decision Making Working Group expressly disclaim all warranties (express, implied, and statutory) related to this Work, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; quality, accuracy, effectiveness, currency, or completeness of the Work or content within the Work. In addition, IEEE and the IEEE and the IEEE VT/ITS/AV Decision Making Working Group disclaim any and all conditions relating to: results; and workmanlike effort. This document is supplied "AS IS" and "WITH ALL FAULTS."

Although the IEEE and the IEEE VT/ITS/AV Decision Making Working Group members who have created this Work believe that the information and guidance given in this Work serve as an enhancement to users, all persons must rely upon their own skill and judgment when making use of it. IN NO EVENT SHALL IEEE SA OR IEEE and the IEEE VT/ITS/AV Decision Making Working Group MEMBERS BE LIABLE FOR ANY ERRORS OR OMISSIONS OR DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS WORK, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Further, information contained in this Work may be protected by intellectual property rights held by third parties or organizations, and the use of this information may require the user to negotiate with any such rights holders in order to legally acquire the rights to do so, and such rights holders may refuse to grant such rights. Attention is also called to the possibility that implementation of any or all of this Work may require use of subject matter covered by patent rights. By publication of this Work, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. The IEEE is not responsible for identifying patent rights for which a license may be required, or for conducting inquiries into the legal validity or scope of patents claims. Users are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. No commitment to grant licenses under patent rights on a reasonable or non-discriminatory basis has been sought or received from any rights holder.

This Work is published with the understanding that IEEE and the IEEE and the IEEE VT/ITS/AV Decision Making Working Group members are supplying information through this Work, not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought. IEEE is not responsible for the statements and opinions advanced in this Work.

Documents
Document Sharing Hub
Copyright © 2022 IEEE. All rights reserved.
Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

TABLE OF CONTENTS

ABSTRACT 5

1. INTRODUCTION 6

2. ASSUMPTIONS IN SAFETY-RELATED MODELS FOR ADS 8

2.1. ASSUMPTIONS ON KINEMATIC PROPERTIES OF ROAD USERS 8
2.2. DRIVING SCENARIOS TO BE CONSIDERED BY ADS-EQUIPPED VEHICLES 9

3. LITERATURE REVIEW 10

3.1. CONTEXTUAL FACTORS TO CONSIDER FOR KINEMATIC PROPERTIES OF ROAD USERS 10
3.2. SUMMARY OF KINEMATIC PROPERTIES OF ROAD USERS 13
3.3. KINEMATIC PROPERTIES OF PEDESTRIANS 13
3.4. KINEMATIC PROPERTIES OF BICYCLISTS 17
3.5. KINEMATIC PROPERTIES OF VEHICLES 19

4. DISCUSSION ON REASONABLY FORESEEABLE BEHAVIOR OF ROAD USERS 25

4.1. DISCUSSION ON PEDESTRIAN KINEMATICS 25
4.2. DISCUSSION ON BICYCLIST KINEMATICS 26
4.3. DISCUSSION ON VEHICLE KINEMATICS 27

5. GAPS ON LITERATURE REVIEW 28

6. CONCLUSIONS 30

7. REFERENCES 31

Documents
Document Sharing Hub

Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATED DRIVING SYSTEMS

ABSTRACT

The task of driving is inherently risky. Human drivers rely on their experience from interacting with other road users to build assumptions of what constitutes a reasonably foreseeable behavior of the surrounding traffic in different situations, such as highway driving and urban driving. Together with explicit traffic rules, these assumptions help human drivers to navigate safely from point A to point B. With the development of Automated Driving Systems (ADS) and the introduction of ADS-equipped vehicles to public roads, the expectation of utilizing such technologies is that they will lead to a reduction of the inherent risk of driving. But in order to enable ADS' participation in traffic as well as to outperform human drivers in terms of safety, it is not enough to only rely on traffic rules adherence; ADS-equipped vehicles need to also consider assumptions about reasonably foreseeable behavior of other road users to be able to navigate safely and naturally on public roads. This document presents a review of relevant literature (e.g., standards, regulations, and scientific publications) that investigated kinematic behavior of road users. This review is intended to serve as a key contribution to the ADS research and industry communities, as well as to current standardization efforts, such as IEEE Std 2846, IEEE Standard for Assumptions in Safety-Related Models for Automated Driving Systems.

Copyright © 2022 IEEE. All rights reserved.

Documents
Document Sharing Hub

Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

1. INTRODUCTION

Automated Driving Systems (ADS) are needed to help reduce vehicle crashes and improve road safety and traffic efficiency. But it is crucial for the industry to come to an agreement of "how safe is safe enough" when considering automated transportation. As recommended by the German Ethics Commission [1], for ADS technology to thrive on public roads there should be a positive risk balance compared to human driving performance.[1] While ADS technology can reduce human error in the transportation system, designing an ADS to account for the theoretical "worst-case" could result in an inefficient transportation system with overcautious, slow-moving traffic. Therefore, finding an appropriate risk balance is critical for the public adoption of ADS technology.

Human drivers today make use of their daily driving experiences when interacting with other road users in public roads. While doing this, drivers develop assumptions about reasonably foreseeable behaviors of the surrounding road users. These assumptions play an important role in the decision-making process of a responsible road user. For example, assumptions about the behavior of a leading vehicle might impact the consideration of an adopted following distance by a human driver. Assumptions about pedestrians near a crosswalk could affect the driver's behavior when approaching the crosswalk.

Assumptions about what are reasonably foreseeable behaviors of other road users can help an ADS to efficiently evaluate the vast space of possible situations it might encounter on the road, while maintaining sufficient safety considerations. When other road users perform within what is reasonably foreseeable to encounter, the ADS is expected to execute the driving task with an acceptable level of risk.

Recently published work on safety-related models for ADS, such as Responsibility Sensitive Safety (RSS) [2], Rulebooks [3], [4], Safety Force Field (SFF) [5], and Model Predictive Instantaneous Safety Metric (MPrISM) [6], among others, make use of assumptions to determine bounds (e.g., maxima or minima) of kinematic variables associated with surrounding road users. These bounds are used to determine an appropriate safety envelope around the vehicle, to constrain the ADS' operations, to rule acceptable vs. unacceptable planning actions, or to model the predicted behaviors of the surrounding traffic.

With such a rich range of implementations of assumptions in ADS safety-related models, the industry is starting to develop consensus on common definitions for such assumptions. This is the focus of IEEE Std 2846™-2022,

[1] The numbers in brackets correspond to those of the references in Section 7.

Copyright © 2022 IEEE. All rights reserved.
Documents
Document Sharing Hub
Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

IEEE Standard for Assumptions in Safety-Related Models for Automated Driving Systems [7]. [2] IEEE Std 2846-2022 defines the minimum set of assumptions on the kinematic properties of road users to be considered by an ADS safety-related model. The standard also illustrates these assumptions by means of a road user taxonomy and sample common driving scenarios to be expected by an ADS. However, IEEE Std 2846 does not provide guidance on the values (or ranges of values) that these kinematic assumptions can take.

Therefore, the goal of this document is to present a summary of peer-reviewed scientific publications, related standard documents and active industry documents aiming to identify values for the kinematic properties of road users from data-driven studies. This publication is not intended to serve as a recommendation on reasonably foreseeable values for the assumptions to be used in safety-related models, as defined in IEEE Std 2846 [7]. The intent of this work is also not to define what constitutes a positive risk balance of ADS technology, nor to define "how safe is safe enough." Instead, this publication is intended to provide an overview of research-derived road user behaviors that could inform safety-related models in ADS. Furthermore, this publication aims to highlight existing gaps and limitations of the research to better focus efforts on understanding road user behaviors for safer ADS.

To this end, relevant published standards, active industry documents, and technical papers from corpus such as IEEE Xplore and SAE Mobilus were evaluated for their contributions to understanding kinematic properties of road users such as velocity, acceleration, or heading rate change. The selected publications were evaluated with respect to scientific rigor, applied methods, clarity, and applicability of the reported findings to values for road user behavior related to the driving task of an ADS, in the context of IEEE Std 2846. The result is a literature review compiling and summarizing reported values of kinematic properties of road users and a discussion of their applicability and use to inform assumptions about reasonably foreseeable behavior of road users. Note that this literature review is not intended to be an exhaustive evaluation of all research related to the kinematic properties of interest. Furthermore, organizations and ADS developers may have access to their own studies and data to supplement this document.

[2] The IEEE standards or products referred to in this section are trademarks owned by the Institute of Electrical and Electronics Engineers, Incorporated.

Copyright © 2022 IEEE. All rights reserved.
Documents
Document Sharing Hub
Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

2. ASSUMPTIONS IN SAFETY-RELATED MODELS FOR ADS

This section provides a high-level introduction of the assumptions about reasonably foreseeable behavior of road users (2.1) and the relevant driving scenarios (2.2) considered in IEEE Std 2846 [7].

2.1. ASSUMPTIONS ON KINEMATIC PROPERTIES OF ROAD USERS

Different types of road users exhibit different kinematic capabilities that may affect their behavior and interactions with an ADS. For example, pedestrians are able to perform larger directional changes than vehicles, but a pedestrian's maximum velocity is much lower than that of most motorized traffic participants. Therefore, within the scope of IEEE Std 2846, the assumptions about kinematic properties are based on the classification of different road user types, namely, Pedestrians, Bicyclists, Vehicles, and Other Vulnerable Road Users (VRUs), such as a person riding an electric scooter, or a person using a wheelchair. The Other VRUs category includes a wider spectrum of diverse road users' characteristics and capabilities, and thus, their kinematic properties may vary greatly, making it difficult to aggregate or summarize the information adequately. Therefore, a summary on kinematic properties for Other VRUs is not included in this literature review.

The kinematic properties of other road users include, among others, longitudinal and lateral velocities, accelerations, and decelerations,[3] and response time. The response time of a road user should be understood as the time it takes a road user to perceive a specific stimulus and start executing a response (e.g., braking, steering, etc.). See TABLE 1 for a complete list of the characteristics considered. Assumptions about these kinematic properties can take the form of bounding limits, such as reasonably foreseeable minimum and maximum boundaries (e.g., $\beta^{lon} \leq \beta^{lon}_{max}$), and their applicability depends on the driving scenario and the safety-relevant road users to be considered.

[3] The lateral deceleration of a road user, β^{lat}, can be understood as a lateral movement that results from an action that corrects or adjusts the lateral positioning of a road user, whereas a lateral acceleration, α^{lat}, can be understood as the lateral movement to perform a lateral maneuver under normal conditions (e.g., lane change).

Copyright © 2022 IEEE. All rights reserved.
Documents
Document Sharing Hub
Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

TABLE 1 List of kinematic properties considered in IEEE Std 2846

Notation	Description
v^{lat}, v^{lon}	Lateral and longitudinal velocity of a road user
$\alpha^{lat}, \alpha^{lon}$	Lateral and longitudinal acceleration of a road user in its direction of travel
β^{lat}, β^{lon}	Lateral and longitudinal deceleration of a road user in its direction of travel
h	Heading angle (yaw) of a road user
h'	Heading angle rate of change (yaw rate) of a road user
λ	Lateral margin for small lateral fluctuation performed by road user moving in forward motion
ρ	Response time of a road user

2.2. DRIVING SCENARIOS TO BE CONSIDERED BY ADS-EQUIPPED VEHICLES

Driving scenarios define the spatial and temporal relationship between road users and include relevant characteristics of the scenery such as traffic signals and traffic rules governing the space [8]. An ADS-equipped vehicle navigating through the real world is expected to encounter a rich variety of driving scenarios, bounded by its Operational Design Domain (ODD) definition.

IEEE Std 2846 defines a non-exhaustive set of high-level driving scenarios in order to derive a minimum set of assumptions about the reasonably foreseeable behavior of other road users to be considered within the safety-related model of an ADS. These scenarios include common driving situations with longitudinal and lateral interactions between the ADS and other road users as well as interactions at intersections with and without the existence of occluded road users. Each scenario also introduces the minimum set of assumptions about reasonably foreseeable behavior, per road user category, to be considered by a safety-related model to avoid overly conservative driving behavior while maintaining the same level of safety operation.

During the temporal progression of a scenario, the ADS-equipped vehicle is expected to consider the defined assumptions and regularly update them, as the environment in which the ADS-equipped vehicle operates is dynamically evolving. Therefore, values of the assumptions for a road user might change as the ADS transitions from one scenario to another or when new road users become safety-relevant in the scene.

The scenarios in IEEE Std 2846 can be grouped into the following four high-level categories:

- **Longitudinal**: driving longitudinally in front and/or behind other road users

Copyright © 2022 IEEE. All rights reserved.
Documents
Document Sharing Hub
Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

- **Lateral**: driving laterally adjacent to other road users
- **Intersection**: negotiating intersecting paths with other road users
- **Occlusion**: driving in areas where other road users could be temporarily occluded

The scenario denominations just listed will be used throughout the rest of the document for mapping reported kinematic properties found in the literature to the scenarios considered in IEEE Std 2846.

3. LITERATURE REVIEW

This section presents the review and summary of relevant studies and documents that provide empirical evidence of the driving behavior and kinematic properties of different road users. The studies are first contextualized by geographical location, experimental setup, road user type, and driving scenario. Following, summary tables containing kinematic values for each road user classification are presented and each reference is summarized to inform readers of how the resulting values were obtained.

3.1. CONTEXTUAL FACTORS TO CONSIDER FOR KINEMATIC PROPERTIES OF ROAD USERS

Driving behavior on public roads is in large part the result of a social construct; driving in Germany may be different than driving in China. What may be considered to be reasonably foreseeable behavior in one place could differ in another place. Therefore, there exist many contextual factors affecting the behavior of road users in public roads that are worth pointing out when studying kinematic properties of road users.

For instance, the geographic region may have an influence on road user behavior, due to the differences in innate social constructs, roadway infrastructure, and traffic rules, among others. Additionally, other factors such as weather-related environmental conditions, road surface conditions, traffic type, or other operational constraints, such as time of day, could impact the behavior of road users in public roads.

Therefore, in this section a summary of relevant contextual factors reported in the reviewed studies are presented. In particular, details about the following points are presented in TABLE 2.

- **Year:** Year(s) when the data collection took place. In case such information is missing, the year when the study was published is reported.
- **Country:** Country(ies) where the data collection took place. In case such information is missing,

Copyright © 2022 IEEE. All rights reserved.
Documents
Document Sharing Hub
Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...

the place where the study took place is reported.

- **Experimental setup:** Whether the study used Naturalistic Driving Data (NDD), data collected at a field test, or data collection from simulation.
- **Driving scenario:** Driving scenario from section 2.2, to which the study applies.
- **Roadway type:** Highway, urban, or campus.
- **Weather-related environmental conditions:** Weather-related information like precipitation and sky condition present in data.
- **Operational constraints:** Non-permissive constraints affecting the data collection, like time of day, or zones (school zone, university campus, etc.)
- **Sensors:** Sensor configuration used to capture the data. *On-board* is for sensors mounted on a road user (e.g., vehicle, or cyclist), and *off-board*, is for sensors not mounted on a road user (e.g., cameras mounted on roadway infrastructure or drones).
- **Data sample size:** The sample size of the data reported in the study.

An effort was made to harmonize the contextual factors of the studies' information with the ODD taxonomy presented by the SAE-ITC The Automated Vehicle Safety Consortium in AVSC Best Practice for Describing An Operational Design Domain: Conceptual Framework and Lexicon [9]. While the purpose of the taxonomy presented in AVSC Best Practice [9] aims at describing the ODD of an ADS, rather than describing the ODD of a particular dataset or study, it is important to make use of existing terminology, where applicable. For this purpose, the information under Operational Constraints column of TABLE 2 was completed based on the definition found in AVSC Best Practice [9] . Information under the Weather-Related Environmental Conditions column follows the definition based on AVSC Best Practice [9] and it also includes information about Road Surface Obscurants, such as wet or icy roads.

It is worth noting that the data sample sizes are shown for reference and details on how each data sample is defined is further described in 3.3, 3.4, and 3.5, where each reference is briefly explained. Since each study was designed differently, a consistent means of reporting the sample size was not possible. Moreover, none of the studies in TABLE 2 specifically addressed the occluded driving scenario considered in the standard.

Copyright © 2022 IEEE. All rights reserved.
Documents
Document Sharing Hub
Full document details: IEEE SA LITERATURE REVIEW ON KINEMATIC PROPERTIES OF ROAD USERS FOR USE ON SAFETY-RELATED MODELS FOR AUTOMATE...