

14th Conference on Transport Engineering: 6th – 8th July 2021

Analysis of the vehicle-bicycles interaction on two-lane rural roads using a driving simulator based on field data

Juan F. Dols^{a,*}, Jaime Molina^a, Sara Moll^b, Griselda López^b, F. Javier Camacho-Torregrosa^b, Alfredo García^b

^a*Institute for Design and Manufacturing (IDF), Universitat Politècnica de Valencia, 46071 Valencia, Spain*

^b*Highway Engineering Research Group (HERG), Universitat Politècnica de Valencia, 46071 Valencia, Spain*

Abstract

The presence of cyclists on Spanish two-lane rural roads is common, so they have to interact with motor vehicles. Due to the speed differential and vulnerability of cyclists, overtaking is one of the most dangerous and frequent interactions. Therefore, a minimum distance of 1.5 m must be observed. The overtaking manoeuvre depends on road section and cyclist group distribution. Interaction between cyclists and vehicles has been characterized in the past but overtaking to cyclist groups has barely been studied. This study uses a driving simulator to analyse how the presence of cyclists and their group configuration affect traffic operation and safety on two-lane rural roads. A fixed driving simulator has been adapted to incorporate cyclists, using speed and lateral position obtained from field studies. Based on field data, a physical scenario and different traffic scenarios have been recreated, so volunteers can drive the simulator – emulating a motor vehicle – tracking their speed, lateral position, and other variables. These results can be compared to those observed for checking the validity of this methodology. The driving simulator offers some results which are difficult to obtain through other methodologies, enabling a better analysis of the phenomenon. By sorting different bicycle patterns and including several volunteers, the impact of bicycle pelotons on traffic performance and safety can be characterized. This will help in offering recommendations to integrate cyclists and motor vehicles in a safer way.

© 2021 The Authors. Published by ELSEVIER B.V.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

Peer-review under responsibility of the scientific committee of the 14th Conference on Transport Engineering

Keywords: Two-lane rural road; bicycle; traffic operation; overtaking; driving simulator; road safety

* Corresponding author. Tel.: +34-3877625; fax: +34-3877629.

E-mail address: jdols@mcm.upv.es

1. Introduction

Nowadays, there is an increasing presence of bicycle traffic on Spanish two-lane rural roads, which must be considered when analyzing safety and operation of traffic on these roads. Most of the cyclists who use rural roads are sport cyclists, and they usually ride individually or in groups. Due to the differences between cyclists and motorized vehicles, the severity of the accidents registered on rural roads are higher than on urban environment. In fact, in 2019, the 60% of the fatal accidents with cyclists involved were registered in rural roads, despite most of the accidents with cyclists involved (72%) were registered on urban environment (DGT, 2019).

Due to the speed differential and vulnerability of cyclists, overtaking is one of the most dangerous and frequent interactions. The overtaking maneuver has been studied in many research using different methods and analyzing different variables. Most of these previous studies were focused on the safety point of view, and they analyzed mainly the lateral clearance between the overtaking vehicle and the bicycle and the overtaking vehicle speed. Regarding the method used to develop these studies, most of them used instrumented bicycles to collect real data (Llorca et al., 2017; Dozza et al., 2016; García et al., 2019; López et al., 2020). Other studies used naturalistic data (Debnath et al., 2018) or test track data (Rasch et al., 2020). Another methodology that allows obtaining data of the overtaking maneuver to cyclists is the use of driving simulators (Bella and Silvestri, 2017; Bianchi-Piccinini et al., 2018; Farah et al., 2019; Mecheri et al., 2020; Goddard et al., 2020; Rossi et al., 2021). This methodology allows obtaining data from the drivers' point of view, investing relatively short time and in an easy and economical way. All the previous studies, that analyze the interaction between motorized vehicles and cyclists on rural roads using a driving simulator, considered only one cyclist riding alone, and simulated scenarios designed by varying the geometric characteristics of the rural road, the position of the cyclist or the oncoming vehicle presence. None of them studied the effect of groups of cyclists riding on rural roads, and real geometric and traffic scenarios considering cycle traffic and oncoming traffic were not simulated.

The presence of cyclists on two-lane rural roads not only affects safety, but also traffic operation. Moll et al. (2021) performed a study using a traffic micro-simulator to analyze the effect of cycle traffic on traffic operation on narrow two-lane rural roads. Their results showed that cycle traffic presence decreases motorized vehicle average travel speed and increases percent followers and delays. The use of a driving simulator allows to obtain several performance measures to characterize and analyze the affection on both safety and traffic operation. Previous studies performed by Llopis-Castelló et al. (2016, 2019) proposed a methodology for road safety analysis using driving simulators. Following this methodology, the virtual scenario is designed, recreated and loaded into the driving simulator based on geometric characteristics of the road and surroundings. Then, a set of driving simulator tests is performed by some volunteers. Finally, the results of the simulator are validated by comparison with the real data obtained on field observations. At last, the results obtained from the simulator can be analyzed to obtain conclusions. This methodology can be used not only to analyze road safety, but also to characterize traffic operation (Dols et al., 2021).

The present study aims to simulate a real geometric scenario and three traffic scenarios obtained from field observations. Other innovation of this study is that the traffic scenarios simulated include groups of sport cyclists, riding in different configurations. Using the driving simulator will be possible to obtain some results which are difficult to obtain through other methodologies, enabling a better analysis of the phenomenon.

2. Method

In this study, a real segment of a two-lane rural road was simulated, and three different traffic scenarios were tested. To achieve that, the first step was to create the road physical virtual scenario. The physical recreation used the methodology developed by Dols et al. (2016) that requires to define the road geometric characteristics (alignment, elevation and cross-section), as well as the environment (side margins, vertical signs, road markings, surroundings, etc.). From this information, the virtual scenario can be recreated and loaded into the driving simulator. In the next step, a group of volunteers (who must be representative), will travel through the virtual scenario using the simulator. Fig. 1 shows the methodology used.

This paper is focused on the first stage. The main objective was to incorporate groups of cyclists inside the driving simulator scenario, and to simulate the real road and traffic characteristics in a realistic way. The traffic scenarios implemented corresponded to real scenarios observed in the segment. Therefore, the results of the simulator can be

validated with field data in order to analyze the behavior of the drivers in the simulator with respect to that observed in the field. In addition, on the second stage, data from driving simulator test can be used to evaluate safety and traffic operation in the road.

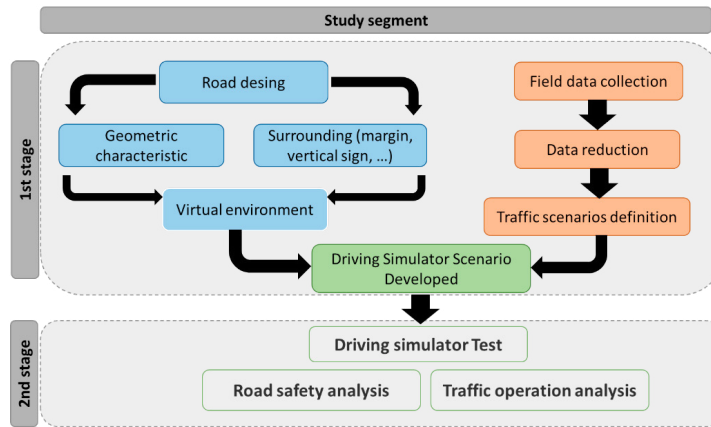


Fig. 1. Methodology used to develop road segment and cross-section characteristics.

2.1. Study road segment description

This study was performed in a segment of two-lane rural road located in the road CV-310, in the region of Valencia (Spain). The study segment is 4,860 meters long, and it has a lane width of 3.2 meters. The road has paved shoulder varying the width between 1.5 and 2 meters. The road has a downward slope of about 7.2% from the beginning to the end of the segment analyzed. An important feature of this segment is that the shoulder is colored in red. The Annual Average Daily Traffic (AADT) of this rural road is 5830 veh/day (Diputació de València, 2020), and the speed limit is 80 km/h). Fig. 2 shows the study segment and cross-section characteristics. The road segment has some warning signs indicating that it is a route with high presence of cycle traffic.

2.2. Field data collection and reduction

Data collection consisted of naturalistic recordings made simultaneously in the extremes of the segment, using small high-definition video cameras. The video cameras were discreetly located so that they could not be noticed by road users. Videos with 30 frames per second were recorded simultaneously at the start and end points. Data reduction beginning with reviewing the videos recorded in the start point of the segment, and the timestamp and the typology of each road user was registered. Finally, the videos recorded at the end point of the segment were reviewed to complete the dataset. This data reduction was realized in both directions of the studied segment. As a result, the time space diagrams considering the trajectories of each road user were obtained and used to select the traffic scenarios with the maximum and the minimum bicycle traffic for the simulations.

2.3. Virtual scenario

The virtual scenario design can be a laborious process. As Dols et al. (2016) indicated, the scenario geometric and traffic characteristics to be modelled will determine the accuracy of the model and therefore the success of the study to be carried out. Modelling the virtual scenario requires a high degree of specialization in many areas (traffic, road design, road safety, among others) as well as graphic simulation techniques and 3D object modelling, to reproduce real-world conditions as good as possible. The present study aims to simulate a real geometric scenario that has to be similar to the real road segment, so their design is based in real data collected on the road and obtained from computer programs based primarily on satellite imagery. Once the physical scenario has been designed and built, the traffic

scenarios have to be designed. The traffic demands considered in each traffic scenario were based on field observations including the groups of cyclists and their observed behavior.



Fig. 2 - Road segment and cross-section characteristics: (a) road segment in CV-310 analyzed; (b) aerial view of a section of the rural road; (c): driver's view along a straight road section.

2.3.1. Physical scenario

The physical scenario was designed by the Institute for Design and Manufacturing (IDF) of the Universitat Politècnica de València based on the Multilayer Editing Procedure (Dols et al., 2016). This methodology implies that the scenario editing procedure of all elements to define the virtual scene are modelled as a multi-layer editing technique in which different data-files are including the types of information needed to model the road and their surrounding virtual scene. The road design was developed using Civil 3D software. Then, the horizontal and vertical alignments, and the cross-section characteristics were provided in an Excel file with the coordinates (x, y, z) of the axis of the road, the edges of the lanes and the platform given at each meter.

One of the characteristics of this section is that the width of the shoulder varies between 1.5 m and 2 m, the majority being 1.5 m wide, while the lane width is constant during all sections. ASC file with the cartography was downloaded from the website of the National Plan for Aerial Orthophotography (NPAO) and combined with a more precise tachymetry. A file in Excel format, with all the elements of the superstructure as vertical signs, road beacons, road markings, lateral safety barriers and lateral walls was completed. Each road and environment element were described and their specific location in the road, referenced to the beginning of the road segment, were registered. For each observed vertical sign, the location where it appears, referenced to the beginning of the study segment, and the margin where it appears were indicated. In addition, the direction of circulation was noted. In the study segment some road beacons to signalize the curves were observed. These road beacons were located in the road indicating their point location, referenced to the beginning of the segment, and their margin and orientation. The lateral centre lines, which separate the lane and the shoulder, were continuous in all the segment, while the centre line presented five different types. These data were reported considering the points where the lines changed along the segment.

The locations of the safety barriers were defined indicating the type "Simple" or "Double", and the point of the road and the length where this containment system exists. In addition, it has been differentiated for each of the road margins

in an increasing direction of road length, referring to the origin of the study segment. In the section analyzed there are several lateral walls whose height and the initial location and length were provided. The texture and color of each lateral wall was registered in order to obtain a similar result in the virtual scenario. A CAD file was also generated with the location of environmental elements that cannot be associated with a specific point of the road, such as buildings and vegetation. Two types of trees were defined in the virtual environment, e.g. orange and pine trees.

2.3.2. Traffic scenarios

As a novelty on driving simulator studies, real traffic scenarios were simulated considering the same cycle traffic and oncoming traffic observed on field. This fact makes the validation process more realistic to validate the simulator results for each traffic scenario simulated in a more exact way. Therefore, the physical appearance of all road users, and their trajectories along the road segment were analyzed. The trajectories of the cyclists along the segment depend on the shoulder width at each point. Therefore, the trajectories of the cyclists had to be incorporated in the simulator considering the lane and shoulder width variations. The positions of the bicycles were different considering the direction, as the lane and shoulder widths. When two cyclists ride two-abreast, they are modelled as two bicycles, separated 1 m and centred in the defined positions for one cyclist. To better reproduce the groups of cyclists in the simulator, the different groups were simulated based on a combination of one cyclists and a couple of cyclists riding two-abreast. The distance considered between cyclists who ride in-line was 1 m. About the speed at which the bicycles ride, there was considered that all the bicycles ride at the same speed, and this speed was considered constant based on the values obtained in filed data.

All the oncoming vehicles were considered to travel at the same constant speed, obtained from the field data collected. Regarding the lateral position, the oncoming motorized vehicles were centred in the lane for both directions, as it was the most common position observed on the field. Due to the vast majority of cyclists who ride on two-lane rural roads are sport cyclist, all of them introduced in the simulator were equipped by sport cyclist clothes and helmet. In that way, the cyclists and the oncoming vehicles that driver participant encounters during the test have different appearance selected at random, as it happens in reality. Fig. 3 shows various examples of overtaking manoeuvres of the vehicle driven in a curve or straight lines section of the scene where the traffic of oncoming vehicles appears at the same time.

In the virtual scenario developed, four types of medium-sized vehicles have been reproduced (5-door sedan, 3-door coupe, sports car and van), with dimensions between 3.8 meters to 4.5 meters in length, widths from 1.72 m to 1.91 m and heights from 1.2 m to 1.82 m. The cyclists modelled occupies a length of 1.52 m, width of 0.52 m and height of 1.52 m, where the only difference between the members of the peloton is the clothing colour they wear.

When two cyclists ride two-abreast, they are modelled as two bicycles, separated 1 m and centered in the defined positions for one cyclist.

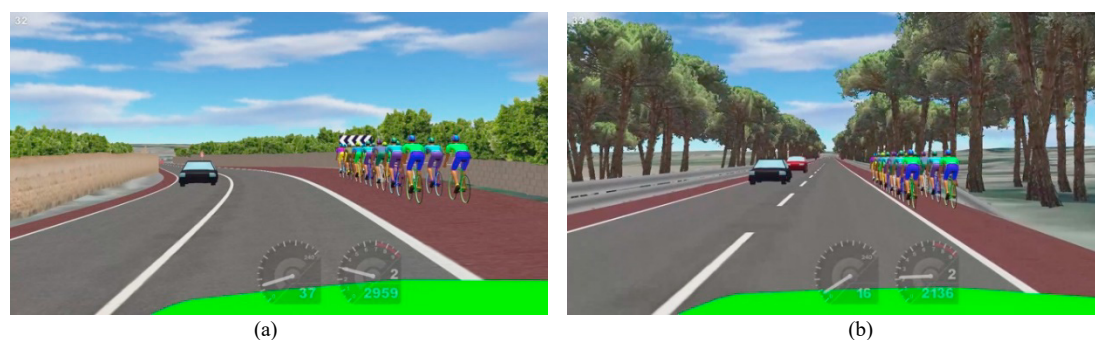


Fig. 3. Cyclist and motorized vehicle appearance reproduced in the driving simulator: (a) overtaking maneuver of cyclist peloton in a curve; (b) overtaking maneuver of cyclist peloton in a tangent segment.

Both bicycle and motorized vehicles traffic data were provided for the simulator in an Excel file, which included the direction of the simulation, the Average Travel Speed (ATS) of motorized vehicles and bicycles, and the initial

location of each road user when the test starts. The simulated traffic scenarios were selected from the field dataset. Regarding the time-space diagrams obtained, the vehicle who overtakes a higher number of cyclists had been chosen as the traffic scenario 1. The traffic scenario 2 was selected from the data obtained in the opposing direction, in that way participants changes the direction of travel and so they are less conditioned to the same travel. The traffic scenario 2 was selected considering a vehicle trajectory which encounters a lower cycle traffic. Then, it is possible to compare the effect on the traffic operation considering one scenario with high cyclist demand and another with a lower one. Finally, a third scenario was designed based on the traffic scenario 1 and doubling the cycle traffic. This scenario was not observed on field but can offer results about how a high cyclist demand affect the safety and traffic operation in a rural road. In these scenarios, a similar volume of oncoming vehicles has been considered, in order to compare the condition generated by varying only the cycling volume.

2.4. Driving simulator

The experimental tool used in this study is the SE2RCO driving simulator, designed and developed by the Institute for Design and Manufacturing (IDF) of the Universitat Politècnica de València (Llopis-Castelló et al., 2016). This tool it is based on a fixed-based simulator which provides the capability for implementation different simulation software, data collection and driving assessment in real time. It is composed by simulation computer, three-screen-display monitors with 120 degrees of field of view (FoW) (1.80x0,34 m and Matrox TripleHead2Go graphics card), steering wheel, pedals, and gear-shift lever and adjustable seat based on a Citroen Saxo. It is capable to acquire longitudinal and lateral speed, location and azimuth with a frequency of 10 Hz. It has been instrumented with load cell (brake pedal force), potentiometers to measure displacement in the three pedals, micro-switch to detect gear-lever position, encoder for measuring steering wheel angle and torque sensor for the steering wheel torques.

3. Results and Discussion

3.1. Field data

The field data collection was carried out on a Saturday morning, since it is when it was expected to see a greater number of groups of cyclists. Table 1 shows the main results of the field data collection. According to the results of average travel speeds (ATS) showed in Table 1, the average travel speed of motorized vehicles in both directions for the simulator were considered as 70 km/h, while for bicycles a different ATS were stabilized considering the travel direction. Then, for bicycles an ATS of 35 km/h in the direction 1, and of 23 km/h in direction 2 were considered.

Table 1 – Bicycles and motorized vehicles and their ATS registered during the data collection.

Direction	Initial hour	Duration	Observed bicycles	ATS bicycles (km/h) Mean (SD)	Observed motorized vehicles	ATS motorized vehicles (km/h) Mean (SD)
1	8:20	4:39	287	34.85 (4.72)	777	69.93 (6.78)
2	8:19	4:14	191	22.64 (3.42)	539	68.44 (6.75)

Fig. 4 shows the time-space diagrams for the three traffic scenarios with the trajectories of the bicycles in orange and those of the opposing vehicles in green. The trajectories correspond to straight lines since it was considered that all of them circulated at a constant speed. The trajectories of two hypothetical vehicles that travel the section at constant speed have been represented in blue, one driving at 70 km/h and the other at 60 km/h. It is observed that when a driver travels the section at a higher speed, interactions with more cyclists are produced.

3.2. Virtual scenario

According to the scenario design methodology developed by Dols et al. (2021), the total development time of the virtual scenario applied in this study, based on the multi-layer methodology, can be divided into three phases: editing time (obtaining and editing data sources with specific software), programming time (preparation, treatment and adaptation of the data for a specific simulator) and processing time (processing time to generate native files adapted

widths and colors, or varying the speed limit of the road. It is also possible to analyze the effect of variations in the traffic demand. Future works applying this methodology would allow the analysis of the road safety from both existing roads and others that are in the design phase, by introducing models of traffic behavior of cyclists and vehicles, according to certain cross section configuration or construction.

Acknowledgements

This study was part of a research project entitled “Improvement of safety and operation of two-lane rural roads with cyclists (Bike2Lane)” (TRA 2016-8089-R) subsidized by Spanish Ministry of Science and Innovation. In addition, the authors would like to thank the Road Department of the Valencian Provincial Council, and General Directorate of Traffic of Spain, for their cooperation in field data gathering.

References

- Bella, F.; Silvestri, M. (2017). Interaction driver-Bicyclist on rural roads: Effects of cross-sections and road geometric elements. *Accident Analysis and Prevention*, 102, 191-201. <https://doi.org/10.1016/j.aap.2017.03.008>
- Bianchi-Piccinini, G. F.; Moretto, C.; Zhou, H.; Itoh, M. (2018). Influence of oncoming traffic on drivers' overtaking of cyclists. *Transportation Research Part F: Traffic Psychology and Behavior*, 59, 378-388. <https://doi.org/10.1016/j.trf.2018.09.009>
- Debnath, A. K.; Haworth, N.; Schramm, A.; Heesch, K. C.; Somoray, K. (2018). Factors influencing noncompliance with bicycle passing distance laws. *Accident Analysis and Prevention*, 115, 137-142. <https://doi.org/10.1016/j.aap.2018.03.016>
- Diputació de Valencia (2020). Área de Carreteras. Servicio de Seguridad Vial y Supervisión. Libro de Aforos 2019.
- Dols, J.F.; Molina, J.; Camacho-Torregrosa, F.J.; Marín-Morales, J.; Pérez-Zuriaga, A.M.; García, A. (2016). Design and Development of driving simulator scenarios for road validation studies. *Transportation Research Procedia*, 18: p. 289-296. <http://creativecommons.org/licenses/by-nc-nd/4.0/>
- Dols, J.F.; Molina, J.; Camacho-Torregrosa, F.J.; Llopis-Castelló, D.; García, A. (2021). Development of Driving Simulation Scenarios Based on Building Information Modeling (BIM) for Road Safety Analysis. *Sustainability*, 13, 2039. <https://doi.org/10.3390/su13042039>
- Dozza, M.; Schindler, R.; Bianchi-Piccinini, G.; Karlsson, J. (2016). How do drivers overtake cyclists? *Accident Analysis and Prevention*, 88, 29–36. <https://doi.org/10.1016/j.aap.2015.12.008>
- Farah, H.; Bianchi-Piccinini, G.; Itoh, M.; Dozza, M. (2019). Modelling overtaking strategy and lateral distance in car-to-cyclist overtaking on rural roads: A driving simulator experiment. *Transportation Research Part F: Traffic Psychology and Behavior*, 63, 226–239. <https://doi.org/10.1016/j.trf.2019.04.026>
- García, A.; Llorca, C.; Serra-Planelles, J. (2019). Influence of peloton configuration on the interaction between sport cyclists and motor vehicles on two-lane rural roads, *Journal of Transportation Safety & Security*, 12:1, 136-150, <https://doi.org/10.1080/19439962.2019.1591557>
- General Directorate of Traffic (DGT) (2019). Las principales cifras de la Siniestralidad Vial España 2019. (ISSN: 2445-0219).
- Goddard, T.; McDonald, A. D.; Alambeigi, H.; Kim, A. J.; Anderson, B. A. (2020). Unsafe bicyclist overtaking behavior in a simulated driving task: The role of implicit and explicit attitudes. *Accident Analysis and Prevention*, 144, 105595. <https://doi.org/10.1016/j.aap.2020.105595>
- Llopis-Castelló, D.; Camacho-Torregrosa, F.J.; Pérez-Zuriaga, A.M.; García, A.; Dols, J.F. (2016). Validation of Low-Cost Driving Simulator Based on Continuous Speed Profiles. *Transportation Research Record*, 2602, 104-114. <https://doi.org/10.3141/2602-13>
- Llopis-Castelló, D.; Camacho-Torregrosa, F.J.; García, A. (2019). Using objective parameters as surrogate measures for Road Safety Audits. In *Proceedings of the Road Safety & Simulation International Conference (RSS2019)*, Iowa City, IA, USA, 14-17 October 2019.
- Llorca, C.; Angel-Domenech, A.; Agustín-Gómez, F.; García, A. (2017). Motor vehicles overtaking cyclists on two-lane rural roads: Analysis on speed and lateral clearance. *Safety Science*, 92, 302-310 <https://doi.org/10.1016/j.ssci.2015.11.005>
- López, G.; Pérez-Zuriaga, A.M.; Moll, S.; García, A. (2020). Analysis of Overtaking Maneuvers to Cycling Groups on Two-Lane Rural Roads using Objective and Subjective Risk. *Transportation Research Record*, 2674, 148-160. <https://doi.org/10.1177/0361198120921169>
- Mecheri, S.; Rosey, F.; Lobjois, R. (2020). Manipulating constraints on driver-cyclist interactions in a fixed travel space: Effects of road configuration on drivers' overtaking behavior. *Safety Science*, 123. <https://doi.org/10.1016/j.ssci.2019.104570>
- Moll, S.; López, G. and García, A. (2021). Analysis of the Influence of Sport Cyclists on Narrow Two-Lane Rural Roads Using Instrumented Bicycles and Microsimulation. *Sustainability*, 13, no. 3: 1235. <https://doi.org/10.3390/su13031235>
- Rasch, A.; Boda, C.N.; Thalya, P.; Aderum, T.; Knauss, A.; Dozza, M. (2020). How do oncoming traffic and cyclist lane position influence cyclist overtaking by drivers? *Accident Analysis and Prevention*, 142, 105569. <https://doi.org/10.1016/j.aap.2020.105569>
- Rossi, R.; Orsini, F.; Tagliabue, M.; Di Stasi, L.; De Cet, G.; Gastaldi, M. (2021). Evaluating the impact of real-time coaching programs on drivers overtaking cyclists, *Transportation Research Part F: Traffic Psychology and Behavior*, 78, 74-90. <https://doi.org/10.1016/j.trf.2021.01.014>