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Speed limit management on two-lane rural roads shared by drivers and cyclists to improve safety and traffic operation

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ABSTRACT

Two-lane rural roads require management that integrates all road users, especially cyclists, who have reached significant traffic levels. Management measures must focus on increasing safety and, wherever possible, also improving traffic operation. Speed limit management can be a solution, however it has to be based on scientific criteria. In this study, various speed limits were simulated on a narrow rural road using a traffic microsimulation model and considering a set of scenarios combining motor and cycle traffic levels. As a results of simulations, performance measures were obtained to characterise safety and traffic operation. The optimal speed limit for each traffic level was obtained by a Multi Criteria Decision Making method, using performance measures as criteria. The results point to the groups of cyclists to ride two-abreast, and to a dynamic management of the road speed limit, reducing the speed during periods of peak motorised and bicycle traffic. It is recommended to adapt the study to each rural road considering its traffic and geometric characteristics, calibrating the traffic micro-simulation model and obtaining a specific dynamic speed limit management model.

1. Introduction

Road cycling is a sport widely practised on two-lane rural roads. These roads account for 90% of the total road network in Spain (Dirección General de Tráfico, 2021), and this coupled with the good climate and topography encourage the practice of this sport. In fact, cycling was the second most practised sport in Spain in 2022 (Ministerio de Cultura y Deporte, 2022a), with 77,972 members of cycling clubs (Ministerio de Cultura y Deporte, 2022b).

Spanish regulations allow cyclists to ride on rural roads on the shoulder or, if the shoulder is not passable, in the right edge of the road. Cyclists can also ride in groups of a maximum two-abreast and a minimum passing distance of 1.5 m is required when drivers overtake cyclists (Ministerio del Interior, 2003). On most two-lane rural roads there is no dedicated lane for cyclists, therefore cyclists and drivers have to share the road and interact, with the overtaking manoeuvre being the most dangerous and frequent interaction between them.

The shared use of rural roads by drivers and cyclists has obvious effects on safety, such as increased risk of traffic conflicts and crashes, especially for cyclists, who have a lower level of protection. Despite actions and campaigns aimed at preventing crashes involving cyclists, on Spanish rural roads 2321 crashes were registered in 2021, and the number of cycling fatalities remains stable at around 50 per year (Dirección General de Tráfico, 2021). Failure to respect the lateral clearance is a key factor in the risk of crashes involving cyclists on the road (Rubie et al., 2020). On the other hand, cycling on rural roads also has a significant effect on traffic operation by causing delays and increasing the travel time of motorised vehicles (Moll et al., 2021a).

In view of the issues raised by mixed traffic of cyclists and drivers on rural roads, speed limit management can be a key measure in improving safety and traffic operation.

Speed limit management on rural roads is related to achieving environmental improvements by reducing fuel consumption and thus increasing air quality by reducing emissions. Another important objective is to reduce crash rates, or in the worst case, to reduce the severity associated with road crashes. It is also important to ensure good traffic operation, without excessive increases on travel time. Often, different objectives can lead in opposite directions in terms of finding the optimal speed limit (Elvik, 2018). So it is important to consider all objectives together when managing the speed limit on a road (Alcaraz Carrillo de Albornoz et al., 2022; Soriguera et al., 2013).

However, the effect of speed limit variations specifically related to roads shared by drivers and cyclists has not been investigated so far. Elvik (2018) noted that studies related to the optimal speed limit

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traditionally only include motorised vehicles, and also concluded that, if the effects of motorised travel speed on walking and cycling are included, optimal speed limits tend to be lower.

On rural roads, when motorised vehicles travel at higher speeds, the likelihood of a serious accident is higher. In previous research related to motor vehicle speed when overtaking cyclists, most findings were consistent with the higher perceived risk, especially for cyclists, when being overtaken at higher speeds (Llorca et al., 2017; Rasch et al., 2022). Motor vehicles traveling at high speed implies a higher probability of overtaking cyclists, and therefore increases the risk of a crash due to rear-end collision or collision during the overtaking manoeuvre, also a higher severity of outcome. In addition, when speed limit is higher, interactions with oncoming traffic are more dangerous, as oncoming traffic is also driving at higher speeds.

On the other hand, lowering the speed limit have adverse effects related to motorised traffic operation by increasing the travel time. Filipi et al. (2022) conducted surveys to test whether people experience disutility related to driving on a motorway at a speed substantially below the legal speed limit. Their results suggest that the loss of travel time should be compensated more when it is caused by a lower driving speed than when it is caused by taking a longer route, highlighting the disutility associated with driving at reduced speeds on the highway. The relationship between speed limit and travel time on two-lane rural roads can be more complex than on highways due to, among other factors, interactions with oncoming traffic and sight distance limitations. Lowering the speed limit also leads to longer overtaking, which requires more time spent in the oncoming lane and generates a higher risk of head-on collision with opposing vehicles.

Therefore, all the consequences of varying the speed limit should be considered, and performance measures should be defined that identify the effects of the performance on the speed limit on all aspects affecting cyclists and drivers.

On some Spanish roads with a high presence of cycle traffic, several measures related to speed limit management have been adopted. These measures are the permanent reduction of the speed limit, and the reduction of the speed limit only during fixed peak cycling hours. These speed reductions are shown to road users through passive vertical signs, which indicate the period of time in which the speed is reduced (generally Saturdays and Sundays morning), reporting that this reduction is due to the presence of cyclists.

Considering the characteristics of road cycle traffic, one traffic management system that can be used with favourable results is variable speed limit (VSL) systems. VLS systems use a control algorithm to adjust the speed limit according to road and traffic conditions (Grumert et al., 2018). The use of VLS is linked to the development of new technologies and the concept of smart roads. An optimal speed limit could be adapted according to the intensity of bicycles and motorised vehicles recorded in real time on each road section, therefore a reliable road user counting system is needed.

However, such measures need a scientific and empirical basis in the calculation of the optimal speed limit. The challenge here lies in the difficulty of obtaining real data on the effects of lowering the speed limit before applying such a measure.

Traffic microsimulation is a tool that allows data to be obtained quickly, economically, efficiently, and without risk to road users. A traffic microsimulation model represents the movement of individual road users, capturing their trajectory and behaviour (Zhao et al., 2022). To be used correctly, these models must be properly calibrated and validated with observations (Barceló, 2010).

The use of traffic microsimulation allows the simulation of scenarios with variations in road geometry, traffic levels or different traffic management measures. Therefore, its use will allow the conclusions of real observations to be extended to a larger number of scenarios and to obtain performance measures that are difficult to measure in the field. In a previous research conducted by the authors, a traffic microsimulation model was developed, calibrated and validated with field observations, which simulates two-lane rural roads where motor vehicles interact with individual and group cyclists (Moll et al., 2021a). By using this specific model, it is possible to simulate different speed limits varying the traffic level, and analyse the effect on safety and traffic operation.

A key issue in analysing the effect of speed limit management on traffic safety and operation is the choice of performance measures that represent the effect correctly. Performance measures should be specific, clear, measurable, realistic, adapted to the objectives, and sensitive enough to differentiate between different scenarios. The methodology described by the Highway Capacity Manual (HCM) 7th Edition (Transportation Research Board, 2022) proposes Follower Density as a performance measure to characterise traffic operation on rural roads, however, in the HCM calculations only motorised traffic is considered, without including interactions with cycle traffic. In the present study it is also necessary that performance measures used are sensitive to cycle traffic.

A useful tool for evaluating and ranking available alternatives against a predetermined set of decision criteria is multi-criteria decision-making (MCDM) analysis (Sitorus et al., 2019). In this study, the different alternatives correspond to different road speed limits, and the decision criteria are the different performance measures used to characterise safety and traffic operation. An objective weighting method was used, where the weights given to each criterion were based on mathematical models and not on the intervention of the decision-maker (Odu, 2019).

It is clear that reducing the speed limit increases safety for cyclists, always linked to maintaining an adequate lateral clearance. However, for motorised vehicles this reduction may improve or reduce the level of risk. Lower speeds result in longer travel times and overtaking manoeuvres, which means more time in the oncoming lane. On the other hand, lower speeds may result in fewer overtaking manoeuvres, as fewer bicycles are overtaken. This study analyses the effect on motor vehicle safety of variations in the speed limit, considering different levels of traffic. Therefore, the focus of this paper is on the safe integration and coexistence of all users, based on efficient traffic management by road administrations.

The main objective of this paper is to propose a methodology to analyse the impact of speed limit management on a rural road shared by drivers and cyclists, considering the effects on safety and traffic operation, including all road users. A traffic microsimulation model has been used to simulate scenarios varying the speed limit, simulating for each speed limit batteries of traffic scenarios combining different levels of motorised and cycle traffic. Finally, the optimal speed limit for each traffic level was selected based on the results of the simulations and a multi-criteria decision-making analysis.

2. Methodology

The methodology followed is shown in Fig. 1.

2.1. Road segment

The study was carried out on a specific road segment located in the CV-502, in the Region of Valencia (Spain). The length of the road segment is 2185 m, and its Average Annual Daily Traffic is 3551 veh/day (Diputació de València, 2022). It is a road without a shoulder, with a lane width of 3.5 m, and a gradient practically nil. The speed limit on the entire section is 70 km/h (click here to visualize the road segment on Google Maps).

It is a narrow road where cyclists and drivers have to share the lane, with high volume of cycle traffic, riding individually and in groups, usually two-abreast (Fig. 2). Cycle intensity has two peaks on weekdays in the early morning and early afternoon, and a single more pronounced peak on weekend mornings. The cross section and traffic level of this road are common in Spain, making this study representative of Spanish narrow roads.

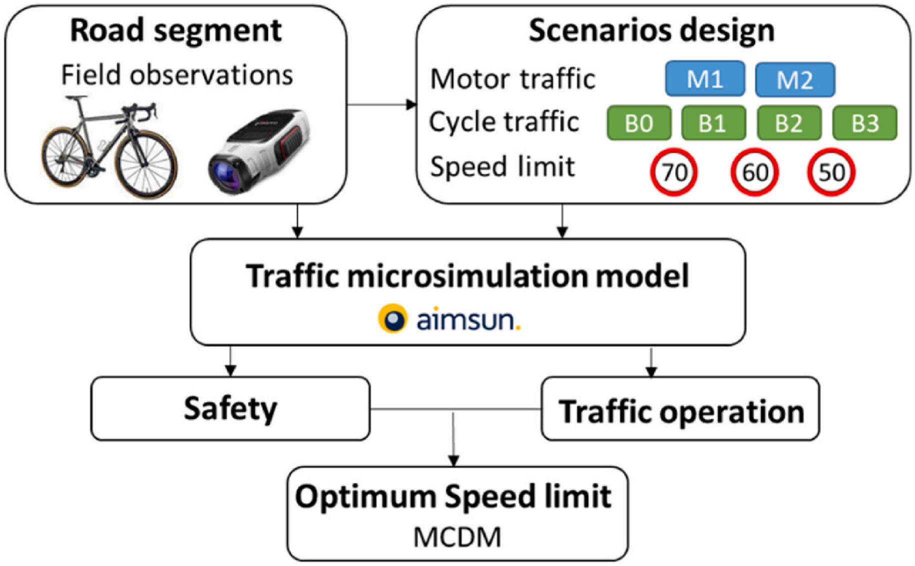

Fig. 1. Method scheme.

Fig. 2. Cross-section of the study road segment.

2.2. Field observations

Two data collection methodologies were developed. On the one hand, instrumented bicycles were used to collect data on overtaking manoeuvres, including lateral distance, speed of the overtaking vehicle and overtaking duration considering different configurations of cyclist grouping. The second data collection methodology consisted of simultaneous video recordings at the entry and exit points of the road segment to collect traffic flow data and macro-level traffic data. These data collection methodologies were explained in depth in previous research by the authors (Moll et al., 2021a

2.3. Traffic microsimulation

The Aimsun Next traffic microsimulator (Aimsun, 2023), version 22.0.1 was used. The software contains a specific module for rural roads where cyclists and drivers travel and interact. This model was developed, calibrated and validated specifically with the data observed on the CV-502 road segment following the methodology described in Moll et al. (2021a). The physical model of the road has been recreated in the microsimulation model based on observations and the geometry of the road, incorporating sight distance and sub-sections with real speed restrictions. The traffic microsimulation model used in this research was calibrated and validated using several observed traffic scenarios, with different intensities of cyclists and motorised vehicles, so that its applicability to other demand scenarios is validated.

Using Aimsun Next software, results were obtained at the microscopic level for each user, and at the macroscopic or segment level. Several specific APIs were also used to obtain data from the traffic microsimulator. In each simulation, a minimum number of replications were carried out in order to obtain results in which the deviations obtained did not depend on the randomness implicit in each replication. It was verified that with 15 replications of each scenario, all the variables analysed complied with a confidence level of 95%.

The results were processed through programming, resulting in the performance measures used to characterise safety and traffic performance for each of the scenarios simulated.

2.4. Simulated scenarios design

A set of traffic scenarios was designed to incorporate variations in both motorised and cycle traffic to cover different demand situations. This design of traffic scenarios was adjusted to the particular characteristics of each road. On this road, the percentage of heavy vehicles observed was very low, therefore only light vehicles were included in the simulations. Each simulation corresponds to 1 h, therefore the traffic scenarios correspond to 1 h for both bicycles and motorised vehicles.

Two motorised traffic scenarios (M) were considered:

- M1: corresponds to the hourly motorised intensity observed on the road segment.
- M2: is the maximum hourly motorised intensity obtained from official traffic data.

The demand for bicycles is more complex than the demand for motorised vehicles, as not only the number of bicycles, but also their grouping and the configuration in which the groups ride, have to be considered. Therefore, specific scenarios considering these factors were designed.

Four different cycle demand scenarios (B) were considered, in which all groups were considered independently, riding in line (L) or two-abreast (TA):

- B0: zero cycle demand.
- B1: 50% of the maximum cycle demand observed.
- B2: 100% of the maximum cycle demand observed.
- B3: 200% of the maximum cycle demand observed.

In terms of management measures, 3 different scenarios were defined by varying the speed limit (SL) of the road segment:

- SL1: current road speed limit.
- SL2: current road speed limit reduced by 10 km/h.
- SL3: current road speed limit reduced by 20 km/h.

In the simulation process the designed scenarios were combined, so that the total number of simulations performed was 2 motorised traffic scenarios x 4 cycle traffic scenarios x 2 configurations of cyclist groups x 3 speed limit scenarios x 15 replications = 720 simulations.

2.5. Characterization of safety and traffic operation

Specific performance measures, sensitive to cycle traffic, were used to characterise safety and traffic operation.

Safety was characterised by a surrogate measure indicating the exposure to the risk of head-on collision with oncoming vehicles due to overtaking cyclists. For this purpose, the average risk exposure time per vehicle (*RET*) was proposed and calculated as the average overtaking duration multiplied by the average number of overtaking manoeuvres realised per vehicle (Equation (1)).

$$RET\ (s) = overtaking\ duration\ (s) * overtakings/veh \tag{1}$$

The *RET* represents the average time a vehicle spends in the opposite lane, implying a risk of head-on collision with oncoming vehicles. However, this surrogate measure of road safety represents an absolute value of average unit time per vehicle and is not useful for comparing risk exposure under different traffic and geometric scenarios.

To enable these comparisons, the percentage risk exposure (*%RE*) was proposed and defined as the time a vehicle spends in the opposite lane due to overtaking cyclists as a percentage of the total travel time of the road segment (*TT*). This percentage risk exposure (*%RE*) is defined in Equation (2).

$$\%RE = (RET\ /\ TT) * 100 \tag{2}$$

On the other hand, traffic operation was characterised using 3 measures:

- ATS (km/h): The average travel speed of the motorised vehicles
- *D/TT (%)*: The percentage of delay time respect the total travel time
- *Ov/veh:* The average overtaking manoeuvres realised per vehicle

An overtaking manoeuvre is considered to be the manoeuvre performed by each vehicle identifying the 4 phases defined by Dozza et al. (2016): approaching, steering away, passing and returning. Therefore, in one manoeuvre it is possible to overtake an individual cyclist or a group of cyclists.

These indicators were calculated by processing the data obtained through the traffic microsimulation model.

2.6. Definition of the optimum speed limit

A multi-criteria decision-making (MCDM) analysis was applied to evaluate and rank the best speed limit alternative, according to safety and traffic operation criteria, for each traffic level.

The first step was to define the alternatives and select the best set of criteria to evaluate them. In this case, the set of *m* alternatives differs at the speed limit, and the set of *n* evaluation criteria will be selected from the performance measures defined in section 2.5.

The decision matrix is defined in (3), where r_{ij} denotes the score of alternative *i* with respect to the evaluation criterion *j*.

$$\begin{bmatrix} r_{11} & \cdots r_{1j} \cdots & r_{1n} \\ \vdots & \ddots \vdots \ddots & \vdots \\ r_{i1} \ \ \cdots & r_{ij} & \cdots \ \ r_{in} \\ \vdots & \ddots \vdots \ddots & \vdots \\ r_{m1} & \cdots r_{mj} \ \ \cdots & r_{mn} \end{bmatrix}_{m\times n} ;\ i = 1, \ldots, m,\ j = 1, \ldots, n \tag{3}$$

The CRITIC (Criteria Importance Through Intercriteria Correlation) method was used, which gives a weighting to each criterion based on the existing intra-criteria contrast intensity and the correlation between criteria (Alinezhad and Khalili, 2019; Diakoulaki et al., 1995; Krishnan et al., 2021).

CRITIC method considers the contrast intensity of each decision criterion by calculating the standard deviation (SD) between the different alternatives, such that higher SD mean that this criterion has a greater variation between the different alternatives and, therefore, it is assumed that it presents meaningful information. Thus, a higher weight is assigned to criteria with higher SD. On the other hand, conflict relationships between criteria are incorporated in the evaluation using a linear correlation coefficient, indicating values close to −1 that both criteria present a strong conflict, while values close to 1 indicate a parallel relationship between the criteria and therefore a redundancy. The CRITIC method gives greater weight to criteria with a higher degree of conflict that present lower correlation coefficients.

The steps to apply the CRITIC method are:

1. Normalisation of the decision matrix by transforming the scores into standard scales ranged from 0 to 1 using Equation (4).

$$x_{ij} = \frac{r_{ij} - r_j^{worst}}{r_j^{best} - r_j^{worst}};\ i = 1, \ldots, m, j = 1, \ldots, n \tag{4}$$

Where r_j^{best} and r_j^{worst} are the best and worst scores of criterion *j*. The best and worst scores for each criterion depend on the nature of the criterion, i.e. whether it is beneficial or not.

2. Calculation of the intra-criteria standard deviation s_j using Equation (5).

$$s_j = \sqrt{\frac{\sum_{i=1}^{m} \left(x_{ij} - \overline{x_j}\right)^2}{m - 1}} \tag{5}$$

Note that $\overline{x_j}$ is the mean score of criterion *j* considering all alternatives, and *m* is the total number of alternatives.

3. Calculation of the correlation matrix among criteria by calculating the linear correlation coefficient between each pair of criteria *j* and *k* by Equation (6).

$$\rho_{jk} = \sum_{i=1}^{m} \left(x_{ij} - \overline{x_j}\right)\left(x_{ik} - \overline{x_k}\right) \Bigg/ \sqrt{\sum_{i=1}^{m} \left(x_{ij} - \overline{x_j}\right)^2 \sum_{i=1}^{m} \left(x_{ik} - \overline{x_k}\right)^2} \tag{6}$$

Where $\overline{x_j}$ and $\overline{x_k}$ are the mean values of *j* th and *k* th criteria.

4. Determining the objective weight (w_j) of each evaluation criteria.

First the index C_j is calculated for each criteria by Equation (7). This index compute the information calculated for each criteria.

$$C_j = s_j \sum_{k=1}^{n} \left(1 - \rho_{jk}\right);\quad j = 1, \ldots, n \tag{7}$$

The objective weight of criteria *j* is determined using Equation (8).

$$w_j = C_j \Big/ \sum_{j=1}^{n} C_j; \quad j = 1, \ldots, n \tag{8}$$

5. Rank the alternatives.

The final score of each alternative is calculated by multiplied the weight of each criteria by the corresponding score of each criteria for a determined alternative (Equation (9)).

$$FScore_i = \sum_{j=1}^{n} \left(w_j * x_{ij}\right); \quad i = 1, \ldots, m \tag{9}$$

The i alternatives are ranked form the higher to the lower score.

3. Results

The first result concerns the data observed on the road. These data were used to calibrate and validate the microsimulation model. Secondly, the design of the traffic scenarios and the variations in the speed limit are presented. This is followed by the results of the simulations combining the different speed limits proposed with the different levels of both motorised and cycle traffic. Finally, the results for the selection of the optimal speed limit depending on the level of traffic are presented.

3.1. Field observations

The instrumented bicycles rode the road segment in the 7 group configurations listed in first row of Table 1 according to the number of cyclists in the group and their in-line (L) or two-abreast (TA) configuration. Table 1 shows the number of overtaking manoeuvres registered, and the mean values and standard deviation (SD) of the overtaking vehicle speed, the lateral clearance and the overtaking duration recorded by each group of cyclists. These results correspond to the real speed limit of the road (70 km/h). The values for overtaking vehicle speed were similar for all groups of cyclists, with no statistically significant differences at the 95% confidence level. Lateral clearance and overtaking duration showed statistically significant differences between the different groups of cyclists. Duration was larger as the number of cyclists in the group increased and when groups rode in-line, while lateral clearance was higher when cyclists rode in-line.

On the other hand, the data obtained from the simultaneous static recordings at the ends of the road segment were processed to obtain equivalent hourly intensities of motor vehicles in both directions of travel and bicycles in the direction of travel (Fig. 3). Fig. 3 shows how motorised vehicle intensity in both directions presented a low variability during the data collection period. On the contrary, cycle traffic intensity showed high variability, reaching a maximum value at around 10:49 h (Fig. 3). The variability of bicycle and motorised traffic coincides with previous observations made on the section.

The observed data represent the phenomenon of road cycling in Spain. Most cyclists start out on the road early in the morning and make the return trip late in the morning, hence the difference in demand observed between cyclists and motorised vehicles. This field observations were used to calibrate and validate the microsimulation model, but also to base the traffic scenarios design.

3.2. Simulated scenarios design

Motorised and cycle traffic scenarios were designed to cover a sufficient range of intensities to obtain acceptable results. This scenario design was based on the maximum hourly demand of cyclists observed on the road (10:49 in Fig. 3). Table 2 shows the values of the two motorised traffic scenarios, where M1 corresponds to the observed motorised traffic, and M2 corresponds to the maximum motorised traffic on this road obtained from official traffic data.

From the hour with the highest observed cycle intensity (B2 in Table 3), the other three scenarios of hourly cycle intensities were designed. B0 refers to the scenario with no cyclists, B1 to half as cyclists as B2 and B3 to twice as cyclists as B2. This represents sufficient variation in cycle traffic to analyse its influence on traffic safety and operation. The grouping of cyclists has been kept proportional to the base scenario B2. The cycle demand scenarios can be seen in Table 3. These scenarios were simulated considering all groups riding two-abreast and in-line independently.

3.3. Microsimulation results

Three scenarios have been considered by varying the speed limit of the road: i) scenario 1 corresponds to the current situation at the time of this study, being 70 km/h, ii) scenario 2 corresponds to a reduction of the speed limit by 10 km/h, resulting in a speed limit of 60 km/h, iii) scenario 3 presents a reduction of 20 km/h, resulting in a speed limit of 50 km/h, corresponding to the speed limit in urban environment. These scenarios have been introduced in Aimsun Next by modifying the speed limit parameters of the road section.

The first result obtained was the overtaking duration to the different groups of cyclists simulated depending on their participants and configuration in line or two-abreast (Table 4). As the road speed limit decreases, overtaking durations were affected, so that the lower the road speed limit, the longer the overtaking duration.

Table 4 shows that a 10 km/h reduction in the speed limit from 70 km/h to 60 km/h increased average overtaking durations by 17% for all groups of cyclists, while reducing the road speed limit by 20 km/h from 70 km/h to 50 km/h increased mean overtaking durations by 47%.

Figs. 4 and 5 show the evolution of the performance measures (ATS, Ov/veh, %D/TT and %RE) considering the different cycle traffic scenarios, road speed limits and cyclist group configuration. Fig. 4 shows the results for the motorised traffic level observed M1, while Fig. 5 shows the results for the higher motorised traffic M2.

In each of the graphs shown in Figs. 4 and 5, six lines were represented as a result of combining the three speed limits with the two configurations of groups of cyclists. The blue lines represent the results obtained considering the 70 km/h road speed limit, the green lines

Table 1
Overtaking manoeuvres registered with overtaking speed, lateral clearance and overtaking duration data (mean and standard deviation (SD)), in the road CV-502 for each cyclist group (number of cyclists and in-line (L) or two-abreast (TA) configuration).

Cyclist group configurations	Observations		Ov. Speed (km/h)		Lateral Clearance (m)		Ov. Duration (s)	
	N	%	Mean	SD	Mean	SD	Mean	SD
1	*37*	16%	65.60	15.66	1.88	0.455	5.65	1.65
2L	*41*	18%	66.39	19.35	1.78	0.461	6.71	2.11
2TA	*42*	19%	62.48	13.94	1.60	0.458	6.17	1.99
4L	*36*	16%	68.46	13.55	1.91	0.42	8.58	2.22
4TA	*31*	14%	63.03	14.84	1.67	0.32	6.84	2.00
10L	*16*	7%	62.06	9.72	1.99	0.39	9.44	2.22
10TA	*22*	10%	64.68	12.75	1.83	0.51	7.59	1.97
Total	*225*	100%	64.85	14.91	1.79	0.45	7.03	2.30

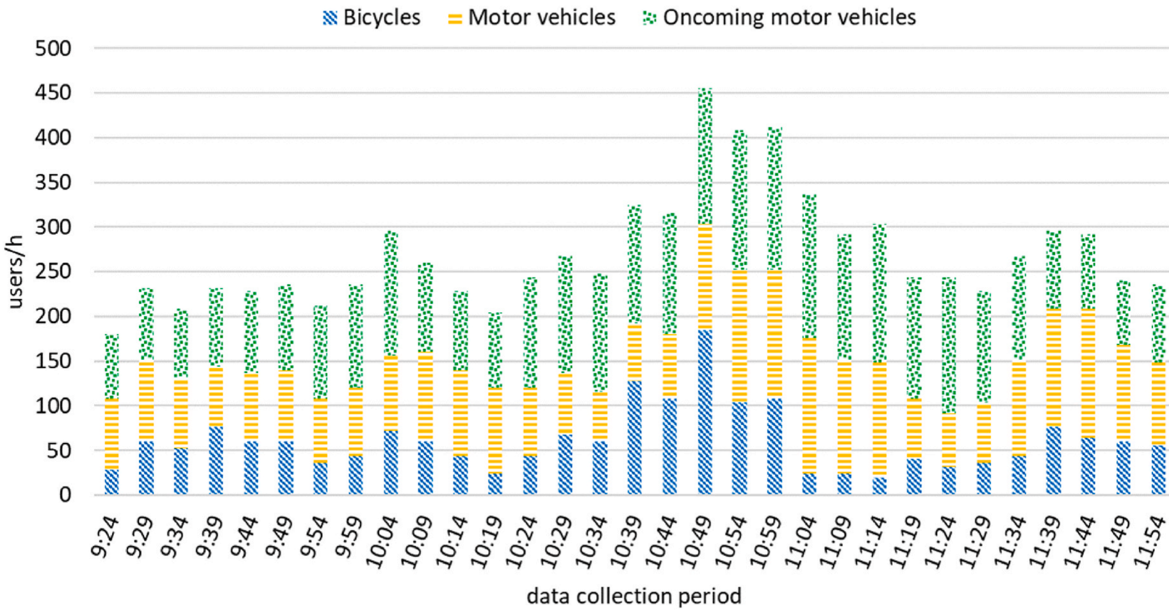

Fig. 3. Equivalent hourly intensities of different types of users calculated from observations on CV-502.

Table 2
Design of motor vehicle traffic scenarios (veh/h) for the road segment CV-502.

	M1	M2
Same direction traffic	120 veh/h	395 veh/h
Oncoming traffic	152 veh/h	500 veh/h

Table 3
Design of traffic scenarios for groups of cyclists based on the maximum observed cycle demand scenario (cyclists/h) for the road segment CV-502.

% Maximum observed cycle traffic	B0	B1	B2	B3
	0%	50%	100%	200%
Individual cyclists	0	20	40	80
Groups of 2 cyclists	0	4	8	16
Groups of 4 cyclists	0	2	4	8
Groups of 10 cyclists	0	6	12	24
Total (cyclists/h)	0	96	192	384

Table 4
Mean value of overtaking duration to the different cyclist groups for the three speed limit scenarios and percentage of variation between scenarios. Cyclist's groups were identified by the number of cyclists and their configuration in line (L) or two-abreast (TA).

	1	2L	4L	10L	2 TA	4 TA	10TA
Speed limit 70 km/h	5.31 s	6.74 s	8.32 s	9.28 s	6.03 s	6.14 s	7.00 s
Speed limit 60 km/h	6.09 s	7.85 s	9.69 s	10.81 s	7.21 s	7.33 s	7.88 s
Speed limit 50 km/h	7.60 s	9.92 s	12.25 s	13.66 s	8.75 s	9.07 s	10.69 s
Variation 70-60 km/h	15%	17%	16%	17%	19%	19%	13%
Variation 70-50 km/h	43%	47%	46%	47%	45%	48%	53%

correspond to the 60 km/h speed limit, while the orange lines correspond to the 50 km/h road speed limit. When the groups of cyclists rode two-abreast, they were represented by a square, while when they rode in line, they were represented by a triangle.

Regarding the average travel speed of motorised vehicles (left-upper graph (ATS) in Fig. 4) it is observed that as the volume of cyclists increased the ATS decreased in all three speed limit scenarios, however, this reduction was more pronounced when the road speed limit was higher. In all three speed limit scenarios the two-abreast configuration of the groups generated slightly higher ATS.

The mean value of overtaking manoeuvres performed per vehicle was represented in the right-upper graph in Fig. 4. It is observed a increase in the overtakings per vehicle when cycle traffic increased, being this increment higher for high road speed limit. However, there was a cycle volume near to B2 where the overtaking per vehicle presented a slope change resulting in a lower variation. Regarding the group configuration, when cyclists rode two-abreast a higher number of overtakings per vehicle was registered in all speed limit scenarios.

The left-bottom graph in Fig. 4 shows the variation of the percentage of delay respect the travel time for motorised vehicles. This performance measure increased when cycle traffic increased, showing a higher increasing tax for higher speed limits. Percentage of delay respect travel time was slightly higher when cyclists groups rode in line.

Finally, the bottom right graph in Fig. 4 shows the variation of the percentage risk exposure of motorised vehicles respect to cycle traffic and for the three speed limits. The %RE presented a logarithmic functional form, resulting in a high increase for low and medium levels of cycle traffic, and a low variation from high cycle traffic around B2. The %RE was higher in the high speed limit scenarios and when groups of cyclists rode in line.

Fig. 5 presents the results obtained considering the motorised traffic level M2. Regarding ATS (upper left graph of Fig. 5), low levels of cycle traffic implied a high reduction in ATS, while the difference when cycle traffic reached high values was minimal. ATS was higher in the high speed limit scenarios, and slightly higher when groups of cyclists rode two-abreast. The upper right graph of Fig. 5 shows the evolution of overtaking manoeuvres per vehicle; the number of overtaking manoeuvres was higher for higher levels of cycle traffic. In scenarios with high speed limits and when groups of cyclists rode two-abreast, the number of recorded overtaking manoeuvres per vehicle was also higher.

The bottom left graph in Fig. 5 shows the evolution of the percentage of delay time relative to travel time when cycle traffic and road speed limit varied. The %D/TT increased as the level of cycle traffic increased, with the increase being high for low and medium levels of cycle traffic.

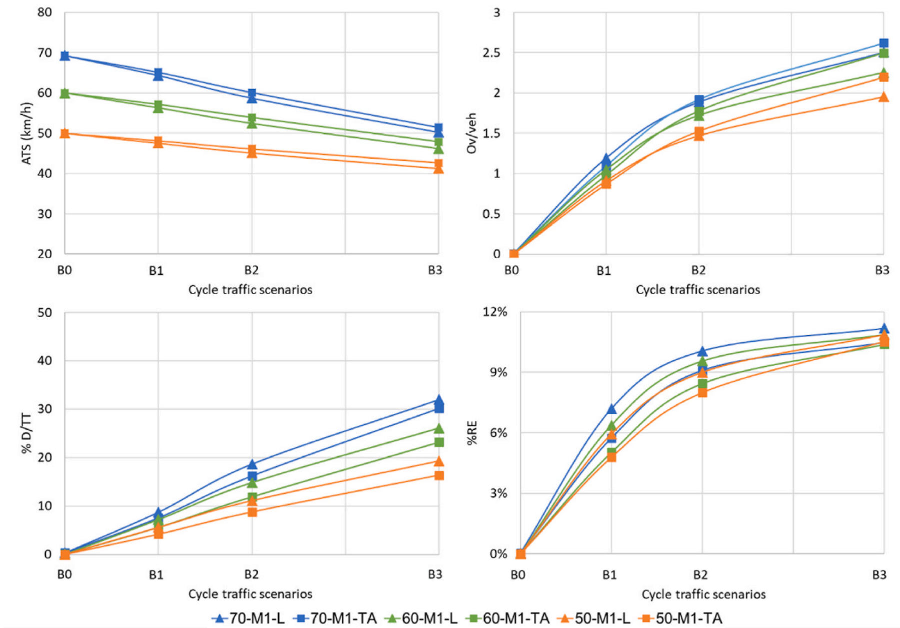

Fig. 4. Performance measures (ATS, Ov/veh, %D/TT and %RE) corresponding to the motorised traffic level M1 considering variations of cycle volume and road speed limit.

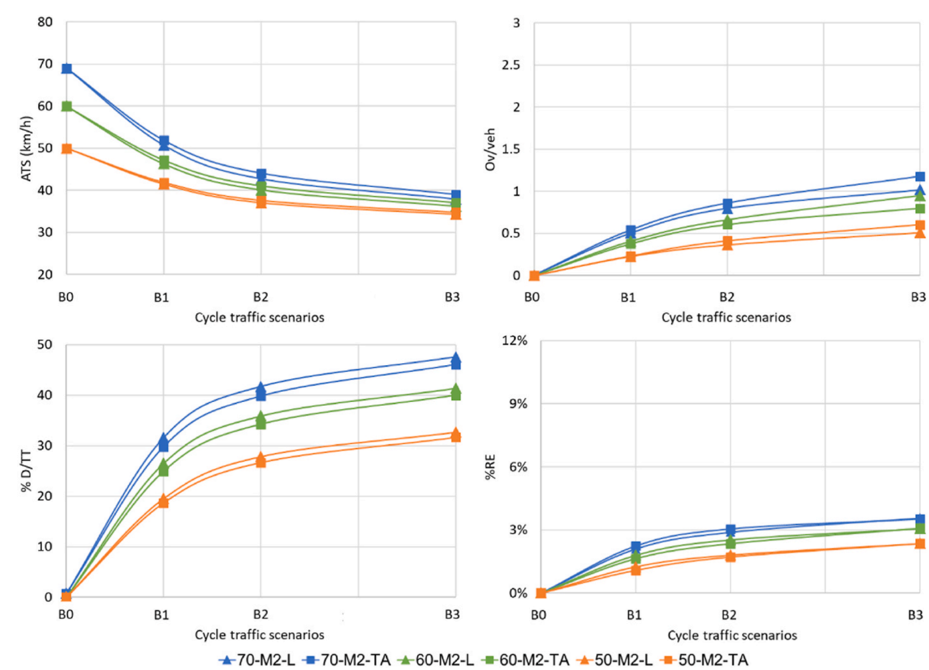

Fig. 5. Performance measures (ATS, Ov/veh, %D/TT and %RE) corresponding to the motorised traffic level M2 considering variations of cycle volume and road speed limit.

The %D/TT was high in high speed limit scenarios and when groups of cyclists rode in line. The %RE is plotted in the bottom right graph in Fig. 5. An increase in %RE was observed when cycle traffic increased. The %RE was slightly high in the high speed limit scenarios, and no differences were observed between the configurations in which groups of cyclists rode.

3.4. Optimum speed limit

Several multi-criteria analyses were proposed corresponding to the different levels of traffic present on the road. By traffic levels we refer to the combination of 2 motorised traffic demand with 4 cycle traffic demand and 2 configuration in which the groups of cyclists ride (in line or two-abreast). Therefore, 16 multi-criteria analysis were performed. This section shows the results of the application of the CRITIC method to evaluate the MCDM problems.

The set of alternatives were the three speed limits tested: A70) 70 km/h, A60) 60 km/h and A50) 50 km/h.

The evaluation criteria (Table 5) were selected based on the performance measures defined to characterise safety and traffic operation. To avoid overlapping information, only the %RE was considered to characterise safety, as this variable includes overtaking manoeuvres per

Table 5
Selected evaluation criteria for the MCDM method.

Aspect	Criteria	Abbreviation	Type
Safety	Risk exposure	%RE	Non beneficial
Traffic operation	Average travel speed	ATS	Beneficial
	Speed limit	SL	Beneficial
	Delay respect travel time	%D/TT	Non beneficial

vehicle and overtaking duration. On the other hand, to characterise traffic performance in the MCDM method, the evaluation criteria selected were ATS, %D/TT and the SL itself. On this road, SL was considered beneficial as it started from a not excessively high value (70 km/h) with respect to the maximum speed limit allowed on rural roads in Spain of 90 km/h.

The 8 decision matrices for the M1 and for the M2 motorised traffic levels were defined in Table 6 including the set of alternatives and the set of evaluation criteria. The evaluation criteria SL had the same values for all cycle traffic scenarios (B), then, it was showed only in the first row.

In the scenario without cyclists (B0), it was not necessary to solve a MCDM problem, since two non-null criteria (ATS and SL) were beneficial, therefore, in these cases the alternative A70 (70 km/h) were preferred.

Regarding the data obtained in Table 6, when groups of cyclists rode two-abreast better performance were achieved, since it generated an improvement in safety, by reducing the %RE, but also an improvement in traffic operation, by increasing ATS and reducing %D/TT. Therefore, the analysis was continued considering only the two-abreast configuration of cyclist groups.

Table 7 shows the values of the normalised decision matrices considering the motorised traffic level M1 and M2. As explained before, cases without cycle traffic (B0) were excluded from the MCDM method. The SL criterion had the same values for all cycle traffic scenarios, so it is only shown in the first row.

From the normalised matrices (Table 7), the next steps of the CRITIC method defined in the methodology were applied, resulting in the weights for each criterion shown in Table 8. It is observed that the values of the weights of each criterion within each scenario were similar. This indicates that the intensity of the intra-criteria contrast was not high, while the correlations between criteria were strong.

Finally, the final score (FScore) and the rank for each alternative was calculated for each level of motorised and cycle traffic (Table 9). For all traffic scenarios analysed, similar values were observed for the three alternatives. A larger difference appeared for the level of motorised traffic M1 and the high level of cycle traffic B3, where the best alternative was A60. For the other motorised traffic scenarios M1, alternative A60 was also the preferred alternative, but showed lower differences with the other two speed limit alternatives.

When the level of motorised traffic was high (M2), the FScore of each alternative was also quite similar. In this case the best alternative was A50, corresponding to 50 km/h, however, the differences with the other two alternatives were very small.

4. Discussion and recommendations

It is clear that mixed traffic considering motor vehicles and cyclists on rural roads have an impact on road safety, as demonstrated by numerous studies related to drivers overtaking cyclists (Beck et al., 2019; Bianchi Piccinini et al., 2018; Brijs et al., 2022; Dozza et al., 2016; Farah et al., 2019; Garcia et al., 2020; Llorca et al., 2017; Rasch et al., 2022; Rubie et al., 2020). But mixed traffic also have an impact on traffic operation by causing queues and delays (Moll et al., 2021a). Most of these previous studies are based on the analysis of the phenomenon and the identification of variables and effects, especially considering the overtaking manoeuvre. However, this study goes a step further and proposes management measures to improve both safety and traffic operation based on observations and scientific methods, integrating all road users on two-lane rural roads.

Speed limit management can be an efficient solution to increase safety and traffic operation on rural roads, especially during peak hours of cycle traffic. In fact, speed management is more effective to reduce speed levels on rural roads with high speed levels than on urban streets with low speed levels (Silvano et al., 2020). It can also be a low-cost solution that road administrations can easily implement. However, it is essential that speed limit management is based on scientific criteria, and for this purpose validated traffic microsimulation is used. This methodology was used by Lu et al. (2023) to evaluate the effects of variations in the speed limit in urban areas, evidencing its adequacy.

Regarding the perception of safety of cyclists on rural roads, several studies suggest that cyclists relate safety to speed during overtaking. López et al. (2020) and Rasch et al. (2022) agree that the higher the speed during overtaking, the higher the perceived level of risk. Fitch et al. (2022) also concluded that greater vehicular volume and speed are usually associated with less perceived safety and comfort for cyclists, and they suggested the use of traffic calming treatments to reduce speed limits to increase comfort. These previous studies are in line with the results obtained in the present study, where the optimal speed limit when the level of cycle traffic is high is reduced.

However, reducing the speed limit on the road has some negative effects, such as increasing the duration of overtaking, with a consequent increase in the risk of head-on collision associated with a longer exposure time for drivers in the oncoming lane. Increased overtaking

Table 6
Decision matrices for the motorised traffic levels M1 and M2 considering the 4 cycle traffic levels (B0, B1, B2 and B3) and the 2 cyclist group configurations (L and TA). A70, A60 and A50 represent the alternatives, while SL, %RE, ATS and %D/TT represent the evaluation criteria. The units of ATS and SL are km/h while %RE and %D/TT are percentages.

			B0			B1			B2			B3		
		SL	*%RE*	*ATS*	*%D/TT*	*%RE*	*ATS*	*%D/TT*	*%RE*	*ATS*	*%D/TT*	*%RE*	*ATS*	*%D/TT*
M1	A70-TA	70	0.00	69.28	0.00	5.72	65.12	7.57	9.12	60.11	16.23	10.53	51.41	30.16
	A60-TA	60	0.00	59.98	0.00	5.01	57.12	5.61	8.46	53.89	11.92	10.43	47.86	23.20
	A50-TA	50	0.00	50.00	0.00	4.77	48.13	4.17	7.98	46.10	8.76	10.53	42.65	16.35
	A70-L	70	0.00	69.28	0.00	7.18	64.34	8.75	10.13	58.72	18.67	11.31	50.19	31.98
	A60-L	60	0.00	59.98	0.00	6.37	56.27	7.21	9.60	52.42	14.83	10.95	46.18	26.06
	A50-L	50	0.00	50.00	0.00	5.92	47.55	5.58	9.00	45.12	11.09	10.90	41.25	19.27
M2	A70-TA	70	0.00	69.05	0.00	2.10	51.85	29.81	2.90	44.05	39.82	3.58	38.96	46.06
	A60-TA	60	0.00	59.99	0.00	1.64	47.15	24.94	2.36	41.03	34.24	3.09	37.03	39.98
	A50-TA	50	0.00	50.00	0.00	1.08	41.87	18.69	1.72	37.59	26.68	2.36	34.76	31.65
	A70-L	70	0.00	69.05	0.00	2.25	50.71	31.58	3.07	42.73	41.71	3.53	37.89	47.56
	A60-L	60	0.00	59.99	0.00	1.80	46.28	26.51	2.54	40.07	35.89	3.07	36.19	41.37
	A50-L	50	0.00	50.00	0.00	1.25	41.44	19.53	1.81	37.03	27.84	2.36	34.26	32.65

Table 7
Normalised decision matrices for the motorised traffic level M1 considering the 3 cycle traffic levels (B1, B2 and B3). A70, A60 and A50 represent the alternatives, while SL, %RE, ATS and %D/TT represent the evaluation criteria.

			B1			B2			B3		
		SL	*%RE*	*ATS*	*%D/TT*	*%RE*	*ATS*	*%D/TT*	*%RE*	*ATS*	*%D/TT*
M1	A70	1.00	0.00	1.00	0.00	0.00	1.00	0.00	0.04	1.00	0.00
	A60	0.50	0.74	0.53	0.58	0.58	0.56	0.58	1.00	0.59	0.50
	A50	0.00	1.00	0.00	1.00	1.00	0.00	1.00	0.00	0.00	1.00
M2	A70	1.00	0.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00	0.00
	A60	0.50	0.46	0.53	0.44	0.46	0.53	0.42	0.41	0.54	0.42
	A50	0.00	1.00	0.00	1.00	1.00	0.00	1.00	1.00	0.00	1.00

Table 8
Criteria weights according to CRITIC method considering the motorised traffic level M1 and M2, the 3 cycle traffic levels (B1, B2 and B3). SL, %RE, ATS and %D/TT represent the evaluation criteria.

	B1				B2				B3			
	SL	*%RE*	*ATS*	*%D/TT*	*SL*	*%RE*	*ATS*	*%D/TT*	*SL*	*%RE*	*ATS*	*%D/TT*
M1-W	0.247	0.255	0.247	0.251	0.250	0.250	0.249	0.250	0.211	0.229	0.204	0.356
M2-W	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.249	0.251	0.250	0.250

Table 9
Final score of each alternative and ranking considering the motorised traffic level M1 and M2.

	M1						M2					
	B1		B2		B3		B1		B2		B3	
	FScore	Rank	FScore	Rank	FScore	Rank	FScore	Rank	FScore	Rank	FScore	Rank
A70	0.311	3	0.322	2	0.299	2	0.337	2	0.338	1	0.340	2
A60	0.371	1	0.356	1	0.449	1	0.325	3	0.324	2	0.318	3
A50	0.319	2	0.322	2	0.252	3	0.338	1	0.338	1	0.342	1

duration also has an impact on traffic performance, penalising traffic by requiring more space in the opposite direction to overtake properly and therefore reducing the number of overtakings per vehicle. On the other hand, lowering the speed limit leads to fewer overtaking manoeuvres, while reducing exposure to risk. These effects of reducing the speed limit on overtaking duration and on the number of overtakings are unified in the percentage of risk exposure (%RE) as a surrogate measure, so that a balance is made between these two variables to characterise safety.

It can be seen in Fig. 4 that as the volume of cyclists increases, the % ER does not increase linearly, but rather its increase was lower for high values of cycle volume. If Figs. 4 and 5 are compared, it is observed that for high values of motorised traffic (Fig. 5) the %ER values were lower than for low values of motorised traffic (Fig. 4). These results corroborate the Safety in Numbers hypotheses for roads with mixed motor vehicle and cyclist traffic.

Reducing the speed limit also reduces ATS. According to Elvik (2010), a ±10 km/h change in speed limit means a ±2.5 km/h change in average speed. In the present study, when the traffic level was low, a 10 km/h reduction in the speed limit caused a reduction of approximately 10 km/h in ATS, because traffic was flowing and motorised vehicles were obliged to respect the speed limit. For high levels of traffic, both motorised and cyclist, the impossibility of overtaking causes motorised vehicles to bring their ATS closer to that of bicycles, in this case, changes in the speed limit have no effect as it is the traffic itself that regulates the ATS. These effects confirm that on rural roads, the overtaking manoeuvre is a key factor in mixed motorised and cycle traffic.

According to previous studies carried out by the authors (López et al., 2020; Moll et al., 2021b), it is confirmed that accelerative manoeuvres occur on roads with section or sight distance limitations, which generally have lower speed limits. Based on these previous studies, reducing the speed limit can increase the number of accelerative manoeuvres, which in principle increases safety for cyclists, as these are performed at lower speed and are also considered by cyclists to be safer.

Regarding the characteristics of the road on which the study was conducted, the speed limit was considered a beneficial criterion, as the alternatives considered were 70, 60 and 50 km/h, which are relatively low for cyclists, and also for drivers, compared to the maximum speed limit of 90 km/h on other rural roads. On roads with higher speed limits, this criterion may change sign and, in general, lower speed limits may be considered more beneficial.

The CRITIC method provides results based on objective weights based on intra and inter criteria variability (Diakoulaki et al., 1995), without incorporating the subjective judgement of the decision-maker. It is evident that in the area of road safety, the decision-maker's judgement is important, and therefore the results obtained by the CRITIC method should be reviewed and assessed by decision-makers in all cases.

Based on the results obtained, some recommendations are derived for narrow rural roads with cycle traffic:

- Reduce the speed limit of the road when cycle demand is high. This reduction can be made in time periods where high cycle traffic intensity is expected, it is advisable to carry out a demand study beforehand to identify the time patterns of cycle demand.
- Cyclists groups riding two-abreast. It has been observed that a shorter overtaking duration is required, thus improving traffic operation and the level of risk exposure. Signs advising groups of cyclists to ride two-abreast can be incorporated at the entrance to the road section.

The main recommendation and conclusion derived from this study is the implementation of a dynamic speed management system on the road which depends on the traffic level of motor vehicles and cycle traffic on real time. Therefore, an effective real time counting system, capable of register, count and discriminate each road user should be needed (Lopez et al., 2022).

The results obtained on this research are limited to the narrow road segment CV-502, however, they can be generalised to roads with similar cross sections and traffic levels.

In the simulations, it has been assumed that motor vehicles respect the road speed limit. In reality, compliance has to be ensured for this measure to achieve its objective. This can be achieved through the use of speed cameras and even penalties for non-compliance, while investing in road safety education campaigns.

It is recommended that the methodology developed in this research be applied to other rural road segments, considering their specific geometric and traffic characteristics, to provide results adapted to each road. The traffic microsimulation model developed in Aimsun Next must be adapted to the characteristics of cyclists, such as their speed and the configuration of the group, with the possibility of simulating other types of cyclists that are more common on rural roads in other countries.

In terms of road geometry, the width of the cross-section plays an important role, as narrower roads have longer overtaking durations (Moll et al., 2021b). Also the slope of the road is important, as it modifies the speed of cyclists. The minimum lateral clearance required or the possibility of crossing the road centre line during overtaking also causes variations in the duration of the overtaking and in the number of overtaking manoeuvres performed. All these aspects should be introduced as parameters in the traffic microsimulation model in order to correctly represent the phenomenon and adapt the results to each real situation.

Future research aims to evaluate the real consequences of the dynamic management of the speed limit, as well as the level of compliance by motor vehicles and the reaction of cyclists in terms of grouping and use.

5. Conclusions

The presence of cyclists on two-lane rural roads is a common phenomenon, which has repercussions both on road safety and traffic operation. Cyclists should be included in the studies in order to manage rural roads efficiently and safely.

The use of traffic microsimulation models, properly calibrated and validated, allows different management measures to be simulated and their effects evaluated before they are applied on the road, avoiding unwanted effects and reducing risks. The performance measures used in this study to characterise safety and traffic operation are appropriate and sensitive to mixed traffic.

On narrow two-lane rural roads, the increase in cycle traffic means a reduction in average travel speed, and an increase in overtaking manoeuvres, delay time and exposure to risk. The riding of cyclist groups two-abreast is recommended, since it presented higher traffic operation level and lower safety risk.

Speed limit management can be an excellent solution to increase safety and traffic operation on rural roads, especially during peak hours of cycle traffic. The results provided by the MCDM method suggest dynamic speed limit management according to the geometric characteristics of the road and the level of both motorised and cycle traffic.

The development of an active traffic signal to implement dynamic speed limit management on the road is suggested. This active signal has to be able to register and discriminate all road users in real time and determine the optimal speed limit using an algorithm based on the method developed in this research.

CRediT authorship contribution statement

Sara Moll: Methodology, Data collection, Investigation, Software, Formal analysis, Writing - original draft. Griselda López: Conceptualization, Methodology, Data collection, Investigation, Formal analysis, Writing - original draft, Supervision. Alfredo García: Conceptualization, Methodology, Investigation, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Aimsun, 2023. Aimsun next [WWW Document]. https://www.aimsun.com/es/aimsun-next/. https://www.aimsun.com/es/aimsun-next/.

Alcaraz Carrillo de Albornoz, V., Molina Millán, J., Lara Galera, A., Muñoz Medina, B., 2022. Road speed limit matters – are politicians doing the right thing? Socioecon Plann Sci 79. https://doi.org/10.1016/j.seps.2021.101106.

Alinezhad, A., Khalili, J., 2019. New methods and applications in multiple attribute decision making (Madm). In: International Series in Operations Research and Management Science. https://doi.org/10.1007/978-3-030-15009-9.

Barceló, J., 2010. Fundamentals of Traffic Simulation, International Series in Operations Research & Management Science, International Series in Operations Research & Management Science. Springer New York, New York, NY. https://doi.org/10.1007/978-1-4419-6142-6.

Beck, B., Chong, D., Olivier, J., Perkins, M., Tsay, A., Rushford, A., Li, L., Cameron, P., Fry, R., Johnson, M., 2019. How much space do drivers provide when passing cyclists? Understanding the impact of motor vehicle and infrastructure characteristics on passing distance. Accid. Anal. Prev. 128, 253–260. https://doi.org/10.1016/j.aap.2019.03.007.

Bianchi Piccinini, G.F., Moretto, C., Zhou, H., Itoh, M., 2018. Influence of oncoming traffic on drivers' overtaking of cyclists. Transport. Res. F Traffic Psychol. Behav. 59, 378–388. https://doi.org/10.1016/j.trf.2018.09.009.

Brijs, T., Mauriello, F., Montella, A., Galante, F., Brijs, K., Ross, V., 2022. Studying the effects of an advanced driver-assistance system to improve safety of cyclists overtaking. Accid. Anal. Prev. 174, 106763 https://doi.org/10.1016/J.AAP.2022.106763.

Diakoulaki, D., Mavrotas, G., Papayannakis, L., 1995. Determining objective weights in multiple criteria problems: the critic method. Comput. Oper. Res. 22 https://doi.org/10.1016/0305-0548(94)00059-H.

de València, Diputació, 2022. Libro de Aforos 2022.

Dirección General de Tráfico, 2021. Las principales cifras de la Siniestralidad Vial España 2021.

Dozza, M., Schindler, R., Bianchi-Piccinini, G., Karlsson, J., 2016. How do drivers overtake cyclists? Accid. Anal. Prev. 88 https://doi.org/10.1016/j.aap.2015.12.008.

Elvik, R., 2018. How can the notion of optimal speed limits best be applied in urban areas? Transport Pol. 68 https://doi.org/10.1016/j.tranpol.2018.05.008.

Elvik, R., 2010. A restatement of the case for speed limits. Transport Pol. 17 https://doi.org/10.1016/j.tranpol.2009.12.006.

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. Transport. Res. F Traffic Psychol. Behav. 63 https://doi.org/10.1016/j.trf.2019.04.026.

Filipi, N., Karlínová, B., Krčál, O., 2022. The disutility of driving below the speed limit on highways. In: Review of Economic Perspectives, vol. 22. https://doi.org/10.2478/revecp-2022-0012.

Fitch, D.T., Carlen, J., Handy, S.L., 2022. What makes bicyclists comfortable? Insights from a visual preference survey of casual and prospective bicyclists. Transp Res Part A Policy Pract 155. https://doi.org/10.1016/j.tra.2021.11.008.

Garcia, A., Llorca, C., Serra-Planelles, J., 2020. Influence of peloton configuration on the interaction between sport cyclists and motor vehicles on two-lane rural roads. J. Transport. Saf. Secur. 12, 136–150. https://doi.org/10.1080/19439962.2019.1591557.

Grumert, E.F., Tapani, A., Ma, X., 2018. Characteristics of variable speed limit systems. Europ. Trans. Res. Rev. 10 https://doi.org/10.1186/s12544-018-0294-8.

Krishnan, A.R., Kasim, M.M., Hamid, R., Ghazali, M.F., 2021. A modified critic method to estimate the objective weights of decision criteria. Symmetry 13. https://doi.org/10.3390/sym13060973.

Llorca, C., Angel-Domenech, A., Agustin-Gomez, F., Garcia, A., 2017. Motor vehicles overtaking cyclists on two-lane rural roads: analysis on speed and lateral clearance. Saf. Sci. https://doi.org/10.1016/j.ssci.2015.11.005.

Lopez, G., Moll, S., Vacalebri, F., Garcia, A., 2022. Challenges to implementing cyclist counting systems on rural roads. In: Contributions to the 10th International Cycling Safety Conference 2022 (ICSC2022). Technische Universität Dresden, pp. 208–210. https://doi.org/10.25368/2022.484.
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. Transport. Res. Rec. 2674 https://doi.org/10.1177/0361198120921169.
Lu, Q.-L., Qurashi, M., Antoniou, C., 2023. Simulation-based policy analysis: the case of urban speed limits. Transp Res Part A Policy Pract 175, 103754. https://doi.org/10.1016/j.tra.2023.103754.
Ministerio de Cultura y Deporte, 2022a. Encuesta de Hábitos Deportivos 2022.
Ministerio de Cultura y Deporte, 2022b. Anuario de Estadísticas Deportivas 2022.
Ministerio del Interior, 2003. Real Decreto 1428/2003, de 21 de noviembre, por el que se aprueba el Reglamento General de Circulación para la aplicación y desarrollo del texto articulado de la Ley sobre tráfico, circulación de vehículos a motor y seguridad vial, aprobado por el Real De. Boletín Oficial del Estado (BOE), pp. 45684–45772.
Moll, S., López, G., García, A., 2021a. Analysis of the influence of sport cyclists on narrow two-lane rural roads using instrumented bicycles and microsimulation. Sustainability 13. https://doi.org/10.3390/su13031235.
Moll, S., López, G., Rasch, A., Dozza, M., García, A., 2021b. Modelling duration of car-bicycles overtaking manoeuvres on two-lane rural roads using naturalistic data. Accid. Anal. Prev. 160 https://doi.org/10.1016/j.aap.2021.106317.
Odu, G.O., 2019. Weighting methods for multi-criteria decision making technique. J. Appl. Sci. Environ. Manag. 23 https://doi.org/10.4314/jasem.v23i8.7.
Rasch, A., Moll, S., López, G., García, A., Dozza, M., 2022. Drivers' and cyclists' safety perceptions in overtaking maneuvers. Transport. Res. F Traffic Psychol. Behav. 84, 165–176. https://doi.org/10.1016/j.trf.2021.11.014.
Rubie, E., Haworth, N., Twisk, D., Yamamoto, N., 2020. Influences on lateral passing distance when motor vehicles overtake bicycles: a systematic literature review. Transport Rev. 40 https://doi.org/10.1080/01441647.2020.1768174.
Silvano, A.P., Koutsopoulos, H.N., Farah, H., 2020. Free flow speed estimation: a probabilistic, latent approach. Impact of speed limit changes and road characteristics. Transp Res Part A Policy Pract 138. https://doi.org/10.1016/j.tra.2020.05.024.
Sitorus, F., Cilliers, J.J., Brito-Parada, P.R., 2019. Multi-criteria decision making for the choice problem in mining and mineral processing: applications and trends. Expert Syst. Appl. https://doi.org/10.1016/j.eswa.2018.12.001.
Soriguera, F., Torné, J.M., Rosas, D., 2013. Assessment of dynamic speed limit management on metropolitan freeways. J. Intell. Transport. Syst. Technol. Plann. Oper. 17 https://doi.org/10.1080/15472450.2012.719455.
Transportation Research Board, 2022. Highway Capacity Manual, seventh ed. National Academies Press, Washington, D.C. https://doi.org/10.17226/26432.
Zhao, J., Knoop, V.L., Wang, M., 2022. Microscopic traffic modeling inside intersections: interactions between drivers. Transport. Sci. https://doi.org/10.1287/trsc.2022.1163.