How do They Ride? Analysis of Cycling Biomechanics (“MODELO-Rad” Project)

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1 ABSTRACT

For the planning and design of appropriate cycling facilities, aspects such as capacity, continuity, and objective safety are often subjects of research, but an understanding from the cyclist´s perspective, including physical and biomechanical characteristics, remains superficial. Findings related to cyclist behaviour have not yet been systematically applied and there is limited information on the relationship between cycling behaviour and characteristics of transport infrastructure.

The “MODELO-Rad” project aims to understand and model cycling from the perspective of cyclists. Desired speed, riding strategy, and braking distance, among others, are important for understanding bike rides and provide insight on the behavioural characteristics of cyclists from a biomechanical perspective. This research suggests that a bike ride in an urban area can be divided into distinctive behavioural phases, characterized by degrees of power, speed, and cadence. To capture patterns of behaviour among cyclists, this study had participants ride along different routes on "SensorBikes,” which are equipped with sensor technology, to collect over 300 km of observations.

The empirical analysis finds that cycling can be described as behavioural phases between stops (mostly between intersections): an acceleration phase, characterized by high power peaks; a route phase, which is subdivided into stages according to the route conditions (constant travel, deceleration and intermediate acceleration, uphill and downhill rolling); and an approach phase to the stopping point, usually at traffic lights or road junctions. Within these phases, results vary substantially between different cycling facilities and across different groups of cyclists. This description of cycling as a mechanical process can serve as a basis for the development of a micromodelling approach to cycling behaviour and can consequently be used to improve the planning of cycling networks and bike infrastructure.

Keywords: infrastructure, planning, biomechanic, behaviour, cycling

2 COLLECTION DATA DESIGN

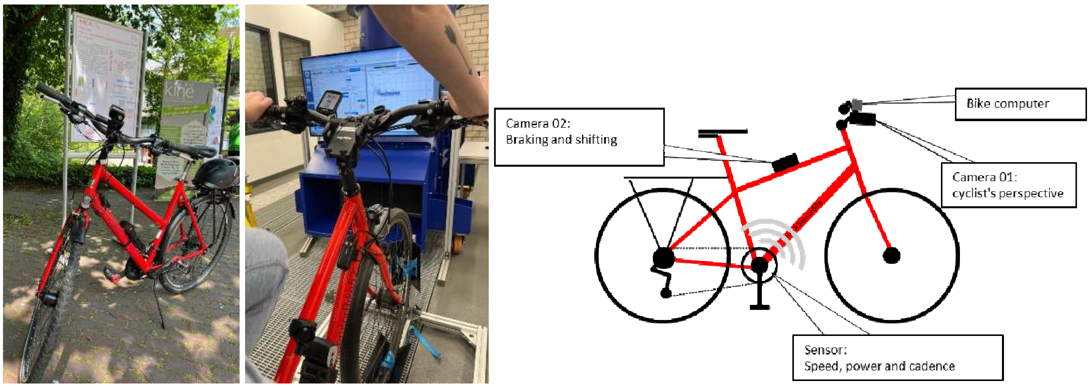
To identify the most relevant aspects of a bicycle ride, different cycling scenarios were observed. The design of the data collection was conceived in such a way that all possible combinations of influencing factors, such as speed variations due to different forms of infrastructure, interactions with other road users, the pedalling power of cyclists before and after traffic-light intersections, and the cadence on uphill sections, were included in a route.

The data collection involved a series of test rides in which the results were progressively evaluated and discussed. The initial test rides presented in this study involve the collection of data for the variables previously mentioned. In the first test, rides on two different routes and eight cyclists totalling over 170 km of observations were carried out. Aspects such as the type of cyclist, the type of bicycle or the representativeness of a specific population were not addressed in this first approach. Based on initial results, a more extensive data collection study including more cyclists and different routes is currently under development.

2.1 Measurement equipment: The “SensorBike”

The data collection required equipment suitable for measuring individual cyclist behaviour. Although research into cycling mobility is relatively new, there are technological developments oriented towards professional sport, which have been integrated into the research of cycling as a mode of transport. Such is the case of different sensors and technologies with a wide variety of configurations that allow the collection of data that were previously uncommon or impossible to measure (Temmen, 2022). The Karlsruhe University of Applied Sciences has progressively realized this idea with the use of different measurement equipment in its bicycle laboratory. The so-called "SensorBike" is a bike and measurement tool, equipped with sensors that enable a large amount of data to be collected simultaneously and then synchronized for analysis (Eckart and Merk, 2021). In this research, the SensorBike collected sensor data for an analysis of the speed, power, and cadence with which the cyclists rode. These three biomechanical variables evaluated from the individual use of a bicycle provide a detailed source of data for evaluating possible variations of speed, power and cadence according to different types of cycling scenarios along predefined routes.

The SensorBike facilitates research into cycling from the perspective of cyclists. For the planned test, two cameras and a bike computer were used in conjunction with the SensorBike. The cameras were used to record the cyclist's field of vision and the use of the brakes. GPS data, speed and route progression, among others, were obtained from the recordings with the bike computer. Sensors built into the test bike were attached to the bike computer, which measured and stored cadence and power.



2.2 Routes and data collection procedures

Different routes were analysed to assess the relationship between cycling infrastructure attributes and cycling. The following aspects were taken into account when creating the routes:

- Frequent interactions in mixed traffic
- Presence of traffic lights
- Sections with priority for cyclists and pedestrians
- Sections with high traffic volumes and parked vehicles
- Sections with ascents and descents of varying gradients
- Sections with interruptions (bus stops, road works, junctions, etc.)
- Sections with no interactions (free-flow travel: desired speed, desired power.)

This resulted in two routes in Karlsruhe, which were divided into sections of equivalent length and similar characteristics (maximally-homogeneous sections). The selected routes totalled a length of approx. 15 km, along which different forms of cycling infrastructure or mixed traffic conditions exist. As shown in the figure below, some of the sections have a high presence of pedestrians and interactions with motorized vehicles. Other sections have more free space, long longitudinal sections, or specific traffic rules.

Fig. 2: Examples of sections on selected routes

The data collection procedure involved three general steps:

- The SensorBike was calibrated and its sensors linked to the bike computer. The test subject received the bike with calibrated sensors, could adjust the height and gears of the bike for optimal use and received instruction for the route.
- The participants performed the test individually and rode the routes sequentially. Participants were instructed to ride as they normally do, and to follow the route marked by the GPS device.
- At the end of each ride, the ride was stored in the bike computer and its data verified. The video from cameras were extracted, differentiating the observation perspectives for their subsequent analysis.

Data quality was ensured by filtering sensor data and the associated video information. To analyse the information, the generated coordinate points (saved every 2 seconds) were displayed in order to link them with the attributes of the routes.

3 SPEED, POWER, AND CADENCE OF A BIKE RIDE

Speed is one of the most commonly used variables for the analysis of bike rides. A speed profile provides an important reference for trip dynamics along a given route or segment.The power exerted by a cyclist is another fundamental variable in the analysis of a cyclist's dynamics and efficiency. Examining cycling power or speed in isolation does not allow a comprehensive analysis of bike rides, but relating them to each other provides important indicators of cycling efficiency in terms of ride performance (Eckart et.al., 2022). Relating speed and cyclist power allows the identification, characterization, and analysis of different cycling situations. One of great importance is the shifting strategy, in which cadence plays an important role as connecting element between desired speed or desired power. Two schematic representations of the observed relationships between the study variables are used in the analysis.

3.1 Aggregate Observations of speed, power, and cadence of all test rides

The power and speed of all test rides can be presented over the ride distance. Figure 3 (left) illustrates changes in speed for participants along 5 Km on the route 01 of the test. It illustrates that a bike ride in an urban setting is characterized by a series of sections delineated by stops at (largely) intersections. Alternatively, visualising power/speed (P/S) ratio data the route (Figure 3, right) results in a dense concentration of points, which provides a first insight into the desired speed and power of each cyclist. The P/S point cloud shows certain distributions of the values when cyclists pedal at a given speed. A first example extracted from the collected data is visualized in the following figures, which show the speed profile of different rides of the same route, as well as the P/S point clouds for these profiles. Although the point cloud does not clearly present specific patterns to be analysed, it allows to observe in a general way, areas of concentration for some of the cycling rides (same colours as in profil). The points allow a range of speeds to be identified between about 10 and 30 km/h, with 20 km/h being the approximate mean value of the point cloud.

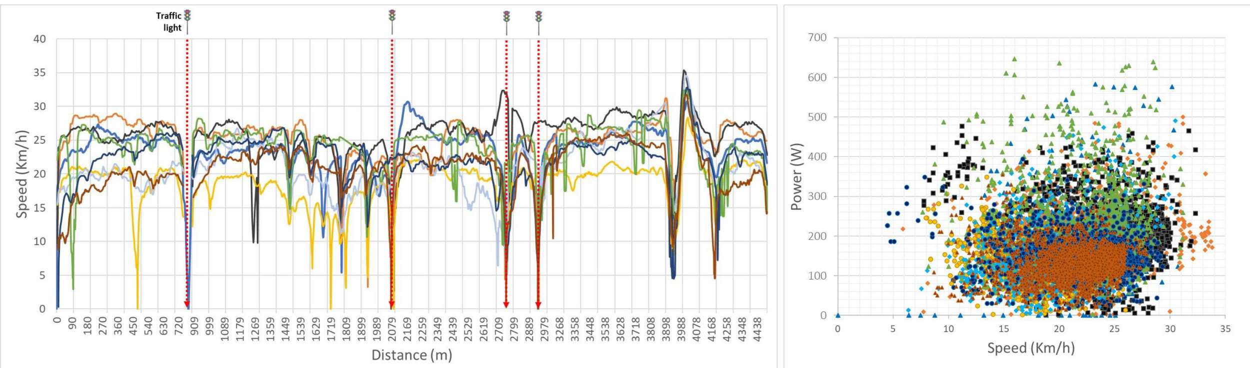


Fig. 3: Speed profil (left) and power-speed point cloud (right) of route 01 by participant

3.2 Aggregate Observations of speed, power, and cadence of a single section

In order to interpret the relationship between speed and power more clearly, it is helpful to focus on the P/S data for a single section of the bike ride between two stops instead of the whole route, for all cyclists. Figure 4 shows interpretations of P/S dynamics. On the left is an illustration of speed, power, and cadence profiles over a distance of approx. 770 m between two intersections. The right illustration is a P/S point cloud for the same section.

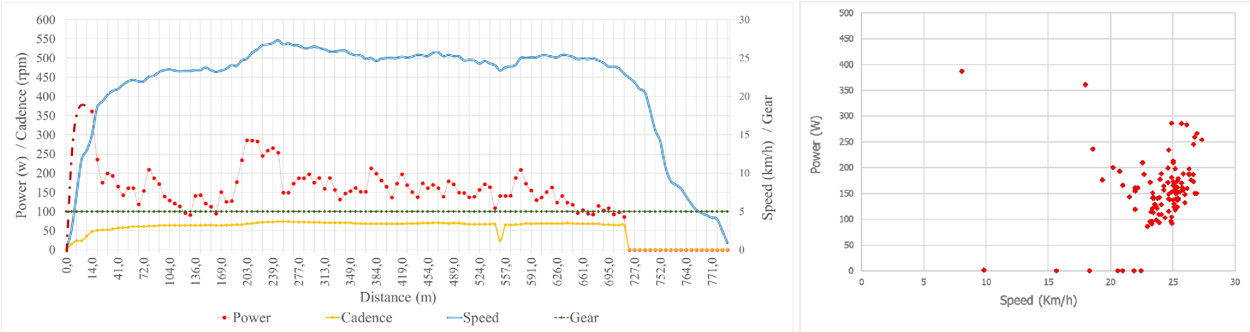


Fig. 4: Speed, power, and cadence profiles (left). Point cloud for same section (right). Example section of route 01

A visual inspection of the profiles and the P/S distribution identifies the following elements of ride dynamics:

- The point cloud shows isolated points in the high power, lower speed areas and on the 0 Watts line at different speeds. These points are associated with the beginning and end of the section, where acceleration and deceleration occur.
- The concentration of points observed as a cloud is related to the intermediate section of the route. The changes observed in the speed profile are associated with variations in power and very slight changes in cadence (when the same bike gear is maintained). This example relates to some research data on the power generated by cyclists, such as that reported by Knoflacher (1995) who highlights values of between 65 and 160 watts or Wilson (2020), who indicates an average value of 150 watts.
- By comparing the point cloud for numerous bike rides with the point cloud for one section of a single bike ride only, it can be observed that the point concentration for a specific ride may significantly vary with respect to others.

3.3 Different phases of a bike ride and the “riding cycle”

A single section of the bike ride can be characterized in detail, in terms of a series of phases. Four phases can be observed in the point clouds. The first phase corresponds to the beginning of the section where the cyclist accelerates until reaching a desired speed. The second phase is related to the progression of the section, where there are variations in speed, power, and cadence as a result of the cyclist's desire or adjustments according to route characteristics. The third phase is related to the cyclist's deceleration after recognition of the stopping point and the fourth phase, once the stop has been reached. The following figure represents the observed progression of phases.

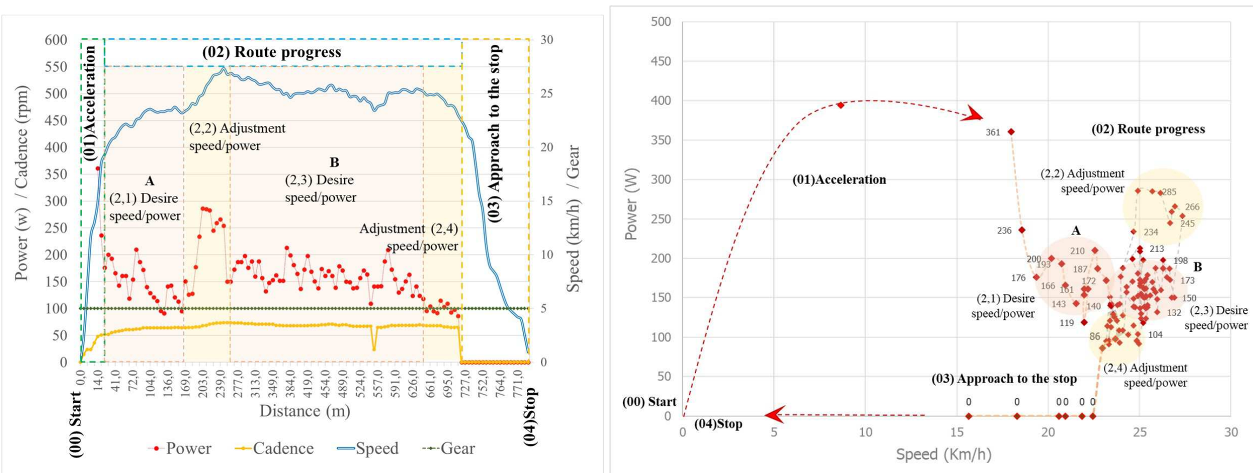


Fig. 5: Analysis of the speed and power adjustment for an evaluation section (example section of route 01)

The different sections of the bike ride share a similar pattern, in which three characteristics are observed: high-power peaks are reached at the beginning of the ride, the concentration of points is observed in sections where there are no interactions or obstacles, and the adjustment of speed or power leads to new concentration points. As soon as the rider stops, this pattern resumes, leading to the observation of different trends depending on the riding scenario.

Based on this oberservation, a bike ride in an urban setting can be described using four phases, including the stops as a waiting phase, which form a "riding cycle" from junction to junction. The phases of the "riding cycle" reflect the desired speed, power, and cadence, allowing the mapping of the ride to identify clear boundaries between phases and riding cycles. In all phases, the shifting strategy plays a role in adjusting cadence and power output.

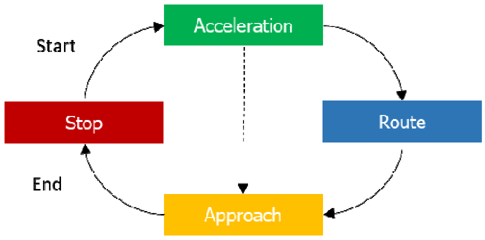


Fig. 6: The riding cycle of an urban bike ride and its phases

Taking into account that the distance between two stop points can be short, it is possible that the acceleration phase leads directly to the approach phase.

3.4 Subphases of the route phase

Interactions, interference, and sections with positive or negative slopes are crucial in the description of the riding cycle, especially in the route phase, where a detailed evaluation of these situations can identify further subphases. Compared to the acceleration and approach phases, the route phase allows an extended analysis of the different triggers for the modification of cycling parameters. As presented in the following figures, an example taken from the collected data identifies the four general phases alongside the subdivision of the route phase. The speed profile of the general phases presents two riding cycles around signalized intersections, where the first does not have a route phase, considering the short distance. The subdivided speed profile for the route phase presents some of the triggers for speed changes and thus for the generation of subphases. Intermediate acceleration, constant ride, increasing resistance due to positive slope, decreasing resistance due to negative slope, and deceleration are the five sub-phases observed within the route phase.

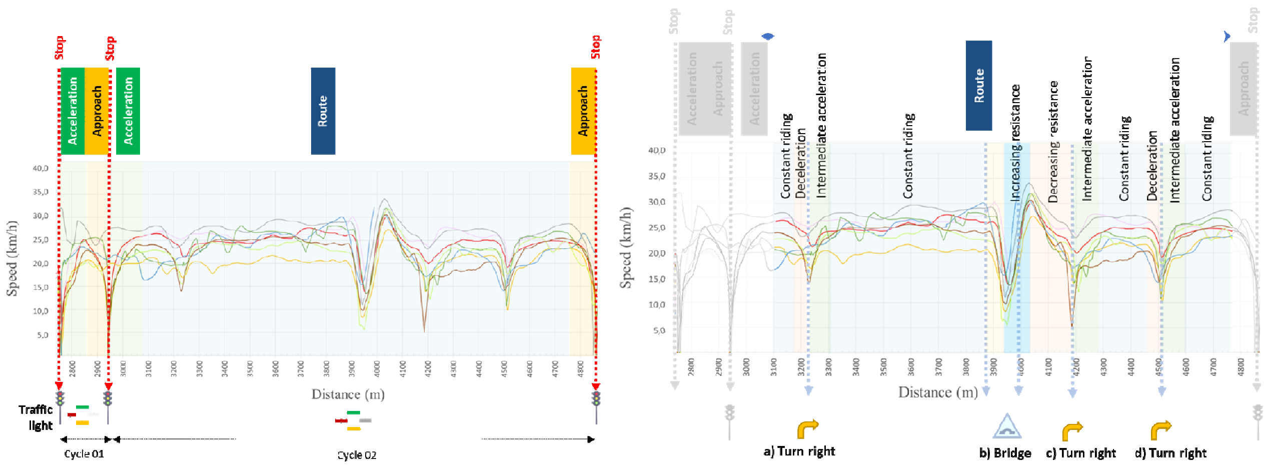


Fig. 7: Speed profile according to phases: General phases and subphases within the route phase (example route 01)

Speed reductions for turns or junctions, stops at signalized intersections, and interference caused by other road users such as pedestrians or motor vehicles are some of the main triggers observed in the test. Before, during, and after each of these triggers, the defined phases can be identified and to this extent, they can be analysed.

4 DESCRIPTION OF RIDE PHASES

In the following paragraphs, the different phases of a bike ride are presented in detail.

4.1 Acceleration phase

The first phase of the riding cycle represents the change of speed of the bike ride from the first movement of the cyclist until the desired speed is reached or until the acceleration is interrupted. Since this situation occurs after every stop, only acceleration phases associated with signalized intersections were analysed. Other stops due to other triggers were not taken into account. If the points collected for all acceleration phases are plotted as a function of the developed speed and the required distance, it can be seen that the data follow parametric functions and that the distances required to reach a desired speed cover an approximate range between 0 m and 130 m. As illustrated in Figure 8 (left), both a linear and a polynomial function are represented and calculated with a high R^2 value. The speed increases rapidly at the beginning and becomes slower the closer to the desired speed. On the other hand, as shown in the figure 8 (right) relating power and speed, different acceleration phases from five cases are characterized by high peak power and a concentration of points defined by the desired speed and power achieved.

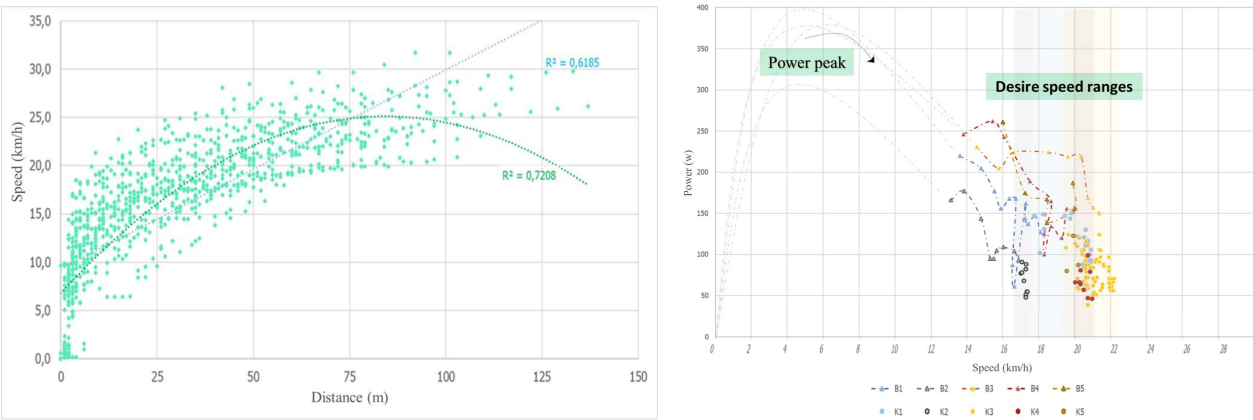


Fig. 8: Speed profile for the acceleration phase recollected from two routes (left) and example of four acceleration cases for the speed-power ratio (right)

In the following stages of this study, calibration improvements will be made with respect to the measurement of the power values for the acceleration phase. This is necessary because several cases were observed where the acceleration curve in its initial phase had no data. This limitation in the measurement with the SensorBike will be overcome by the use of additional calibration instruments.

An additional aspect of analysis regarding the dynamics of the three biomechanical variables (speed, power, and cadence) during the acceleration phase is the use of the bicycle's gears. Shifting patterns are different between riders. For the figure 9 (left) related to the profiles of speed, power, and cadence for a small sector, two moments of gear shifts can be observed. In the first (A), the cyclist shifts up and adjusts their cadence, which reaches a high number due to the previous acceleration. In the second (B), the cyclist shifts up again, decreasing the cadence and increasing the power, in order to continue raising their speed.

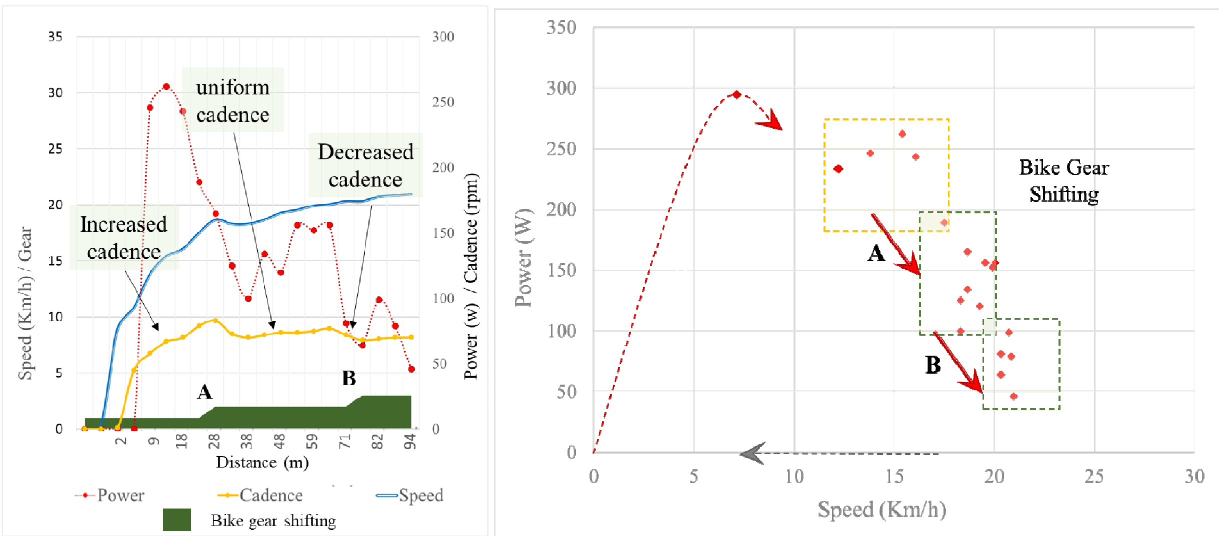


Fig. 9: Effect of bicycle shifting on cadence and power output for an evaluated section

Considering this example, it is possible to identify a couple of common characteristics around cycling dynamics and the power-speed relation:

The speed adaptations from shifting define specific areas in the representation of the power-speed relationship. These point concentrations are much more distant from each other when shifting is performed. Without shifts, as presented in the previous example, the displacement of the spot areas is mostly progressive.

The cyclist generally seeks to overcome interactions or interference as much as possible with a pre-defined power and speed. To achieve this, an optimum cadence is usually reached, which for normal cyclists is between 50 and 60 rpm (Gressman, 2022). This trend can be seen in the example presented as the final result of the two bike-shifting scenarios.

The shifting strategy is recognizable and allows certain riding situations to be described on the basis of external conditions. The most important example took place under increasing resistance. Empirical observations show differences between participants in terms of the use of gears, so this can be a starting point for future classifications of rider types, considering their relevance in the power-speed relationship.

4.2 Route phase

4.2.1 Constant riding

During the route phase, there are sections in which the cyclists maintain a constant ratio between speed, power, and cadence. The main reason for this is the absence of interactions or interference, resulting in an almost linear movement. The constant ride therefore corresponds to the best riding scenario for cyclists in terms of energy consumption and the ability to regulate it. On constant speed sections, the desired speed and power are achieved, but there may be several desired intervals. As presented in the following figures, the speed profile obtained for one of the rides relates specific sections of constant speed. These are represented in the power-speed graph, with which it is possible to observe a very specific concentration and range of points.

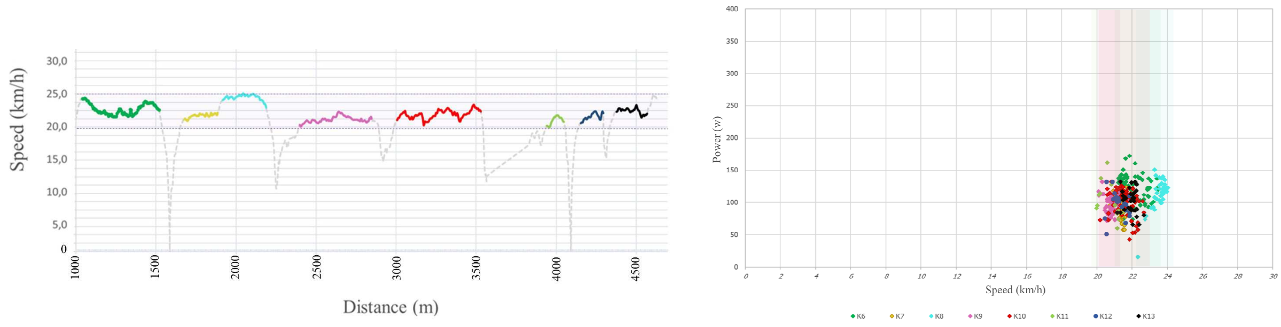


Fig. 10: Speed profile of a bicycle ride section and power-speed ratio

4.2.2 Intermediate acceleration and deceleration

Intermediate acceleration often occurs after deceleration due to braking. In this case, cyclists are forced to reduce speed as a result of interactions or interferences. Once the speed is reduced, the power increases in order to increase the speed again. The cadence depends on the shifting strategy, becoming faster or slower. In addition, a constant cadence of zero can also lead to deceleration, and this often occurs when cyclists ride with caution, such as in front of a traffic junction or in a pedestrian zone.

A second case arises as a result of the cyclist's desire to reach a higher speed. The long sections covered in the test (more than 200 meters) were often ridden at two speed intervals. This means that after a certain distance and a constant speed, cyclists increase their power in order to ride faster. This desire for higher speed is possible over distances without interactions or interference, or due to the desire to overtake other road users (usually other cyclists).

The deceleration observed in the collection data is linked to the braking or speed reductions where the power and cadence values are zero. A video analysis was carried out to describe the events. The observed braking was mainly identified in six situations:

- Before signalized intersections

- Before left or right turns
- At junctions with the 'right before left' rule.
- During interactions in pedestrian areas
- During interactions with other modes of transport, especially motor vehicles
- When adjusting speed after descending on sections with negative gradients

The deceleration caused by braking shows, for example along two of the evaluated routes, a speed reduction of up to 3 km/h in 58% of cases, and more than 5 km/h in 14% of the cases. The average braking distance for these routes corresponds to 17.3 metres. The deceleration caused by the absence of cadence is reflected in very short periods of time, mainly in situations where cyclists must decide whether to brake or return to pedalling. The use of the brakes and the effect of rolling by the inertia is the most frequent strategy to achieve a reduction in speed.

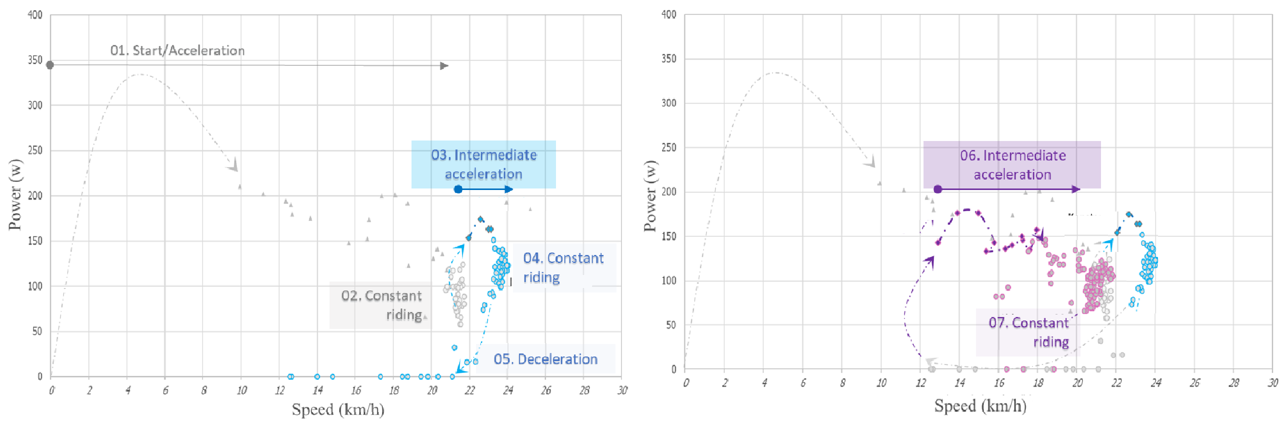


Fig. 11: Speed profile for the acceleration phases and example for the speed-power ratio

Increasing and Decreasing Resistance

Increasing resistance can be recognized on the basis of strenuous performance situations. Air resistance and climbing resistance are the most important and most frequent factors. The sections in the test performed with increasing resistance show acceptance of a higher power output (with limited lower cadence) for limited periods of time, which can reach the cyclist’s power limit, given the shifting strategy. Consequently, increased resistance due to gradients can very quickly become decisive for riding behaviour.

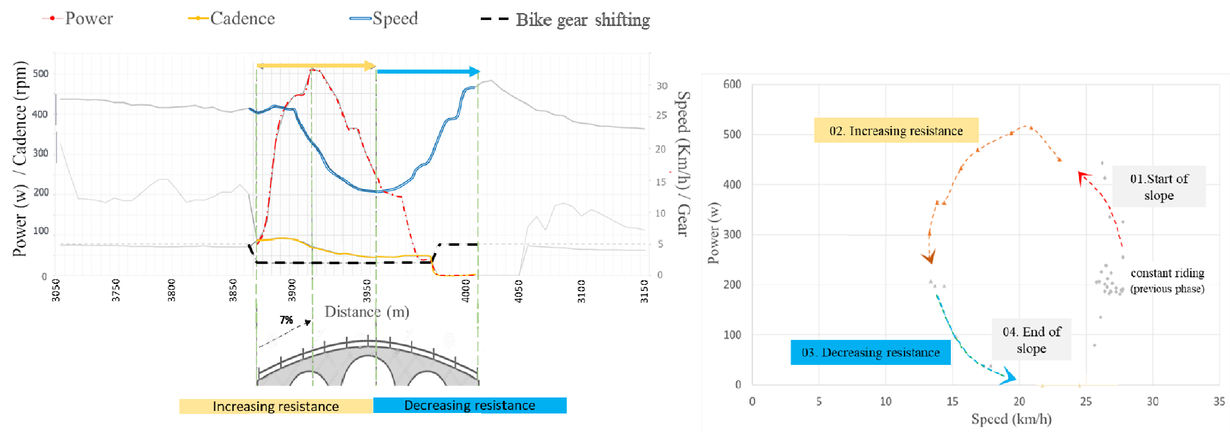


Fig. 12: Speed profile of a bicycle ride section with increasing and decreasing resistance and speed-power ratio

The power/speed values resulting from this situation show a different trend in the point cloud compared to all phases of the riding cycle. The first part of the P/S diagram shows a counterclockwise circle. An inverted "U" is shown with respect to the start of the slope and its highest point. Consequently, the speed increases and the power decreases due to the absence of cadence. In line with the results for increasing resistance, another situation can be described using a downward gradient. When the peak of the uphill section is passed, the power is considerably reduced and a high speed is reached. It is unclear whether the desired maximum speed is recognizable in these results. It should be noted that all participants apply a speed adjustment, so the limit reached could correspond to a rider's feeling of subjective safety.

The resistance situations are illustrated below using an example one of the bridge sections along one of the evaluation routes.

4.3 Approach phase

At the end of the riding cycle, the last few meters before a stop are ridden under specific dynamics. Before cyclists enter the stop phase at a traffic light intersection, the final section is strongly characterized by cadence and braking. Cyclists recognize the red phase from a certain angle and distance. Subsequently, they react by reducing their speed through the braking function and stop pedalling. As a result, the speed adjustment results in an approach distance which can be influenced by different environmental conditions, such as type of infrastructure, traffic flow, weather conditions, or visibility of the traffic light.

Three situations were often observed in this phase: (i) The deceleration starts from a certain distance or time before the stop, so the main action is to stop pedalling, (ii) Cyclists pedal much more lightly or stop pedalling altogether, and (iii) subsequent, active braking occurs.

The speed values of the first 75 m (in the figure below between -100 m and -25 m) show a decreasing trend, so that the deceleration is clearly recognizable. Thereafter, the values are represented by a mostly decreasing trend, which means that the braking causes a rapid reduction in speed. The data collected in this phase for two routes are ilustraded in the figure below.

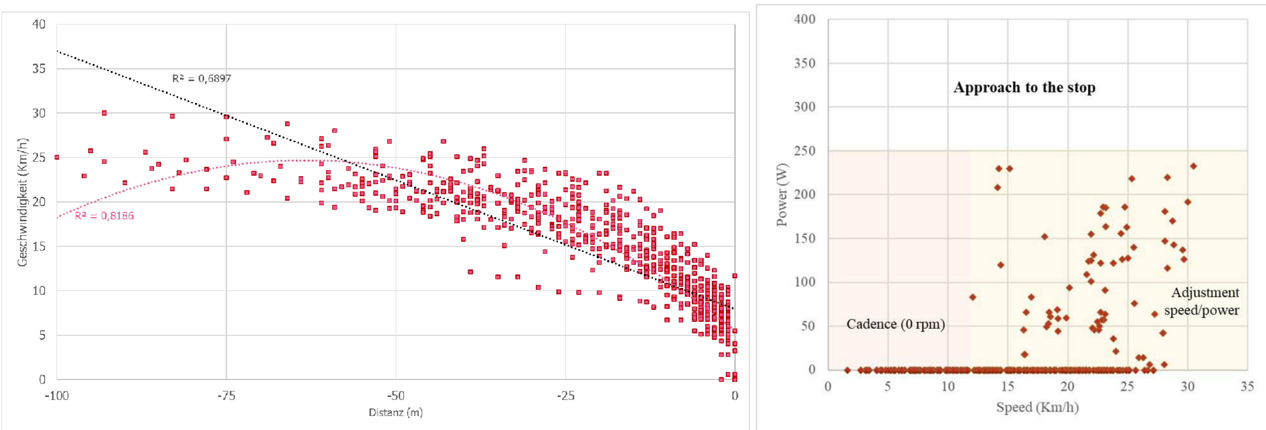


Fig. 13: Speed profile for the deceleration phase (Recollected data from two routes).

5 CONCLUSION

Cycling within an urban setting can be described in short sections between stops. The riding cycle concept leads to systematic analyses depending on the route. In this sense, a route can represent several riding cycles and can be divided into characteristic phases. Such phases are suitable for describing power, speed, cadence, braking, and the shifting strategy.

It is possible that there is a preference for one variable over another when it comes to bicycle riding (for example, speed as the main desire). In a riding cycle, several desired speeds can occur; however, it was not directly identified in the tests whether the desired power is the primary variable of desire or the speed itself. A possible way to identify the desired power is through the examination of shifting strategies. The power peaks avoided in the acceleration phase or in the route phase provide information regarding the desired power intervals.

Consideration for the speed, power, and cadence of everyday cyclists makes it possible to derive information for the planning and evaluation of cycling infrastructure. Efficient infrastructure has a low number of interactions between cyclists and other road users. In this case, cyclists need less power to reach a certain average speed than on sections where there are many interactions. This is due to the fact that braking processes and power peaks in the subsequent acceleration processes are eliminated due to the traffic situation. Furthermore, it is not necessary to reduce speed out of consideration for other road users. The test rides with the SensorBikes provide a survey methodology that allows the power requirements and speed of cyclists to be measured in a comparable manner. This analysis can support cycle traffic planning and cycling promotion in identifying optimal route variants for cycle routes as well as inefficient network sections.

However, with the survey methodology of SensorBikes, parameters for the efficiency of cycling infrastructure can only be collected in existing situations. In order to take this into account in the planning of future infrastructure, tools for the microsimulation of cycling are required that can map the speed and power requirements of cyclists depending on the characteristics of the forms of cycling guidance, even for cycling infrastructure that does not yet exist. Hence, a micro-simulation for cycling should be developed, based on the physical modeling of bicycle journeys and biomechanical patterns from this study. The power and speed ranges that can be extracted from different situations are key for the development of modelling according to the biomechanical behaviour of cyclists. The patterns obtained in different cases suggest that it is possible to systematize the data obtained for cases related to cycling infrastructure, interference, or external conditions, among others.

The simulation tool is aimed at local authorities, engineering firms, and all stakeholders involved in cycling planning and promotion. It can support cycle traffic planning and promotion in the following tasks:

- Decision support for cycling route/infrastructure variants under consideration (identification of the variant to minimize travel time, power requirements, etc.);
- Identifying optimization requirements for existing and planned cycle routes/infrastructure with regard to time losses, performance, and safety;
- Area-wide evaluation of cycling infrastructure and identification of sections with potential for improvement (high performance requirements, high travel time losses, etc.);
- Estimation of cycling travel times for travel time comparisons with other modes of transport;
- Determining the effects of closing gaps and expansion measures in the cycling network on travel times and performance requirements as a basis for cost-benefit analyses.

Through simulation, the perspective of cyclists can represent a measure of quality and thereby effectiveness in the planning and evaluation of cycling infrastructure. The tool can be used for existing or future infrastructure. The planning processes can be standardized on the basis of the uniform cycling impact parameters provided by the micro-simulation

6 REFERENCES

Eckart Jochen, Merk Jule: Die Vermessung der Radfahrenden Analyse des Radverkehrs mit einem SensorBike mit ubiquitären Sensoren, in Lecture Notes in Informatics (LNI), Gesellschaft für Informatik. Bonn, 2021.

Eckart Jochen, Temmen Martin, Hauenstein Jan, Rabes Max, Welz Christoph: Kräftig reintreten - Die Effizienz verschiedener Führungsformen des Radverkehrs, in Transforming Cities. 2022.

Gressmann Michael: Fahrradphysik und Biomechanik. Bielefeld: Delius Klasing & Co. KG. Bielefeld, 2022.

Knoflacher, Hermann: Fußgeher- und Fahrradverkehr: Planungsprinzipien. Böhlau Verlag, Wien, 1995.

Temmen Martin: Wie die Radverkehrsforschung von der Digitalisierung im Radsport profitieren kann. In Fahrradlabor Hochschule Karlsruhe. Karlsruhe, 2022.

Wilson, D. G. S. T. Bicycling Science. MIT Press. 2020.