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Assessment of bicycle experimental objective handling quality indicators

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Abstract:

Understanding and mastering handling quality is a critical concern for bicycle designers, as it directly impacts safety, comfort, and performance. However, this aspect has received limited attention to date. Existing literature offers experimental handling quality indicators based on bicycle kinematics, but their validity has yet to be established. This study aims to assess the predictive power of these indicators using experimental data derived from subjective assessments of handling quality. These data, obtained from a protocol involving 20 participants and 2 bicycles, enabled testing 39 experimental indicators. The results indicate that certain vehicle kinematic quantities are indeed correlated with the perception of handling quality but with low predictive power. Indicators based on handlebar movement are the most effective in explaining the sensation of handling quality. These indicators perform particularly well at low speeds, where physical and cognitive workload are associated with the quantity of control actions on the handlebars.

Keywords:

Bike, Kinematic, Subjective, Single-track Vehicle

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1 Introduction

1.1 Context

Cycling has become increasingly popular in urban areas in recent years. Its use is intensifying and diversifying. As well as being a recreational vehicle, bicycles are becoming (or re-emerging) as a means of transport (personal or professional) in urban environments. The emergence of new uses, in particular cargo bicycles (for people or goods transportation), is driving changes in vehicles and practices. This wider use raises questions about the comfort, performance and safety of these vehicles. Mastering these characteristics will help facilitating the inclusive development of this low-carbon mobility, whatever the level of proficiency of users.

Given this context, it appears of primary importance to be able to characterise how well one can "handle" a given bicycle.

1.2 Handling quality definition

Handling quality is a 2-dimensional quantity defined by the ease and precision with which a pilot may complete a given task (Cooper and Harper, 1969). It describes the quality of the interaction between a cyclist and its bicycle. This concept is relatively consensual and is used in the automotive and aeronautical industries as well as for 2-wheeled vehicles (Cooper and Harper, 1969; Sugizaki and Hasegawa, 1988; Horiuchi and Yuhara, 1998; Kuroiwa et al., 1995; Weir and DiMarco, 1978; Hess, 2012).

1.3 Handling quality subjective assessment

To date, the most promising approach for bicycle handling quality remain the subjective scale of Cooper-Harper (Hess, 2012) developed in the the aeronautic field (Cooper and Harper, 1969). It is interesting to note that this scale integrates both the cyclist's workload (which refers to ease) and performance (which refers to precision).

In similar fields (motorcycles and automotive), handling quality is mainly based on rider physical workload (omitting the performance component). The latter is often derived from steering torque measurement (Kuroiwa et al., 1995; Zellner and Weir, 1978; Cossalter and Sadauckas, 2006). But given the low torque needed to be control compared to a motorcycle, this approach is irrelevant for bicycles. Other objective measures of the physical and cognitive workload (using physiological approach, like fNRIS) remain complex and difficult to deploy in an ecological setting.

Finally the most suitable approach for bicycle handling quality is the subjective rating scale developed by Cooper and Harper (1969). However, an objective approach to overcome, data variability and methodological precautions inherent in the questionnaires is highly desirable. It would make possible the handling quality evaluation of bicycles on larger scales and under ecological setting. As pointed by the review Schwab and Meijaard (2013), this question is still a little-addressed research issue. The authors also highlight the lack of standardised procedures for assessing the handling quality of a bicycle in a given experimental condition. Ideally, such indicators would be based solely on the vehicle kinematics or dynamics, that could be easily accessible.

1.4 Existing objective handling quality indicators

To date, Takagi et al. (2022) are among the few to propose objective experimental indicators (SST evaluation and Handle Per Roll) based on vehicle kinematics, to attempt to correlate them with cyclists' feeling (riding instability). This assessment methodology has not been addressed yet to bicycle handling quality.

The motorcycle, as a single-track vehicle, is probably the most similar vehicle for identifying handling quality indicators for bicycles. However, although both vehicles are primarily controlled through handlebar actions (Schwab and Meijaard, 2013), the magnitudes of the forces involved are not of the same order of magnitude: a few N.m for bicycles (Cain and Perkins, 2010) compared to a few tens of N.m for motorcycles (Kuroiwa et al., 1995). Thus, motorcycle indicators based on steering torque will not be included in the study. However, motorcycle handling quality indicators based on kinematic quantities such as Yaw factor (Zellner and Weir, 1978) and Mozzi axis (Cossalter and Doria, 2004) are included, as well as indicators for analysing bicycle motion that have been previously dedicated to studies. These indicators can be categorised into 2 approaches: variability of motion and quantification of

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steer into the lean strategy. In the variability approach, the variability of bicycle state variables (roll angle, yaw angle, and steering angle) and their derivatives are studied (Moore et al., 2010; Cain et al., 2016, 2012; Matsuzawa et al., 2009). The quantification of *steer into the lean* strategy generally involves the analysis of correlations between bicycle state variables, such as roll rate/steer rate (Cain et al., 2016, 2012) and steer rate/roll angle (Takagi et al., 2022).

In the context of studying indicators fully based on vehicle kinematics, indicators based on the cyclist' torso lean will not be considered .

1.5 Objective and outline

This article aims to assess the predictive power of 39 objective handling quality indicators. To do this, an experimental dataset was constructed by recruiting 20 cyclists who were asked to perform a line tracking task on a track with bikes equipped of IMUs. Participants subjectively rated the handling of bicycles from questionnaires. These data have served as a reference for the assessment of handling quality indicators.

2 Material and methods

2.1 Cyclists

A sample of 20 cyclists over the age of 18 who declared that they knew how to ride a bicycle, were included in the protocol. Participants under 155 cm were excluded in order to be able to adjust the bicycles to their height. These cyclists declared that they had no balance problems and no particular physical disabilities.

2.2 Experimental bicycles

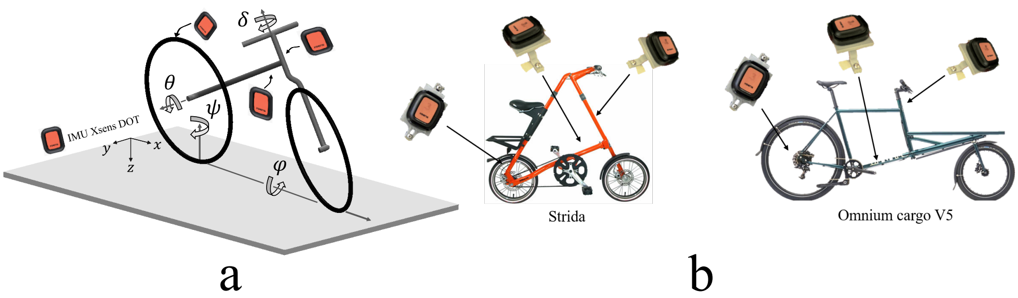

Figure 1. (a) Bicycle state variables and sensors setup, (b) The experimental bicycles

Bicycles setup Two commercially available urban bicycles were used for the experiment: a folding bicycle from Strida™ and a cargo bicycle from Omnium™ (Figure 1 (b)). These two bicycles were chosen for their unusual design regarding average city users' habits.

Bicycle motion is describe by the following state vector: $(\delta, \phi, \psi, \dot{\delta}, \dot{\phi}, \dot{\psi}, u)$ as illustrated in Figure 1(a). Its components respectively describe: steering, roll and yaw angles and their time derivatives and the bicycle speed.

This state vector was estimated using 3 XSens DOT inertial sensors sampling at 60 Hz placed on the handlebar, frame, and rear wheel of each bicycle, as presented in Figure 1 (a) and (b). The sensors were synchronised so that the XSens fusion algorithm could be used to provide the orientation of each sensor relative to a global reference frame.

The rear wheel sensor was used to estimate the speed of the bicycle u from the rear wheel radius r_R and the wheel angular velocity $\dot{\theta}$. The other inertial units were used to measure angle and angle rates of the frame roll $(\phi, \dot{\phi})$ and yaw $(\psi, \dot{\psi})$, and the handlebar steering angle $(\delta, \dot{\delta})$.

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2.3 Track

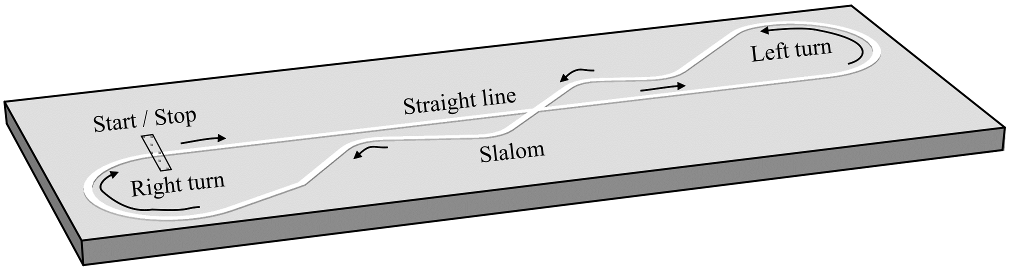

Figure 2. The track consists of a 130-meter-long white line painted on the ground, composed of a straight line, a slalom and two U-turns.

A path-tracking task was chosen so that a clear set of instructions could be defined and allowing self-assessment of the performance achieved. This task was chosen because it requires control qualities that are useful for mobility in an urban environment. Also, by its restrictive nature, this task seeks to exacerbate the participants' control difficulties.

Thus a 130 m long track was marked out on the ground of a flat tarmac car park closed to traffic. The circuit consists of a 10 cm wide line of white paint .

The circuit is made up of a 43 m straight line, a circular left turn (5 m radius), a slalom (4 curves) and a circular right turn (5 m radius) (see Figure 2. This track was designed as a mixed circuit, inspired by standard motorcycle manoeuvres, combining a straight, a slalom and two U-turns. The trajectories are deliberately demanding to create variations in difficulty.

2.4 Subjective assessment of handling quality

Among handling quality rating scales found in the literature, Cranfield Aircraft Handling Qualities Rating Scale (CAHQRS) from Harris et al. (2000) originally derived from the work of Cooper and Harper (1969) was chosen. This scale provides a discrete unidimensional measurement on 10 levels including performance and the load perceived by the cyclist. Its use for bicycle evaluation has already been suggested by Hess (2012). The CAHQRS has been translated in French and adapted for use on bicycles. The scale used starts at level 0: "I achieved the task, extremely easily, I needed minimal compensation", and ends at level 9: "I failed in controlling the bike, I stopped, I needed maximal compensation".

2.5 Experimental procedure and conditions

The experiments were performed in two consecutive blocks, one per bicycles. The order of the blocks was randomised between subjects.

For each block, the bicycle saddle setup was adjusted to the participants, ensuring that they could at least touch the ground with the tip of their foot while sitting on the saddle. This position enabled them to stop easily and stabilise the bicycle with their feet.

The participants then had 5 minutes of training, during which they were free to test the circuit. The aim of this training is to allow the cyclists to familiarise them with the bikes so they could be comfortable to vary their speed.

At the end of this learning period, the participants were asked to perform laps of circuit at different speeds: as slowly as possible, at the optimal control speed, or faster than the optimal control speed. The optimal control speed is define as the speed the cyclist self-estimate to be the best to control the bike on this specific task. A total of nine laps was performed per block (three per requested speed). The order of the requested speed was randomised, except the first lap was always at the optimal control speed.

For each lap, the instructions given were: (1) Complete a single lap without breaking, (2) Try to keep the front wheel on the white line, (3) Try to maintain a constant speed.

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2.6 Included Indicators

Yaw factor and derived In this paper, the Yaw factor (Y_F), initially utilised as a handling indicator in Zellner and Weir (1978), was subsequently chosen as variable of interest. This variable is a ratio that quantifies the amount of yaw rate per unite of steer angle. Unlike Zellner and Weir (1978) which uses a theoretical model to evaluate the experimental Yaw factor, Y_F was a variable used as a basis for calculating potential handling quality indicators. Three indicators are defined based on Y_F: its standard deviation, its mean value and its entropy. Using the same state variables ψ and δ (and their derivatives), additional indicators were constructed based on cross-correlation approach. Table 1 describes the 9 indicators derived form the Yaw factor and the additional indicators.

Variable(s)	Fomula	Indicator	Description
Y_F	$\frac{\dot{\psi}}{\delta}$	$\mu(Y_F)$	mean value
		$\sigma(Y_F)$	Standard-deviation
		$H(Y_F)$	Average entropy over 10^3 draws, for samples of 10^3 points
(ψ,$\dot{\delta}$), ($\dot{\psi}$,δ), ($\dot{\psi}$,$\dot{\delta}$)		$\lvert R(.,.)\rvert$	absolute value of cross-correlation maximum peak
		$\lvert \tau(.,.)\rvert$	Associated time lag to absolute value of cross-correlation maximum peak

Table 1. Indicators based on the Yaw factor

Mozzi axis The Mozzi Axis, or instantaneous screw axis, is a concept proposed by Cossalter and Doria (2004) to study arbitrary two-wheels manoeuvres. This approach is based on the idea that any manoeuvre is a generalised form of slalom where the spacing between the cones is not constant. The Mozzi axis is the velocity vector of the vehicle frame from which 2 variables are calculated: 1- the transverse coordinate of the intersection point between the instantaneous screw axis and the ground (noted y_M), 2- the angle of the instantaneous screw axis with respect to the horizontal (θ_M). In Cossalter and Doria (2004), a qualitative interpretation of the trajectory of y_M and θ_M highlights the importance of the peaks and discontinuities of these variables from a handling quality perspective. Peaks and discontinuities in y_M and θ_M are, by definition, associated with the change in sign of roll and yaw rates, and therefore with the oscillation of the bicycle frame. The 7 indicators based on Mozzi axis are presented in Table 2.

Variables	Fomula	Indicators	Description
y_M	$\frac{\dot{\psi}V}{\dot{\psi}^2+\dot{\phi}^2}$	$\sigma(y_M)$	Standard-deviation of y_M
		$H(y_M)$	Average entropy over 10^3 draws, for samples of 10^3 points
		$N_{peaks}(y_M)/T$	number of peaks per unit of time
		$\mu_{peaks}(y_{Mozzi})$	mean value of peaks
		$max_{peaks}(y_M)$	maximum value of peaks
θ_M	$\arctan(\frac{\dot{\psi}}{\dot{\phi}})$	$\sigma(\theta_M)$	Standard-deviation
		$H(\theta_M)$	Signal entropy

Table 2. Indicators based on the Mozzi axis

State variable variability Movement variability has been proposed several times as an approach to quantifying handling quality (Moore et al., 2010; Cain et al., 2016, 2012; Matsuzawa et al., 2009). This classic approach to human equilibrium is based on the principle of minimal actions (Todorov, 2004), which may imply that high variability in the amount of control action is synonymous with low handling quality. In this study, the variability (standard deviation and entropy) of the steering, roll and yaw angles and their time derivatives are candidates, which leads to 12 indicators.

***Steer into the lean* strategy** In Cain et al. (2016, 2012), the authors studied the balance of the bicycle under the cyclist's control using approaches similar to those for standing balance. They are interested in the cyclist's ability to align the centre of pressure with the centre of mass of the system while riding straight (bicycle + cyclist). In the case of the bicycle, this balance strategy can be summed up in the notion of *steer into the lean*. Maintaining the bicycle's balance seems to be a prerequisite for carrying out any manoeuvre. This is why balance indicators are also candidates to explain part of the handling quality. Thus roll and steering angle (and their time derivatives) are two variables of interest in our study. Based on Cain et al. (2016, 2012); Takagi et al. (2022), 11 candidate indicators are presented in Table 4. Indicators based on an SST (Singular Spectral Transformation) approach are very sensitive to the analysis parameters. In this paper, the window width is 60 points and 2 components have been used.

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Variables	Fomula	Indicator	Description
δ, $\dot{\delta}$		$\sigma(.)$	Standard deviation
		$H(.)$	Average entropy over 10^3 draws, for samples of 10^3 points
ϕ, $\dot{\phi}$		$\sigma(.)$	Standard deviation
		$H(.)$	Average entropy over 10^3 draws, for samples of 10^3 points
ψ, $\dot{\psi}$		$\sigma(.)$	Standard deviation
		$H(.)$	Average entropy over 10^3 draws, for samples of 10^3 points

Table 3. Indicators based on state variable variability

Variables	Indicators	Description
ϕ, $\dot{\delta}$	$\mu(SST)$	mean anormality degree
	$max(SST)$	maximum anormality degree
	$\sigma(SST)$	Standard deviation of anomality degree
(δ,ϕ),(δ,$\dot{\phi}$), ($\dot{\delta}$,ϕ), ($\dot{\phi}$,$\dot{\delta}$)	$\|R(.,.)\|$	absolute value of cross-correlation maximum peak
	$\|\tau(.,.)\|$	Associated time lag to absolute value of cross-correlation maximum peak

Table 4. *Steer into the lean* strategy derived indicators

2.7 Data analysis and statistical methods

As a reminder, the aim of this study is to evaluate a set of objective handling quality indicators based on kinematic variables analysing the movement of the bicycle. The evaluation is carried out by quantifying the capacity of the objective indicators to explain the subjective feeling measurements considered here as our reference data.

In order to remove the effects of drift associated with IMU measurements, a high-pass Butterworth filter were applied on the angle signals (5th order, cut-off frequencies of 0.05 Hz).

The acceleration and braking phases present over the complete laps and the initial (straight line) and final segments (right turn) have been cut to exclude the transient effects.

The handling ratings show a break in monotony around 2.5 m/s (Ronné et al., 2023), so laps were grouped in two subsets based on their average speed: below (and respectively above) 2.5 m/s. A third group gathers all data regardless of speed. Analyses were performed either on the whole lap or on one of the 4 segments of the lap: straight line, left turn, slalom, right turn (see Figure 2). Segments were identified thanks to the estimation of the distance travelled obtained by integration of the speed vector.

Each indicator is evaluated by a univariate robust linear regression model (robust_linear_model.RLM from python statsmodels library). As explained in the supplementary material section, the code used to generate the results is supplied.

For each model, 2 criteria are calculated to evaluate the tested indicator: 1- the signed Pearson coefficient squared ($sign(R)R^2$), which gives the explanatory power of the indicator and the direction of the correlation, 2- the normalised root mean square error (NRMSE), which measures the prediction performance. The RMSE is normalised using the full amplitude of the handling quality scale.

Given the subdivision of the data (3 speed groups and 4+1 segments), the 39 indicators were evaluated in 15 statistical models each. Only those having a p-value greater than 0.05 are presented.

3 Results

3.1 General results

Our dataset includes (before filtering) 386 laps. Subjective ratings of handling quality on CAHQRS are normally distributed with a mean of 2.9 (level 3 : " I achieved the task correctly, I needed medium compensation") and a standard deviation of 1.3 (see Figure 3) .

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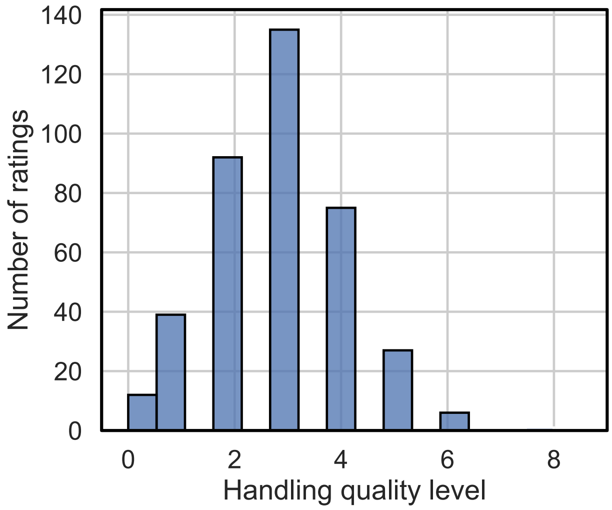

Figure 3. Distribution of the subjective handling quality ratings

The results are presented by indicator family in bar charts showing the mean value $sign(R)R^2$ between the 5 segments considered. The error bars represent the standard deviation. The absence of a bar indicates that only one segment is statistically significant. Indicators are listed in descending order of R^2.

3.2 Yaw factor and derived

Among the Yaw factor indicators, 7 out of 9 show a significant correlation on at least one of the 15 conditions. On average, the explanatory power (R^2) of the models was less than 5%, while the root mean square error was around 12% of full scale. In general, the models show very little explanatory power for speeds above 2.5 m/s. The $|R(\dot{\psi}, \dot{\delta})|$ indicator is the best overall, showing the most versatile performance across speed groups in the family.

3.3 Mozzi axis

Among the Mozzi axis indicators, 4 out of 7 show a significant correlation on at least one of the 15 conditions. On average, the explanatory power of the models is less than 5%, as for the previous family of indicators, while the mean square error is also of the order of 12% of full scale. The indicator $N_{peaks}(y_M)/T$ has the highest R^2 while the others based on y_M have very little explanatory power, as do the variability indicators. For this family too, the models with the highest R^2 are also the most versatile over all the segments, even if this family seems less predictive than the previous one. Association between the indicators and the perceived handling quality seems stronger for the lower speed group (v<2.5 m/s)

3.4 State variable variability

Among the state variable variability indicators, 9 out of 12 show a significant correlation on at least one of the 15 conditions. On average, the explanatory power of the models is less than 5%, as for the previous family of indicators, while the root mean square error is also around 13% of full scale. The best model, based on $\sigma(\dot{\delta})$ reaches 10% explanatory power for $v < 2.5$ m/s. Very similar indicators: $H(\dot{\delta})$,$H(\delta)$,$\sigma(\delta)$, also based on steering motion, present comparable trend results although they perform less well. Models based on the variability of other state variables performed even less well. Like in the previous family, the association between the indicators and the perceived handling quality seems stronger for the lower speed group (v<2.5 m/s).

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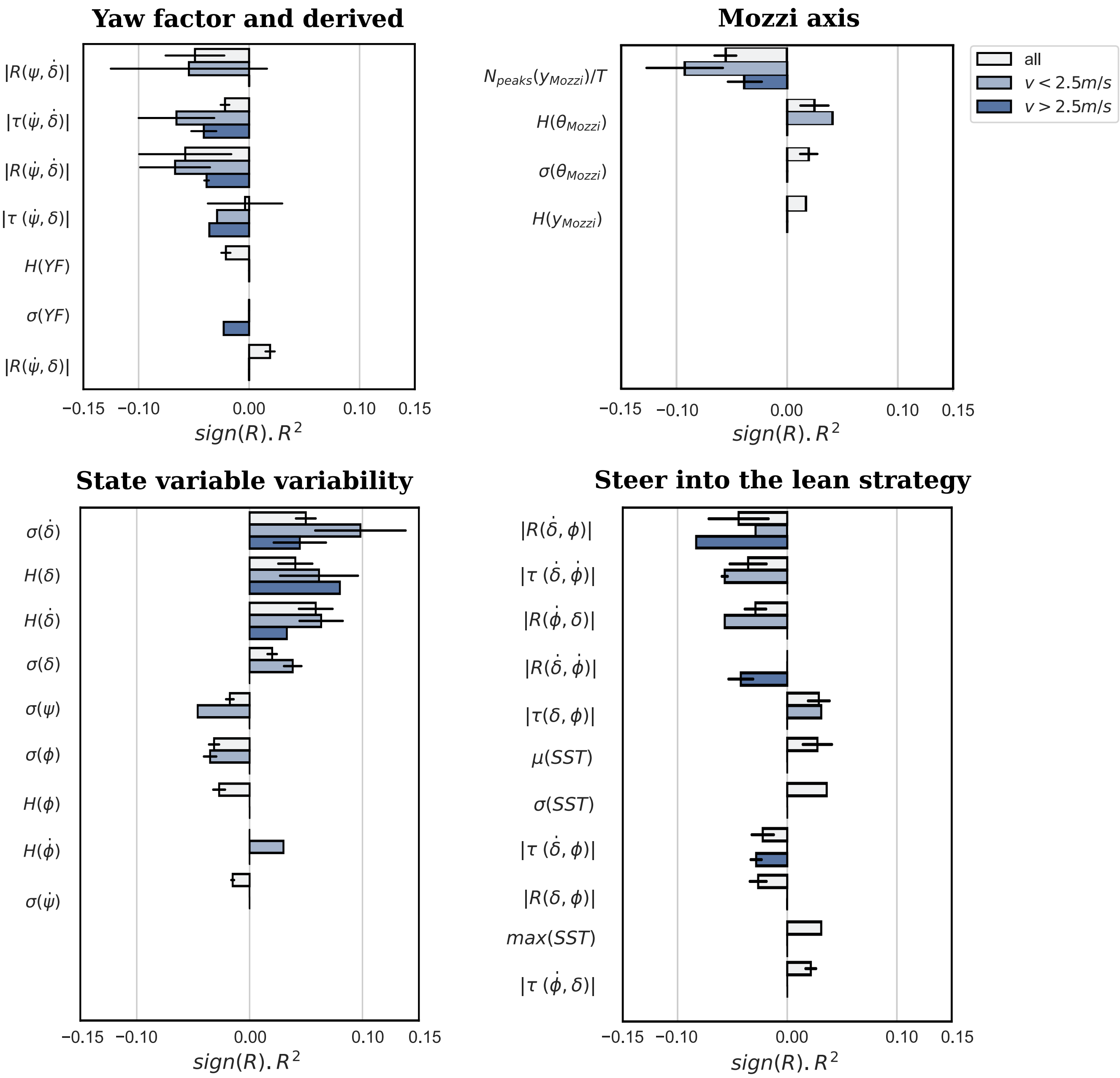

Figure 4. Significant (p<0.05) regression results for the 4 indicators family

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3.5 *Steer into the lean* strategy

Among the *Steer into the lean* indicators, 11 out of 11 show a significant correlation on at least one of the 15 conditions. On average, the explanatory power of the models is less than 5%, as for the previous family of indicators, while the root mean square error is also around 12% of full scale. The model based on $R(\dot{\delta}, \phi)$, reaches about 9% of explanatory power, which is the best performance overall for $v > 2.5$ m/s.

4 Discussion

Most of the tested indicators demonstrate statistical significance (p<0.05) in at least one tested condition (segment and speed). The root mean square error is relatively independent of the tested models and is on the order of 12% of the full scale. However, the explanatory power of univariate models for handling quality remains low (13% at best). Although the measurement variability with the Cooper-Harper scale has never been studied in the field of cycling, it is highly likely that the inherent intra- and inter-individual variability associated with such a subjective measurement limits the predictability of the models.

The best results are obtained for speeds below 2.5 m/s. These are the indicators quantifying the amount of control actions on the handlebars ($\sigma(\dot{\delta})$, $H(\dot{\delta})$, $H(\delta)$, $\sigma(\delta)$). This supports the hypothesis of Ronné et al. (2023) that in this speed range, handling quality is related to a phenomenon of instability. Indeed, in this range, low handling quality is associated with a strong sense of balance loss and intense handlebar movements (Ronné et al. (2023)). Thus, the effectiveness of models based on the quantity of control actions on the handlebars can be explained by the fact that they capture some of the characteristics of bicycle motion associated with a balance-seeking situation. Hence, it is consistent that indicators based on the *steer into the lean* strategy are also significant at low speeds.

Above 2.5 m/s, the tested indicators no longer capture the movement-specific aspects associated with handling quality as effectively. The division of speeds does not prevent the same indicators from showing significant results above 2.5 m/s. However, these models are not very explanatory, which is likely due to the presence of a few instability situations in the data. This can also be explained by the fact that at higher speeds, performance deteriorates (and so does the ratings), even though this phenomenon is not captured by the kinematic indicators. A transition between the mechanisms governing the sensation of handling quality is very likely to occur around 2.5 m/s in our data. These conclusions would benefit from being extended to other bicycles and tasks.

Based on these results, the best univariate model, based on $\sigma(\dot{\delta})$, explains (at best) approximately 15% of the variability in the sensation of handling quality for speeds below 2.5 m/s. With an NRMSE of 12%, it does not allow differentiation of experimental conditions with precision below 2 units on the Cooper-Harper scale. Although it performs less well for speeds above 2.5 m/s, it is significant for all three speed groups tested. It is also significant for several segments of the circuit. Given its limited precision, it seems more relevant in the current state of knowledge to use it as a trend indicator rather than a direct predictor of the handling quality. This is especially true as the model adjustment likely incorporates a circuit-specific effect used in the experiment.

In cases where $\sigma(\dot{\delta})$ is used under similar conditions, lower variability in the steer rate indicates a lesser amount of control actions and, consequently, a lower physical and cognitive workload. However, since handling quality encompasses both ease and precision, the latter should not be overlooked. Indeed, one limitation of this indicator is that it does not control the actual performance achieved. In the case of a bicycle with a very stiff steering, $\sigma(\dot{\delta})$ could be low while the steering torque required is high and performance is compromised.

Conclusion

Handling quality is a desirable attribute for designing safe, comfortable, and high-performance bicycles. The literature presents various experimental indicators based on vehicle kinematics, the validity of which has not yet been evaluated. Our experimental dataset has allowed for the statistical assessment of these indicators, revealing that a significant portion of the sensation of handling quality can be explained. Consequently, indicators measuring the quantity of control actions on the handlebars perform the best, in particular at lower speed (<2.5 m/s). However, these indicators remain simplistic, and future research will aim to better define their scope of application and potential enhancements.

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Supplementary materials

We provide the data table containing the calculated indicators and the subjective ratings. We also provide the full regression results table. The code for reproducing the results and displaying the figures is also provided. All there materials can be find here : RONNE, Jules; DUBUIS, Laura; ROBERT, Thomas, 2023, "Assessment of bicycle experimental objective handling quality indicators", https://doi.org/10.57745/TKPDBV, Recherche Data Gouv

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