Effects of a Lane Marking Nudge at a Cyclist T-Intersection

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***Abstract*—**
This research paper investigates the speed behaviour and safety effects on cyclists and mopeds sharing the cyclist T-Intersection with and without the application of a lane marking nudge. Unsignalised cyclist T-Intersection gives rise to more safety-critical instances, which include unsafe braking and evasive maneuvers. It is also found that uncontrolled T-intersection can create an issue when priority is assigned to the intersecting (right) arm because drivers on the straight road have a high perception of priority and fail-to-yield. Even though many studies have analysed the positive influence of the lane markings for cars, the influence of it on cyclists have not been explored. The safety criticality in this paper is investigated using critical deceleration and jerk as Surrogate Safety Measures, because they are found to perform better at identifying potential conflicts compared to other time proximity measures, such as Time to Collision. Based on the results, the nudge did not show any strong evidence for reducing the speeds or safety criticality at the T-Intersection. So, it cannot be implemented as a traffic calming measure at the T-intersection without further research or modifications. So, this paper suggests key improvements with the lane marking nudge, and some crucial changes have to be implemented to avoid these kinds of unexpected outcomes in future. So, an elaborate discussion is made on what could be the possible changes with the implementation of the nudge for further investigations. Few intervention functions from the MINDSPACE framework and improvements from the behavioural change wheel have to be considered in the future researches with nudges.

***Keywords*—Lane Marking Nudge, behaviour, cyclist, mopeds, deceleration ranges, jerk, surrogate safety measures.**

I. Introduction

The Netherlands is one of the few countries in the world where the cycling culture is well established and is widespread among the people of different age groups for various transportation purposes [1]. However, one of the crucial problems that have to be tackled is cycling safety. From the literature studies shown in II-A, one type of intersection in which the on-field behaviour and interaction of cyclists have not been explored in detail is the T-intersection (or T-Junctions). A T-intersection is composed of three arms, in which two of the arms belong to a straight road, and one of the components is perpendicular to the straight road almost resembling the letter "T". At T-intersection, an understanding of priority perception is crucial since it affects the decision, speed, maneuver and safety of the road user depending on the type of action taken. Moreover, the behaviour and safety at T-intersection have not been explored in depth as done with the car traffic.

For this research, the lane markings are implemented to check whether it alters the behaviour of cyclists and mopeds in a safer way or not, since the speed reducing effectiveness through lane markings has been well explored with cars ([2]; [3]) and proven to have a significant positive impact on the speed reduction of the vehicles. The lane markings have the advantage to captivate (to influence and dominate) the road users for an automatic response (as a nudge) without the necessity of a conscious decision compared to the signalised control, relatively cheap and attractive. To the best of author's knowledge, the safety and behavioural studies at T-intersection have not been carried to capture the naturalistic behaviour.

So, this paper explores if there is a significant influence on the cyclists' & the mopeds users' speeding behaviour along with quantifying the safety criticality with and without a transverse lane marking nudge at the T-Intersection. So, one of the key contributions is to understand if the nudge help to reduce the speed of cyclists & mopeds along with whether it has an impact of the safety criticality of the road users. In this research, the safety criticality is the critical braking events, to detect evasive actions such as sudden speed changes of individual road users. This research also explores if all the elements for the lane marking nudge implementation are incorporated in the existing generic frameworks for the behavioural change interventions and suggest some actions to be taken for its successful nudge implementation in the real world.

The rest of the paper is structured as follows. A detailed literature review is performed to understand the speed behaviour and safety criticality in section II. Then a descriptive idea of the data collection of the road user trajectories is explained in section III. Section IV, help to understand the steps to assess the performance of the nudge by calculating all the relevant indicators. The interpretations of all the findings are presented in section V. A dedicated section on policy implication is presented in section VI to understand the necessary improvements for a better nudge in the future, which is followed by the final conclusions in section VII.

II. Literature Review and Background

A. Safety of Cyclists and Mopeds

The Netherlands has a total population of over 17 million with over 23 million bicycles [4]. Apart from this, more than one-quarter of all trips made by Dutch residents are travelled by bicycle. Apart from cycling, the use of mopeds is also becoming common with increasing penetration in the Netherlands [5]. But, in the existing literature, it is not clear and evident with regard to what extent does the shared use of the bicycle path with mopeds lead to a potential conflict between these two road users. On top of that, the few studies which experiment only on the light moped road users ([6]; [7]; [8]; [9]) did not focus on the safety criticality of the light mopeds sharing the bicycle infrastructure.

The signalised intersections including the motorised vehicles have been identified as risk locations for cyclist ([10]; [11]; [12]). Since the intersections with motorised vehicles are so unsafe, ideally the cyclist-car interaction should be avoided when designing a bicycle network and cyclists should only intersect with other cycling streams. However, there is not much research on that to prove whether it is indeed an efficient or safer alternative, especially when shared with the mopeds which have higher speeds than cyclists. Also, there are not many studies which focus specifically on the individual safety of cyclists and mopeds at the T-intersections.

B. Necessity of Speed Reductions

In the studies involving car drivers, it has been found that uncontrolled T-junctions creates an issue when priority is assigned to the intersecting (right) arm because drivers on the straight road have a high perception of priority and fail to yield [13]. When priority perception is high, drivers, as well as cyclists, tend to have higher speeds and minimal head movements to observe their surroundings, which can result in unsafe interactions [14]. All these studies, however, investigated either only car traffic or mixed car-bicycle flows, where the priority was indicated by road signs.

C. Nudging

The nudge concept, which was initially developed by Richard Thaler and Sunstein (2008) has turned out to have many benefits. One of the terms most associated with behavioural economics, and its application to influence behaviour, is the concept of "Nudge", introduced by [15] and he explained the term nudge in the following way, *"A nudge, as we will use the term, is any aspect of the choice architecture that alters people's behaviour in a predictable way without forbidding any options or significantly changing their economic incentives. To count as a mere nudge, the intervention must be easy and cheap to avoid"*. Despite few of the researches in the past showing that the policy nudges have a good impact on altering the human behaviour in a positive way, there are not many studies focusing on the infrastructural nudging to influence the road user behaviour in a positive way.

D. Road Marking and Lane Marking Nudges

Road markings can contribute to giving visual cues to categorise the different elements of the road infrastructure and its purpose properly [16]. There are few kinds of research in the past which used the transverse lane markings (as shown in figure 1) as an infrastructural nudge with decreasing separations distance to create an illusion that the vehicle is going faster than the actual speed, which successfully nudges the driver to decrease his speed ([17]; [18]).

E. Surrogate Safety Measures

Surrogate Safety Measure (SSM) is a proactive approach (which are not based on the accidents) to study the safety of the cyclists' interaction without accident or injury data. More focused on the intersections and road users, the additional surrogate safety measures include approach speed as well as the speed and deceleration distributions. The individual safety criticality, i.e. the safety-critical braking event, is defined as, "Crashes or situations that require a sudden, evasive manoeuvre to avoid a hazard or to correct for unsafe acts performed by the driver himself/herself or by other road users" [19]. Similarly, the traffic safety indicators, designed to detect evasive actions [20] such as sudden speed changes (deceleration and jerk) and swerving behavior (yaw rate) of motorcycles were found to be better at identifying motorcycle conflicts than individual time-proximity measures, such as time-to collision (TTC).

Deceleration measure is widely and commonly used to quantify certain traffic situations such as conflicts and near-crashes in naturalistic driving studies or when in the researches where individual kinematic vehicle data is gathered ([21]; [22]; [23]; [24]; [25]) and is thus considered to be a valid measure for comparison. From the AASHTO Guide to the Development of Bicycle Facilities, the 85th percentile of cyclist deceleration is 3.3 m/s^2 which was calculated from using braking distance and braking time for each participant to then compute their deceleration [26]. Apart from deceleration ranges, jerk is also be used to quantify the safety critically, which has started to gain familiarity a few years back. The process and development for jerk analysis were broadly explained by [27] for the car users, which performed between for detecting the safety-critical instances compared to critical decelerations. So, this paper fills the scientific gap by implementing the transverse lane markings as an infrastructural nudge at cyclist T-Intersection along with the application of jerk as a SSM apart from the conventional deceleration ranges.

Figure 1: Transverse Lane marking Nudge at the T-Intersection

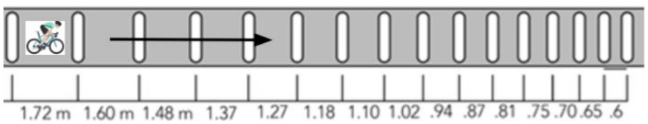

Figure 2: 2D representation of the Transverse Lane Marking Nudge

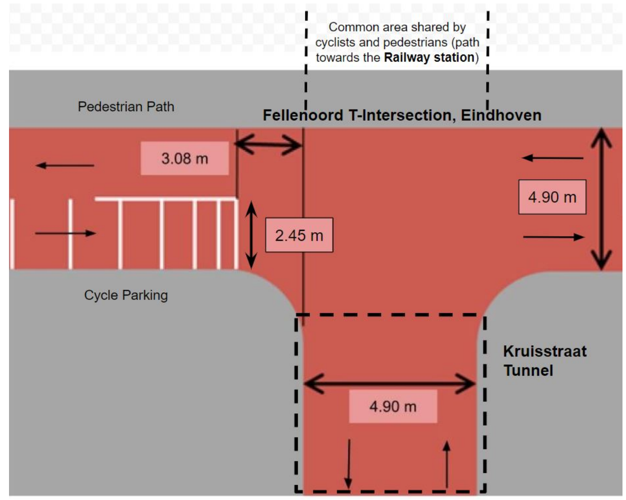

Figure 3: 2D representation of T-Intersection with the measurements. *Note: The dotted box represents the tunnel*

III. Road-User Trajectory Data

A. Data Collection at the T-Intersection

The study area is the T-intersection located on the field at Kruisstraat-tunnel and Fellenoord intersection in Eindhoven. It is a busy cycling infrastructure at Eindhoven, located near the railway station and has a cycle parking facility for the convenience of the cyclists to transfer to public transport for long distant commuting. The decision of the selection of the location and the data collection was performed by a third party. So, the raw trajectory data, which includes the global coordinate positions and the corresponding time stamps of all cyclists and mopeds was provided for further analysis.

The lane marking nudge was applied on this T-intersection which is 16.06 meters in length as shown in figure 2. The nudge consists of a series of perpendicular transverse stripes over one direction in the lane, with reducing space in between, up to the intersection as shown in figure 2 along with a cyclist representing the direction of movement with respect to the lane marking nudge. More detailed measurements are shown with the figure 3.

Two cameras were used to observe the road users at the T-Intersection using the lane marking implemented location, the actual views from these cameras are shown in figures 4 and 5 along with the position of the nudge (the nudge representation is approximate in these three figures, since the actual pictures were taken without the nudge implementation).

There is a gap with the video surveillance coverage from camera 1 and camera 2. The gap is 2.5m, so effectively camera 1 covered the road users approaching the T-Intersection (upstream) including only the first 4m from the start of the nudge and camera 2 covers the last 9.5m from the middle till the road users cross the nudge. The exact measurement period of the initial phase of the raw data with the transverse lane marking nudge was from 12:00 AM on 1st of December 2019

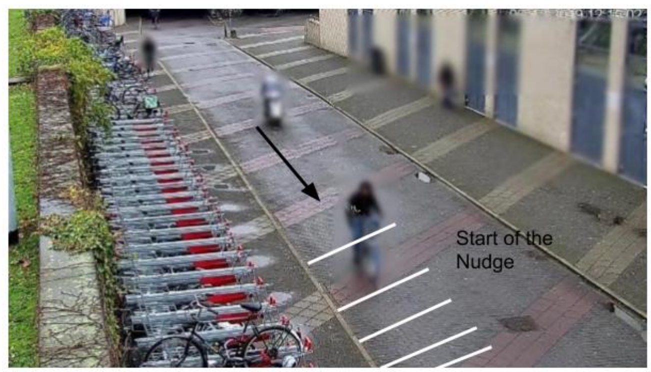

Figure 4: Actual view from Camera 1

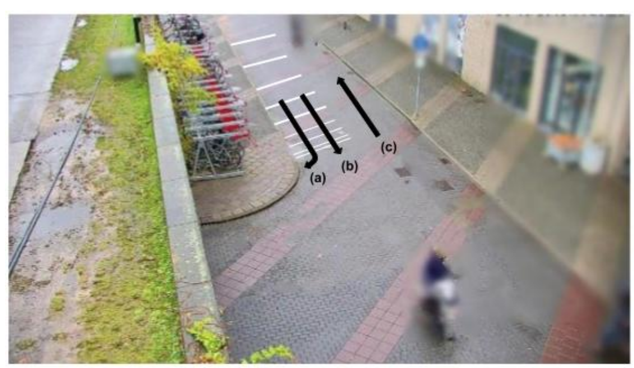

Figure 5: Actual view from Camera 2 (a) Turning (b) Through (c) Opposite-Through Movements

for a continuous-time till 10:00 AM on 3rd December 2019. The second phase of the scenario without the lane marking Nudge was chosen from 12:00 AM on 8st December 2019 for a continuous-time till 10:00 AM on 10st December 2019. So, the data set for a realistic comparison was chosen to be on Sunday, Monday Morning Peak (MP) and Monday Evening Peak (EP) in both the scenarios, to have similar trip purposes.

B. Road User Counts and Flows

The cyclists counts were more than 2000 on Sunday and were around 1000 during the peak hours on Monday. Whereas, the moped counts was comparative very less which were around 350 on Sunday and close to 150 during the peak hours on Monday. Also, the traffic flows on Sunday is less than the flows on Monday peak hours due to varying trip purposes. Another point to be highlighted, is that the overall traffic flows of both road users during the nudge scenario is more than the no-nudge scenario, due to different weather conditions with slight rains in the no-nudge scenario which reduced the flows. Also, the speeds and acceleration distributions were visualised along the entire stretch of the trajectory within each camera coverage, along with checking the rationality of the speed and acceleration magnitudes.

IV. Methodology for Assessing the Performance Indicators

A. Conceptual Model

The figure 6 broadly depicts how certain characteristics of the Road Infrastructure (with and without the nudge) influences the speed and safety of the individual road users along with the performance indicators necessary to quantify them.

The road users speed and safety are influenced by various attributes and elements (including the time of day, movement or maneuver type). The elements like time of day (morning peak, evening peak or off-peak), weekday or a weekend and the various maneuvers (or movement types) performed by the road users affects their individual position and travel time as visualised in figure 6, which eventually have an influence with all the other individual (speed, acceleration and jerk) and aggregate (mean speed and mean accelerations) attributes. Here, the time of day and whether it is a weekday or a weekend is an independent variable which is not affected by any external factor.

So, from the conceptual model in figure 6, the mean of the velocities and accelerations of the road users serve as the indicators to check the speed behaviour at a particular road infrastructure. The deceleration and the jerk counts of the individual road users are used to obtain the safety-critical instances. So, the critical deceleration counts and critical jerk counts are the two safety performance indicators used to quantify the safety criticality of the road users using the T-intersection.

B. Expectations with the implementation of Nudge

1) Expectations with the Time of Day: It is expected to have different effects on a weekend and on a weekday. Also, within the weekday, the nudge would have a varying influence in the morning peak and the evening peak. Because, high flows might result in congestion and thereby decreasing the overall speed of the road users, with or without the nudge. So, with the relatively less flow on weekends (as presented in section III-B), the speeding illusion could be high, compared to weekdays where high flow with a lot of road users (increased congestion) might also be an additional reason to slow down even with the presence of the nudge.

2) Expectations with the road user type: A generic and an overall expectation is that, with different speeds, the influence of nudge would be different. Because the speeding illusion directly depends on the speed at which the lane marking nudges are approached by the road users. Since the traverse lane marking is proven to be effective with cars which have high speeds compared to the cyclists and moped users of this study. So, mopeds are expected to have a high influence with the nudge compared to cyclists.

3) Expectations with the movement types: The through cyclists going at a high speed might have the intended speeding illusion and slow down with the presence of the nudge. In reducing the speed, it might also give rise to high-speed changes and critical braking instances with the through road users. On the other hand, the turning cyclists may not have high speeds changes with the nudge scenario compared to the through cyclists. So, they might not have any significant difference with and without the nudge. Additionally, the turning road users are anyway going to slow down at the junction for turning. So, the turning road users are also not expected to have differences with the safety performance indicators with and without the presence of the lane marking nudge.

4) Expectations within the Nudge Stretch: The five sectional areas where the performance indicators are analysed are, 10m before the start of the nudge implemented location, at the start, middle end of the nudge stretch and also at the sectional area after crossing the nudge. The road users are expected to behave differently because the speeding illusion expected to be significantly more at the middle and the end of the nudge implemented location relative to the other parts with respect to the nudge.

5) Expectations with the road users not using the nudge: There are road users who have no direct or indirect effect due to the implementation of the transverse lane marking nudges moving in the opposite direction relative to the upstream and through road users. So, they are termed as the "Control Group" road users. It is important to check the behaviour of the road users using the adjacent lane next to the nudge implemented location in the opposite direction. These control group road users are also observed in the same time period as the other road users with and without the transverse lane markings. Clearly, they will not use the transverse lane marking nudges and therefore expected to have no change in their behaviour or safety criticality with and without the nudge scenarios. The

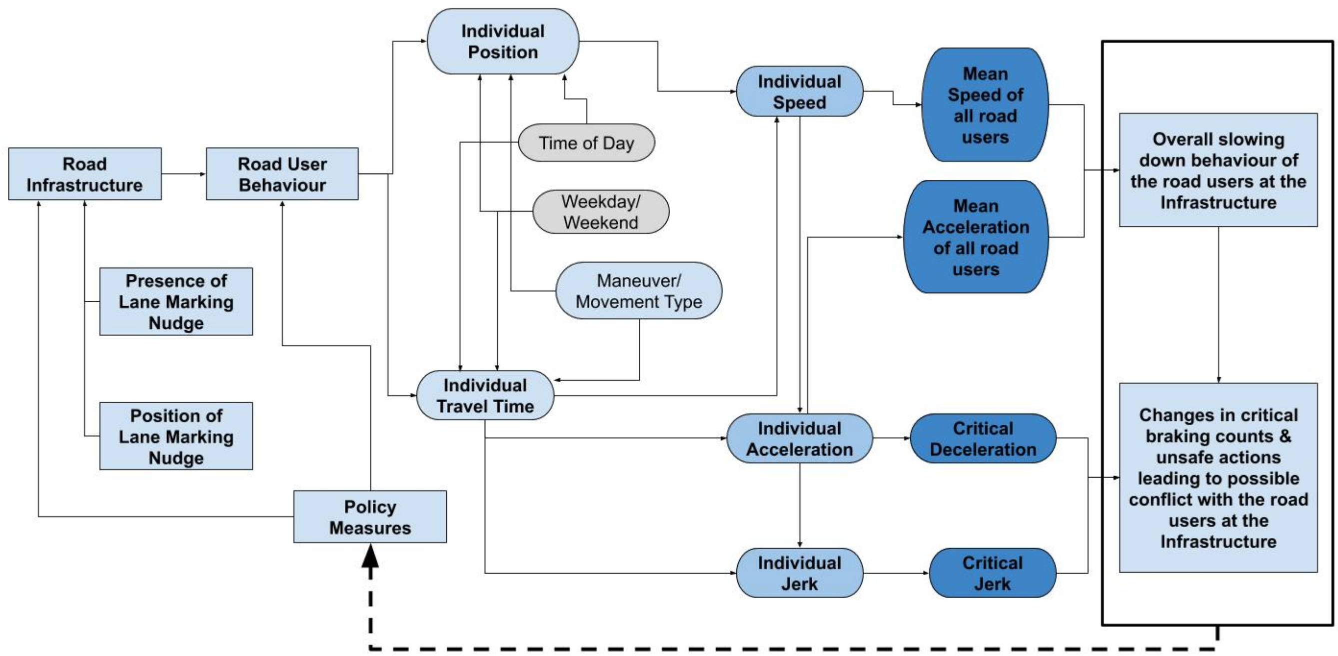

Figure 6: Conceptual Model with Performance Indicators
(**Note**: The solid line represents the direct relation and dependence between all the elements and the dotted lines represent the feedback loop based on the outputs, to draft the policy measures. Grey cells are independent variables and the dark blue cells are the performance indicators)

purpose of the control group road users is to check if the differences in the behaviour and safety are mainly because of the nudge or due to other factors.

C. Data Sub-Groups

The basis of the data sub-groups for answering the expectations and hypotheses are based on:

- Presence of the Nudge: With and without the lane marking nudge
- Time of day: Sunday, Monday MP and Monday EP
- Road user type: Cyclists and moped users
- Movement type: Upstream users, through only, turning only and opposite-through (control group road user movement)

So, each sub-group (or a case) always has one of the four criteria, which gives a total of 48 (2*3*2*4) sub-groups to be analysed, to obtain an extensive understanding on all the different cases. It should be highlighted that the interactions of the road users are not explicitly studied since this research focuses on individual surrogate safety indicators as explained in the literature review. So, the individual road user also brakes or performs a sudden critical maneuver because of the interactions which are also captured using the deceleration and jerk as a SSM.

All of the movement types were extracted, by visualising the trajectories, along with manually plotting the coordinate polygons to categories the trajectory based on the various necessary movement types. So, the data is sub-grouped into 4 different movement types including the road user movement

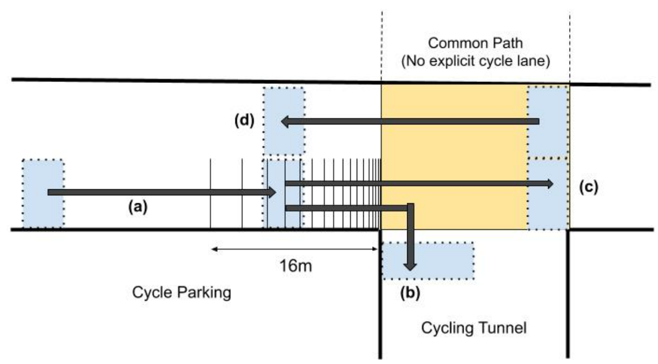

Figure 7: Road User movement (a) Upstream (b) Turning-Only (c) Through-Only (d) Through-Opposite, where the dotted boxes are the Coordinate Polygons

opposite the direction of the through road users (control group) approaching the nudge in the adjacent lane are depicted in figure 7. For better clarity and understanding for the reader, the actual trajectories of 20 upstream cyclists are shown in figure 8.

D. Cross-Sectional Bands for Analysis

The purpose of the cross-section band is to analyse specifically the trajectories within the cross-sectional band to calculate all the performance indicators. All the cross-sectional bands are chosen to be 3m, covering different parts of the nudge. Two cross-sectional bands (a) and (b) shown in figure

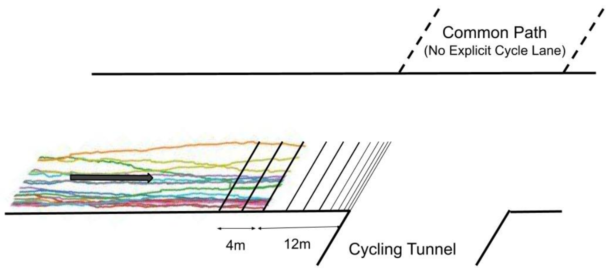

Figure 8: Twenty Upstream Cyclist Trajectories approaching the Intersection (from Camera 1)

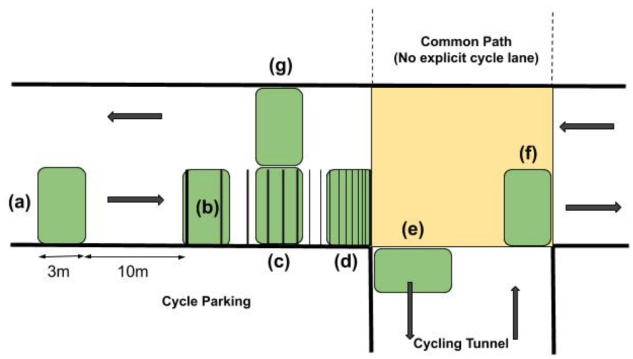

Figure 9: Cross-sectional band at the: (a) Before (b) Start (c) Middle (d) End w.r.t. the nudge and the Cross-sectional band after crossing of the nudge: (e) for Turning and (f) for Through road users (g) Adjacent Lane movement

9 are used to analyse the upstream roads users before and at the start of the nudge implemented location, respectively. Similarly, all the other cross-sectional bands at the middle, end and after crossing the nudge implemented location separately for through and turning traffic as depicted in figure 9. The actual trajectories of 20 through cyclist specifically within the middle 3m cross-sectional band are shown in figure 8 for better clarity.

E. Definitions - Performance Indicators

Before calculating the performance indicators it is important to understand a few definitions related to the performance indicators with respect to the data (using the frames of each road user trajectory).

- **Frame-Section**: Five consecutive frames of a road user trajectory [28], since the window size of 5 consecutive frames would give more accurate value (compared to other window sizes) when applying moving averages to calculate the values of the variables with the trajectory data [28].
- **Instantaneous Speed**: Speed calculated using a frame-section, referred to as instantaneous frame-sectional speed.
- **Average Speed**: It is the mean of all the instantaneous frame-sectional speeds calculated within the stretch, using the method of moving averages [28].
- **Instantaneous Acceleration**: It is the difference between any two consecutive frame sectional speeds divided by the corresponding time interval.
- **Average Acceleration**: It is the mean of all the instantaneous accelerations calculated within a stretch.
- **Instantaneous Jerk**: It is the difference between any two consecutive instantaneous acceleration divided by the corresponding time interval.
- **Average Jerk**: It is the mean of all the instantaneous jerks calculated within a stretch.

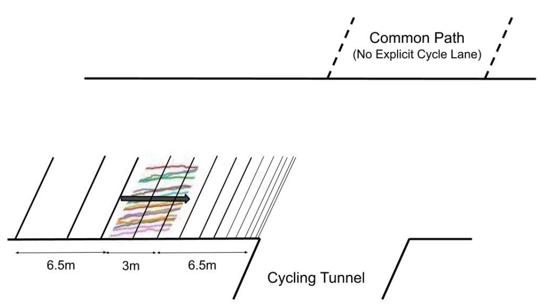

Figure 10: Twenty Through Cyclist Trajectories within the 3m (middle) cross sectional band

F. Performance Indicators Calculations

For a better structure and consistency within and between the calculations of speed, acceleration and jerk, frame sections (with 5 frame window size [28]) are used for all the calculations to obtain the instantaneous and average values within the cross-sectional band for each road user. So, the instantaneous frame sectional speeds are calculated using the method of moving averages [28]. Then two consecutive instantaneous speeds are used to calculate all the instantaneous accelerations. Similarly, two consecutive instantaneous accelerations are used to calculate instantaneous jerks. Using all the instantaneous values across the cross-sectional band, the mean is calculated to obtain the average speed, acceleration and jerk of each road user, using the definitions mentioned earlier.

As mentioned in the literature review, it is considered to be safety-critical (or critical braking instances which might give rise to potential conflict if not performed correctly) if the road user has a deceleration magnitude more than 3.3 m/s^2 [26]. So, across each cross-sectional band per road user type and time of day, the number of users having a deceleration magnitude above the critical threshold is counted. They are normalised by dividing it with the corresponding number of road users with that specific case and multiplying it with 1000. This gives the normalised stay critical instance for 1000 road users for comparison with and without the nudge scenario.

Since this research was the first of its kind to apply jerk as an SSM at a shared cyclist T-Intersection, there was no concrete threshold to measure the safety criticality of the road users. So, for each specific case of the sub-grouped data with and without the transverse lane marking nudge, cumulative distribution curves of the mean jerks were plotted. From the cumulative distributions curves, the bottom 1% of the value is considered as the critical jerks for the nudge and no-nudge scenario, respectively. To be conservative and capture the safety criticality for comparison, the high jerk (low negative jerk) among the two critical jerks is considered as a critical threshold to obtain the normalised number of critical counts, similar to critical deceleration counts.

V. Results and Interpretations

From the results obtained from calculating the performance indicators, it is crucial to check if all the cases with and without the nudge scenarios have statistical differences or not. So, with the mean speeds and accelerations of all the road users, initially, the Kolmogorov-Smirnov test for normality is used to check if the samples are normally distributed. If they found to be normally distributed then an independent 2-sample t-test is applied, to check the differences in the means of speeds and accelerations. If they were not normally distributed then a non-parametric Mann Whitney U-test is performed. Also, 2-sample Kolmogorov Smirnov tests are used to check the differences with the distributions of declaration and jerks counts. All these tests were all done at a standard 5% significance level. If the p-value is less than 0.05, then the two samples have significant differences.

Unexpectedly, the control group cyclists had differences in mean speeds. It had around 6.2% less speed with the nudge scenario on Sunday and around 2% less on Monday MP with the cyclists compared to the no-nudge scenario. On the other hand, the mean accelerations did not significantly differ. So, the mean acceleration changes with the cyclists and mopeds is majorly due to the presence of the lane marking nudge. The variations with the control group road users could be due to multiple reasons like, variation with the weather, demographics of the road user or with the presence of the tunnel which are not been incorporated with the data collection. Due to the differences with the control group, the variations of all the performance indicators with and without the nudge scenario was not only due to the presence of the nudge at the infrastructure.

First of all, the mean speeds of all the cases which had statistical differences were high in the nudge scenario, as shown in tables I and II. Clearly, the differences with the mean speeds are not only due to the presence of the nudge, but also due to other factors which are supported by the differences with the control group road users. Especially, since, there was rain during the no-nudge scenario, this could be an influential factor which might be responsible for the lower speeds in the no-nudge scenario.

The mean accelerations of the upstream cyclists (table III) did not have any differences, before reaching the nudge implemented location, as expected. Since, the cyclists have not reached the lane markings which has no effect in creating a speeding illusion, without the road user crossing them. Whereas, the upstream mopeds (table III) had a high magnitude of deceleration before reaching the nudge implemented location on Monday MP. This implies that, the upstream moped going for work have noticed the lane marking and have high deceleration to be cautious or there is a possibility that the sudden appearance of the lane markings before reaching the intersection could also act as a surprise and resulted in sudden braking.

Almost all the cases with significantly different mean acceleration, the nudge scenario had a high deceleration or reduced accelerations compared to the scenario without the lane markings. This implies that the transverse lane marking implemented in this field study does not create a speeding illusion, but might be responsible for,

- creating an illusion of a stop line (but no road user fully came to halt),
- the nudge to be thought as an obstacle on the lane,
- suddenly surprising the road user, or
- causing a distraction and then sudden realisation to brake when reaching the T-Intersection.

Similarly, relative to the no-nudge scenario, the mean accelerations of the cyclists at the start of the nudge implemented location (on Sunday) accelerate less, and decelerate more at the middle and end of the nudge implemented location (on Monday MP), with the nudge scenario. Similarly, on an average the turning cyclists (table IV) tend to decelerate at the start, middle and end of the nudge implemented location on all three times of days chosen. This was same with the case of turning mopeds (table III) in the middle of nudge implemented location on Monday MP, with a relatively high deceleration in the nudge scenario. Also, the turning cyclists were decelerating with the nudge scenario and accelerating without the nudge scenario, after crossing the nudge implemented location (on Sunday, Monday MP and Monday EP). All these could also strengthen the inference that the lane marking nudge is creating a distraction or surprised the road user to brake more often.

On the other hand, the mean accelerations of the through cyclists (table III) and mopeds did not have any differences in their means, after crossing the nudge implemented location. Because these road users have already crossed the lane marking nudge and accelerate in the same way as the no-nudge scenario after crossing the lane markings. So, it can also be inferred that there the through cyclists and mopeds do not have the post-learning effect in the presence of the nudge after crossing the lane implemented location. However, this was not the same case with the turning cyclists (table IV) after crossing the nudge. Even after crossing the nudge implemented location, turning cyclists tend to decelerate more in the nudge scenario after crossing the lane markings. Because the turning cyclists might have some post-learning effect in the presence of the nudge after crossing it.

Importantly, since, the transverse lane marking nudges might create an illusion of a stop line, obstacle or a surprise to make the road use decelerate more at the start, middle and the end of the lane marking implemented location with the nudge scenario, it can also be inferred that it eventually leads to increased critical braking instances and high jerk counts (tables

Table I: Mean Speeds of Upstream Cyclists and Upstream Mopeds

Movement Type/ Road User		Upstream Cyclists						Upstream Mopeds		
Time of Day		Sun		Mon MP		Mon EP		Sun	Mon MP	Mon EP
Cross-Sectional Band		Before	Start	Before	Start	Before	Start	Before	Before	Before
Mean Speed (kmph)	Nudge	14.99	15.90	17.05	16.87	16.67	16.34	23.63	22.70	23.84
	No-Nudge	13.84	15.53	15.87	16.74	15.29	15.70	21.92	21.78	21.21
% Change in Mean Speed of Nudge w.r.t to No-Nudge		8.30	2.38	7.41	0.78	9.02	4.07	7.80	4.23	12.43

Table II: Mean Speeds of Through and Turning Cyclists

Movement Type/ Road User		Through Cyclists				Turning Cyclists								
Time of Day		Sun			Mon EP	Sun			Mon MP			Mon EP		
Cross-Sectional Band		Middle	End	After	Middle	Middle	End	After	Middle	End	After	Middle	End	After
Mean Speed (kmph)	Nudge	15.09	14.83	14.78	15.14	12.80	12.01	11.90	13.46	13.16	13.00	13.27	11.92	11.81
	No-Nudge	14.80	14.61	14.23	14.82	10.44	10.33	11.63	11.23	10.95	12.28	10.73	10.93	11.57
% Change in Mean Speed of Nudge w.r.t to No-Nudge		1.90	1.50	3.82	2.17	22.70	16.20	2.33	19.88	20.26	5.84	23.65	9.08	2.11

Table III: Mean Accelerations of Upstream road users, Through Cyclists and Turning Mopeds

Movement Type/ Road User		Upstream Cyclists	Through Cyclists		Upstream Mopeds	Turning Mopeds
Time of Day		Sun	Mon EP		Mon MP	Mon MP
Cross-Sectional Band		Start	Middle	End	Before	Middle
Mean Acceleration (m/s^2)	Nudge	0.118	-0.052	-0.149	-0.908	0.103
	No-Nudge	0.135	0.126	-0.019	-0.274	0.501
% Change in Mean Acc of Nudge w.r.t to No-Nudge		-12.621	CD	680.001	231.431	-79.343

Table IV: Mean Accelerations of Turning Cyclists

Movement Type/ Road User		Turning Cyclists								
Time of Day		Sun			Mon MP			Mon EP		
Cross-Sectional Band		Middle	End	After	Middle	End	After	Middle	End	After
Mean Acceleration (m/s^2)	Nudge	-0.193	-0.258	-0.349	0.103	-0.085	-0.563	-0.219	-0.421	-0.143
	No-Nudge	0.407	0.200	0.240	0.501	0.131	0.263	0.331	0.179	0.220
% Change in Mean Acc of Nudge w.r.t to No-Nudge		CD	CD	CD	-79.343	CD	CD	CD	CD	CD

Table V: Critical Deceleration Counts of Upstream road users, Through Cyclists and Turning Mopeds

Movement Type/ Road User		Upstream Cyclists	Through Cyclists		Upstream Mopeds	Turning Mopeds
Time of Day		Sun	Mon EP		Mon MP	Mon MP
Cross-Sectional Band		Start	Middle	End	Before	Middle
Relative Critical Dec Count/ 1000 road users	Nudge	4.25	36.88	22.63	83.19	9.88
	No-Nudge	4.08	22.14	8.16	85.51	0.00
% Dec Difference of Nudge Scenario w.r.t. No-Nudge		4.14	66.57	177.43	-2.72	NA

Table VI: Critical Deceleration Counts of Turning Cyclists

Movement Type/ Road User		Turning Cyclists								
Time of Day		Sun			Mon MP			Mon EP		
Cross-Sectional Band		Middle	End	After	Middle	End	After	Middle	End	After
Relative Critical Dec Count/ 1000 road users	Nudge	35.22	9.39	9.39	9.88	4.94	9.88	21.85	16.39	0.00
	No-Nudge	4.35	4.35	2.17	0.00	15.00	0.00	7.89	0.00	0.00
% Dec Difference of Nudge Scenario w.r.t. No-Nudge		710.13	116.04	332.07	NA	-67.06	NA	176.96	NA	NA

V, VI, VII and VIII). It is same with all the corresponding cases where there was a high deceleration with the nudge. So, it is not required to repeat all the cases as done for the cases with high magnitude of deceleration or reduced acceleration with the presence of the lane marking nudge.

VI. Discussions on Policy Implications

Based on the inferences from the empirical analysis from the field study, the policy implications and lessons learnt are:

- The transverse lane marking nudge is not ready to bring the intended changes in the behaviour and safety of the road users.
- The road users do not tend to reduce their speeds with the presence of the transverse lane marking nudge.
- The road users tend to either have a less acceleration or a high deceleration in the presence of the nudge scenario.
- In all the cases within the nudge stretch, the reduced acceleration or the increased deceleration, will give rise to increased critical deceleration and jerk counts.
- Further studies and research have to be performed, on understanding how the nudges implemented in the past were successful and effective.
- A more systematic and structured approach should be incorporated and learnt with the use of successfully established generic frameworks for a behavioural change intervention (similar to the transverse lane marking nudge implemented in this research).

Since, the transverse lane marking nudge implemented in this field study, there should be few important lessons learnt from the past studies which had a successful and effective use of nudge to bring behavioural changes with the users. Few of the crucial lessons were, to use active approaches instead of passive approaches, longer intervention duration and address the fundamental problem of behavioural change, beyond the intuitive and impulsive changes. These can be assisted with the help of, creating a strong link between the intention and the behaviour. That is, to produce an intention to perform the behavior, the intervention must be targeted at behavioral, normative, and control beliefs that ultimately determine the behaviour of interest. Apart from all the lessons learnt for a successful and effective nudge implementation mentioned, the crucial leanings from the two generic frames works, “MINDSPACE” and the “Behavioural Change Wheel” are:

- Not to only rely on influencing the behaviour subconsciously, So, additional elements have to be incorporated to achieve the intended behaviour with the nudge.
- Draft an effective and better way of persuasion since the road users are heavily found to be influenced on who communicated the information.
- Increasing the knowledge of providing brief and attractive information cues and creating more awareness of nudges.
- Improved link with the environment restructuring and enablement to understand what exactly would help the intervention to target at behavioural, normative, and control beliefs that eventually determine the behavior of interest.

VII. Conclusions

To understand the behaviour and improve the safety of cyclists at T-Intersection, a transverse lane marking nudge is implemented through a field study. The performance indicators used for understanding the speed behaviour and safety are the mean speed, mean acceleration, critical deceleration counts and critical jerk counts.

The control group road users used in this field study was expected not to have any differences with all the performance indicators, which was true with the mean accelerations with and without the nudge scenarios. So, the changes with the mean accelerations in all the different cases are most probably due to the presence of the transverse lane marking nudge. But, there were significant differences with the mean speeds (on Sunday and Monday MP) with the cyclists. This was same for the moped users on Sunday as well. So, the variations in the mean speeds across the different cases cannot be concluded that it is only due to the presence of the nudge and other factors have to be explored further, such as the weather and demographics of the road users.

The key findings on the performance indicators from the implementation of transverse lane marking nudge in this field study are:

- The mean speeds of cyclists and mopeds was high with the presence of lane markings relative to the no-nudge scenario. Since, during the field study, there were slight rains throughout the no-nudge scenario, which could also be a major reason for the less speeds in the no-nudge scenario.
- The accelerations of the upstream cyclists did not have any differences in their means, as expected, before reaching the nudge implemented location and also at the start of the lane markings. This was also the case with the through cyclists and moped after crossing the nudge implemented location, as expected.
- But all the other cases with the cyclists and mopeds including the through and turning movements at all the correctional bands, either resulted in a less mean acceleration or high mean decelerations in the nudge scenario. This implies that the transverse lane marking implemented in this field study does not succeed in creating a speeding illusion, but might create an illusion of a stop line, serve as an obstacle, surprise the road user or distract them. So, it can also be inferred that it eventually leads to increased critical braking instances and high jerk counts. It is same with all the corresponding cases where there was a high deceleration with the nudge.

Finally, based on all the discussions of what to do and what not to do, along with the list of learning from the generic frameworks for successful and effective nudge implementation as a behavioural change interventions, few concrete improvements are recommended for the future nudge implementations.

- Considering a longer intervention duration to study the intended behaviour.

Table VII: Critical Jerk Counts of Upstream road users and Through Cyclists

Movement Type/ Road User		Upstream Cyclists	Through Cyclist			Upstream Mopeds
Time of Day		Mon EP	Sun		Mon MP	Mon MP
Cross-Sectional Band		Start	Middle	End	After	Before
Relative Critical Jerk Count/ 1000 road users	Nudge	21.05	13.68	11.40	12.18	34.39
	No-Nudge	11.16	11.65	19.97	53.11	15.95
% Jerk Difference of Nudge Scenario w.r.t. No-Nudge		88.54	17.47	-42.90	-77.07	115.66

Table VIII: Critical Jerk Counts of Turning Cyclists

Movement Type/ Road User		Turning Cyclists								
Time of Day		Sun			Mon MP			Mon EP		
Cross-Sectional Band		Middle	End	After	Middle	End	After	Middle	End	After
Relative Critical Jerk Count/ 1000 road users	Nudge	50.95	48.53	50.95	148.08	204.25	163.40	56.45	101.61	50.81
	No-Nudge	11.15	11.15	11.15	15.38	15.38	15.38	16.18	16.18	16.18
% Jerk Difference of Nudge Scenario w.r.t. No-Nudge		357.15	335.38	357.15	862.56	1227.66	962.13	248.85	527.94	213.97

- Since, passive approaches are generally ineffective and unlikely to result in behavior change, the nudges implemented in the future should involve active changes with the choice architecture made by the road user.
- It should be ensured that there is a significant link from the intentions to behaviour by inducing road users to form an implementation intention, i.e. to form a relevant plan detailing, when, where and how the intended behaviour will be performed with respect to the lane marking nudges.
- The nudge intervention must be targeted at behavioural, normative, and control beliefs that ultimately determine the behavior of interest.
- Dedicated study to check the steps needed to incorporate the stronger motivation for a safer behaviour of the road users.
- Inspired from the generic frameworks on behavioural change interventions, few actions from the MINDSPACE framework, like choosing the correct way of spreading awareness and few elements from the behavioural change wheel, like better persuasion or education have to be considered and definitely not relying only on the fact that the nudge to subconsciously change the road user behaviour.

Every research might have limitations or influences which that researcher cannot control. These can be some shortcomings, weather conditions, or other influences of this sort which have no control and also place restrictions on the research methodology and conclusions. It gives a wider picture of the performed research incorporating the encountered limitations to improve in the further researcher. The limitations and future recommendations are:

- Presence of the cycle parking facility and the tunnel at the T-Intersection. These two factors could indirectly affect the actual intended use of the lane marking nudges. So, explicit research has to be performed to understand the safety effect due to the cycle parking facility and the presence of the tunnel, separately. Especially the right tuning cyclists coming out of the tunnel may not be having a full view of the through road users approaching at high speeds.

- Rain during the data collection in the scenario without the lane marking nudge. The weather conditions have to be considered for future researches, since it might have a significant influence on the speed behaviour of the road users.
- Collecting the data with the nudge scenario first might bring a leaning effect for the data collected without the nudge scenario later. So, it is recommended to collect the data without the nudge and then with the nudge, to avoid any kind of unintended behavioural adaptation.
- There was an interruption with the data collecting during the nudge scenario due to a technical problem with the video camera, which shortened the time window for the nudge scenario.
- Both the SSMs presented in this paper were not validated. So, it is recommended to validate these SSMs to assess the deceleration and jerk as SSMs for future applications and check which SSM performs better in detecting the actual unsafe situations.

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REFERENCES

[1] J. Pucher and R. Buehler, "Making cycling irresistible: lessons from the netherlands, denmark and germany," *Transportation Review*, vol. 28, no. 1, pp. 495–528, 2008.

[2] T. J. Gates and D. A. Qin, X.and Noyce, "Effectiveness of experimental transverse-bar pavement marking as a speed-reduction treatment on freeway curves." *Transportation Research Record: Journal of the Transportation Research Board, No. 2056*, pp. 95–103, 2008.

[3] H. Dind, X. Zhao, J. Rong, and J. Ma, "Experimental research on the effectiveness of speed reduction markings based on driving simulation: A case study." *Accident Analysis and Prevention*, vol. 60, no. 1, 2013.

[4] KiM, "Cycling facts, netherlands institute for transport policy analysis,," 2018.

[5] R. J. Davidse, K. Van Duijvenvoorde, M. Boele, W. Louwerse, A. Stelling, C. W. A. E. Duivenvoorden, and A. & Algera, "Light moped crashes on the bicycle path; characteristics, crash scenarios and possible interventions; an in-depth study," *SWOV Institute for Road Safety Research, The Hague*, vol. 12, no. 1, pp. 1–12, 2017.

[6] S. d. Craen, Y. R. Bos, K. Van Duijvenvoorde, Y. Van Norden, R. W. N. Wegman, and S. & Van der Zwan, "The safety of powered two-wheelers in the netherlands; some topical points of attention in the limelight," *SWOV Institute for Road Safety Research, The Hague*, vol. 1, no. 1, pp. 1–12, 2013.

[7] M. Kuhn, A. Lang, J. Priester, and B. Wilhelm, "Crashes involving light powered two-wheelers," *Forschungsbericht. Nr. 20). GDV Unfallforschung de versicherer, Berlin*, vol. 1, no. 1, pp. 1–12, 2013.

[8] R. Methorst, J. Schepers, and W. Vermeulen, "Light mopeds on the bicycle path," *Rijkswaterstaat Dienst Verkeer en Scheepvaart, Ministerie van Infrastructuur en Milieu, Delft*, vol. 1, no. 1, pp. 1–12, 2011.

[9] M. Moller and S. Haustein, "Factors contributing to young moped rider accidents in denmark," *Accident Analysis & Prevention*, vol. 87, no. 1, pp. 1–7, 2016.

[10] K. Schleinitz, T. Petzoldt, J. Krems, and T. Gehlert, "The influence of speed, cyclists' age, pedalling frequency, and observer age on observers' time to arrival judgments of approaching bicycles and e-bikes," *Accident Analysis and Prevention*, vol. 92, no. 1, pp. 113–121, 1994.

[11] A. Guo, J. Harvey, and S. Edwards, "Older travellers and technology engagement." Report for TSC, DfT, Tech. Rep., 2016.

[12] T. Buch and S. Jensen, "Incidents between straight-ahead cyclists and right-turning motor vehicles at signalised junctions," *Accident Analysis and Prevention*, vol. 105, no. 1, pp. 44–51, 2017.

[13] G. Helmers and L. Aberg, "Driver behavior in intersections as related to priority rules and road design. an 17 exploratory study," *Linko ̈ping, Sweden: VTI*, vol. 167, no. 1, pp. 1–12, 1978.

[14] M. Costa, A. Bichicchi, C. L. M. Nese, V. Vignali, and A. Simone, "T-junction priority scheme and road 19 users yielding behavior," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 60, no. 1, pp. 770–782, 2019.

[15] R. Thaler and C. Sunstein, "Nudge: Improving decisions about health, wealth and happiness," *Yale University Press, New Haven, CT.*, vol. 1, no. 1, 2008.

[16] SWOV, "Oversteekvoorzieningen voor fietsers en voetgangers," 2006.

[17] G. Denton, "The influence of visual pattern on perceived speed at newbridge," *Laboratory Report LR531. Crowthorne: TRL Limited*, vol. 1, no. 1, 1973.

[18] S. Godley, "A driving simulator investigation of perceptual countermeasures to speeding (phd thesis)," 2000.

[19] O. Bagdadi, "Assessing safety critical braking events in naturalistic driving studies," *Transportation Research Part F*, vol. 16, no. 1, pp. 117–126, 2013.

[20] A. Tageldin, T. Sayed, and X. Wang, "Can time proximity measures be used as safety indicators in all driving cultures? case study of motorcycle safety in china," *Transportation Research Records: Journal of Transportation Research Board*, vol. 2520, no. 1, p. 165–174, 2015.

[21] S. B. Mclaughlin, J. M. Hankey, and T. A. Dingus, "A method for evaluating collision avoidance systems using naturalistic driving data," *Accident Analysis & Prevention*, vol. 40, no. 1, pp. 8–16, 2008.

[22] T. Nishimoto, Y. Arai, H. Nishida, and K. Yoshimoto, "Development of high performance drive-recorders for measuring accidents and near misses in the real automobile world," *JSAE Review*, vol. 22, no. 3, pp. 311–317, 2001.

[23] W. Van Winsum and W. Brouwer, "Time headway in car following and operational performance during unexpected braking," *Perceptual and Motor Skills*, vol. 84, no. 3, pp. 1247–1257, 1997.

[24] W. Van Winsum and A. Heino, "Choice of time-headway in car-following and the role of time-to-collision information in braking," *Ergonomics*, vol. 39, no. 4, pp. 579–592, 1996.

[25] X. Yan, M. AbdelAty, E. Radwan, X. Wang, and P. Chilakapati, "Validating a driving simulator using surrogate safety measures," *Accident Analysis & Prevention*, vol. 40, no. 1, p. 274–288, 2008.

[26] AASTHO, "Guide for the development of bicycle facilities," 1999. [Online]. Available: https://www.transportation.org/

[27] O. Bagdadi and A. Várhelyi, "Development of method for detecting jerks in safety critical events," *Accident Analysis & Prevention*, vol. 50, no. 1, pp. 83–91, 2011.

[28] H. Song and J. Lee, "Detecting positioning errors and estimating correct positions by moving window," *PLOS ONE*, vol. 10, no. 12, pp. 1–12, 2015.