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

A field study at Eindhoven, Netherlands

- Girish Kumaar (G.K.) Srinivasan Ravi Kumar

TU Delft
Delft University of Technology

SWOV
INSTITUTE FOR ROAD SAFETY RESEARCH

MeBeSafe

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

by

G.K. (Girish Kumaar) Srinivasan Ravi Kumar

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Thesis Committee

Chair	**Dr. Ir. W. (Winnie) Daamen**	Delft University of Technology
Daily Supervisor	**Ir. A. (Alexandra) Gavriilidou**	Delft University of Technology
Company Supervisor	**Dr. Ir. M. (Matin) Nabavi Niaki**	SWOV (Institute for Road Safety Research)
External Supervisor	**Dr. Ir. J.A. (Jan Anne) Annema**	Delft University of Technology

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Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	**Explanation**
2D	Two-Dimensional
ANOVA	Analysis of Variance
AASTHO	American Association of State Highway & Transportation Officials
CBA	Cost Benefit Analysis
CBS	Central Bureau of Statistics
CD	Change in Directionality
CDF	Cumulative Distribution Function
CET	Central European Time
DOCTOR	Dutch, Objective Conflict Technique for Operation & Research
DR	Deceleration Ranges
EP	Evening Peak
EU	European Union
GPS	Global Positioning System
GT	Gap Time
ID	Identity
KS-test	Kolmogorov-Smirnov-Test
LSRM(s)	Longitudinal speed reduction marking(s)
MCDA	Multi-Criteria Decision Analysis
MP	Morning Peak
PET	Post Encroachment Time
PTW	Powered Two-Wheeler
RSMA	Road Safety Markings Association
SRM	Speed Reducing Marking
SSM(s)	Surrogate Safety Measure(s)
TPB	Theory of Planned Behaviour
TTC	Time to Collision
VTTI	Virginia Tech Transportation Institute

Abstract

The main objective of this master thesis is to investigate the speed behaviour and safety effects on cyclists and moped users sharing a T-Intersection with the application of a transverse lane marking nudge as a traffic calming measure. The main purpose of this research is to slow down the through road users, who might have inverted priority perception at the T-Intersection, eventually improving the safety at the cyclist T-Intersection. The research was performed with the trajectory data of the road users obtained through a field study conducted at the cyclist T-Intersection in Eindhoven, separately with and without the application transverse lane marking nudge. Speeds and acceleration were analysed to understand the behaviour and analyse whether the transverse lane marking nudge could be used as a traffic calming measure to reduce the vehicle speed and improve the safety at the T-Intersection. Deceleration ranges and Jerk are used as a Surrogate Safety Measures (SSMs), designed to identify various evasive actions, abrupt changes in speeds and were found to be better at identifying conflicts than individual time-proximity measures, such as Time-to Collision (TTC) with motorised vehicles, hence adopted in this research.

Based on the results, the transverse lane marking nudges do not show strong evidence for reducing the speeds of both cyclists and mopeds at the T-Intersection. So, it cannot be implemented as a traffic calming measure at the T-Intersection without further research or changes. Additionally, the presence of the transverse lane marking nudge introduced a high number of critical braking instances and more critical jerks decreasing the safety at the T-Intersection for the road users sharing the bicycle T-Intersection. This is because, the transverse lane markings implemented in this study would have created an illusion of a stop line, the road users would have thought that as an obstacle, a sudden surprise or as a distraction when passing the T-intersection in the presence of the nudge.

In the past researches using the nudge strategy, there were several instances in which the nudge was effective and successful. The key reasons for success are, (a) involving active changes with the choice architecture made by the road user; (b) Ensuring that there is a significant link from the intentions to behaviour; (c) the nudge intervention must be aimed to focus on the behavioural, normative, and control beliefs that captures the behaviour of interest; and finally, (d) to create effective intended behaviour of nudge is to consider a longer intervention duration to study the intended behaviour. This would help in bringing a sufficient number of changes in the behaviour and assist the individuals behave in an intended way for effectiveness.

So, clearly the lane marking nudge has to be improved, and some crucial changes have to be implemented in order to avoid unexpected outcomes in future studies. With this regard, an elaborate discussion is made on the possible changes with the implementation of the transverse lane marking in the future. If not all, at least few intervention functions from the MINDSPACE framework like choosing the correct way of persuasion and inspired improvements from the Behavioural Change Wheel like better education or spreading awareness have to be considered and definitely not only relying on the fact for the nudge to subconsciously change the road user behaviour.

Detailed Executive Summary

Introduction

One of the crucial problems that have to be tackled is cycling safety, despite the higher popularity of cycling in the Netherlands. Especially when the cycling infrastructure is shared with moped users (including light-moped users). Due to the various complex movements at the unsignalised cyclist T-Intersection, it gives rise to more safety critical instances, which include unsafe braking and evasive maneuvers with sudden or rapid changes in speed. Also, it has been found that uncontrolled T-Intersection can create an issue when priority is assigned to the intersecting (right) arm because through road users have a higher perception of priority and fail to yield. This makes the through road user approach the intersection with high speeds and increased safety critical instances at the T-Intersection. So, to improve safety, it is essential to initially study and analyse why and how unsafe situations occur and why there is a higher risk at the intersections. For this research, the lane markings are chosen as a measure to check whether it alters the behaviour of cyclists (and moped users) in a safer way or not. The safety with the application of the lane marking nudge is quantified with the use of Surrogate Safety Measures (SSMs) because of its proactive nature. This research also introduces the application of an unconventional indicator to quantify the safety of the road uses at the shared cyclist T-Intersection by promoting jerk as a SSM apart from using deceleration ranges as a SSM. These two safety performance indicators were found to be better at identifying conflicts than individual time-proximity measures, such as Time-to Collision (TTC) with motorised vehicles, hence adopted in this research. Analysing the road users' naturalistic behaviour through field study provides a more realistic understanding of the actual and real-world behaviour of cyclists and mopeds. In the previous research, the safety and behavioural studies at T-intersection have not been carried using a field experiment to explore the influence of the lane marking nudges. So, the three main research questions to achieve the main goals this research are:

- *Q1: "What are the effects of the transverse lane marking nudge on the speed behaviour of the road users at a cyclists T-Intersection?"*
- *Q2: "What are the effects of the transverse lane marking nudge on the safety criticality of road users at a cyclists T-Intersection?"*
- *Q3: "How can the transverse lane marking nudge can be translated as an effective behavioural change intervention policy in the future?"*

Key Performance Indicators

The research was performed using the trajectory data of the road users obtained through a field study conducted at the cyclist T-Intersection in Eindhoven, separately with and without the application transverse lane marking nudge. Based on the available data from the field study, a conceptual model is generated to explore the relationship with various elements (i.e. the individual and aggregate attributes of each road user) necessary to obtain the performance indicators with the support of an elaborate literature review. This assists to quantify the speed behaviour and safety criticality with and without the application of the transverse lane marking nudges. The speed behaviour is understood with the mean speeds and accelerations of the road users. Similarly, the safety criticality is assessed by using the deceleration and jerk as a Surrogate Safety Measure (SSM). Additionally, the independent variables like Time of day, i.e. whether it is a weekend or a weekday, and peak or off-peak on a weekday also influences the speed behaviour and safety criticality.

Before testing the various hypotheses, an extensive list of expectation and possible outcomes were discussed, which illustrates that, the lane marking nudges can have a varied effect based on, road user type (cyclists and mopeds), Time of day (Sunday, Monday Morning Peak (MP) and Monday Evening Peak (EP)), maneuver types (upstream, through, turning and opposite-through). These are the various sub-groups (or specific cases) for the analysis of the performance indicators. The opposite-through are the "control group" road users assumed to have no influence with the presence of the nudge, since they were not using the lane where the nudge was implemented. Finally, it is also expected that the nudges could have a different influence based on the different sectional areas with respect to the nudge implemented location. So, five sectional areas are chosen for the testing the hypotheses, which is the area 10m before reaching the nudge, at the start, middle, end and after crossing the nudge implemented location. So, all the different cases are analysed in the relevant sectional areas, to infer the effect of the lane marking nudge.

Results and Inferences

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. So, based on the detailed interpretations the summary of all the key findings are:

- First of all, the mean speeds of all the cases which had statistical differences were high in the nudge scenario, for both cyclists and moped users, Clearly, the differences with the mean speeds is not only due to the presence of the nudge, but also due to other factors which is 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 compared to the nudge scenario.

- The mean accelerations of the upstream cyclists 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 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.

- In 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.

  Moreover, the control group road users no differences with the mean acceleration, which strengthens these inferences with the variation of the mean accelerations with the presence of the nudge. So, all these inferences with the chances in the mean acceleration had a higher changes, that it is because of the presence of the lane marking nudge. So, 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 tend to decelerate at the start, middle and end of the nudge implemented location on all three times of days chosen. The same was with the case of turning mopeds 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 the other hand, the mean accelerations of the through cyclists and mopeds did not have any differences in their means, after crossing the nudge implemented location, as expected. Since, 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 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. So, probably the tuning 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 gives rise 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.

Conclusions

- Overall, with the presence of the lane marking nudges the mean speed of the roads users did not tend to decrease. Other factors such as the weather, especially the rain have to be taken into account since there were differences in their mean speed of the road users who were not expected to get influenced with or without the nudge.
- Both the cyclists and mopeds including the through and turning movements, either resulted in a less mean acceleration or high mean decelerations in the presence of the transverse lane markings. This implies that the transverse lane marking implemented in this field study is not successful in creating a speeding illusion, but might be responsible for, creating an illusion of stop line, as an obstacle or sudden surprise in distracting the road users, eventually increasing the safety critical instances.
- Since, the transverse lane marking nudge 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 gives rise 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.

Based on these conclusions from the empirical analysis specifically from the field study conducted in this research, the policy implications and lessons learnt are:

- The transverse lane marking nudge is not yet 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 focus on the 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 nudge intervention must be aimed to analyse the behavioural, normative, and control beliefs that captures the behaviour of interest.
Finally, based on all the action steps 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 are:

- Since, passive approaches are mostly inadequate and not likely to bring the intended behaviour change.So, the nudges implemented in the future should involve active changes with the choice architecture made by the road user.
- Should ensure that there is a significant connection from the intentions to behaviour by inducing road users to form an implementation intention, that is to come up with a specific plan elaborating, when, where and how the desired behaviour will be performed with respect to the lane marking nudges.
- The lane marking nudges must be aimed to bring changes at behavioural, normative, and control beliefs that influences the behavior of interest among all the road users.
- Dedicated study to check the steps needed to incorporate the stronger motivation for a safer behaviour of the road users.
- Considering a longer intervention duration to study the intended behaviour, and incorporate crucial elements like, better persuasion and awareness inspired from generic successful frameworks.

1 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 (Pucher & Buehler, 2008). This is evident by comparing the population and the cycle counts and cycling penetration in the Netherlands. Given the high popularity of cycling in the Netherlands, one of the crucial problems that have to be tackled is cycling safety. Especially when the cycling infrastructure is shared with moped users (or light-moped users) who have high speeds compared to the cyclists, it induces more unsafe instances between both road users, due to the differences in their speeds (making it non-homogeneous traffic). The literature studies in section 2.1 clearly show a generic necessity and importance of the improvements needed with the safety of the cyclists and the moped users and also the subsequently concluding with the safety criticality associated with the cyclist safety shared cycling intersections. It has to be noted that in the entire report "mopeds" refers to the moped or the light moped users sharing the cycling infrastructure. Also, the term "safety criticality" in the rest of the report refers to the critical braking events and sudden evasive actions by the road users.

To improve safety, it is essential to initially understand why and how unsafe situations occur and why there is a higher risk at the intersections. So, to ensure the safety of cyclists, the global framework plan of action for road safety was considered as an inspiration (UNRSTF, 2018), with the various associated areas and the corresponding pillars associated with it. For this research only two pillars from the framework were relevant, i.e. the pillar of "Safe User" can be achieved by analysing cyclist behaviour, that is the decisions cyclists make to speed up or slow down and similarly the pillar of "Safe Road" can be incorporated by altering the infrastructure designs and standards and improving the situational awareness of the road users sharing the bicycle infrastructure. The detailed framework with the various pillars are presented in Appendix A.

From the state-of-the-arts, the road users speeds have a high influence on the probability of crash occurrence and the severity of the injury (Elvik, Christensen, & Amundsen, 2004). It is also found from the literature that an unsignalised cyclists T-Intersection have multiple complex movements which reduces the safety compared to other supervised intersection. 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 and the behaviour of the other road users (mopeds in this research) as well. There is also enough evidence from the literature that, there is a misunderstanding of the priority perception of the through road users at T-Intersections where a higher priority is given to the road users coming from the right. Moreover, the behaviour and safety at T-intersection have not been explored in depth as done with the car traffic. An elaborate necessity and relevance of making the T-Intersection safer are explained in section 2.2, highlighting the need for traffic calming and speed reduction.

For an improved safety and as a traffic calming option at a shared cyclist T-intersection, many solutions exist which includes, road markings, signalised intersections, speed bumps and rumbles. For this research, the lane markings are chosen as a measure to check whether it alters the behaviour of cyclists and mopeds in a safer way or not. The lane markings have the advantage to captivate (to influence and dominate) the road user for an automatic response without the necessity of a conscious decision compared to the signalised control. Apart from this, lane markings are also a relatively cheaper and efficient alternative, which makes it an attractive choice to apply and study its impacts on road users and used as a traffic calming measure to reduce the speeds and the safety criticality of the road users. Another motivation for choosing the lane marking is also because it has been proven to have a high degree of positive influence and safer behaviour adaptation with respect to the car users. The concept of lane marking as a nudge and the reason for choosing this type of judge will be elaborated further in detail with the literature review presented in section 2.4. This section also gives an elaborate background on the application of "nudge theory" in practice.

It has been well established in the literature that the transverse strips as a lane marking nudge with a reducing space between them have resulted with the speed reduction since it gives an illusion that the vehicle is going faster than the actual speed which makes the road users slow down subconsciously (making the transverse lane marking serve as a traffic calming measure or nudging the road users to slow down). The speed reducing effectiveness has been well explored with cars (Gates and Qin (2008); Dind, Zhao, Rong, and Ma (2013a)) and proven to have a significant positive impact on the speed reduction of the vehicles. So, this research mainly focuses on filling the scientific gap on the safety and behaviour changes of the cyclists and mopeds with the implementation of a lane marking nudge at a T-intersection through a field study. Analysing the road users' naturalistic behaviour through field study provides a more realistic understanding of the actual and real-world behaviour of cyclists and mopeds. To the best of author's knowledge, in the previous research, safety and behavioural studies at T-intersection have not been carried to capture the naturalistic behaviour. Hence this research helps to understand and explore whether the implementation of lane marking nudge at the T-intersection would change the behaviour of cyclists and mopeds. Eventually, exploring whether these behavioural changes would result in increased safety criticality of the road users at the T-intersection or not.

Moreover, there is a lack of concrete policy measure related to applying the nudge as a behavioural change interventions for alerting the road users behaviour. So, apart from improving safety by understanding the behaviour of the cyclists at the T-intersection, this research also aims to provide relevant policy implications and recommendations as well concerning to the applications of nudges in the future. These policy implications are directly based on the empirical analysis from the field study conducted in this research. This section also includes a separate and dedicated literature on the state of arts, available frameworks and methodology used for behavioural change intervention (nudges) with regard to taking suitable policy measures, improvements and actions. This helps the policymakers to cross-verify if all the elements needed or focused upon with the use of generic and well established behavioural change intervention frameworks.

The key scientific contributions of the research include a detailed literature study which includes identification of the scientific research gaps, the importance of nudging and its influence to quantify the behavioural and safety performance indicators. An elaborate conceptual model based on the necessity and the data available, to extract the necessary elements and indicators to understand cyclists and moped users behaviour and safety at T-Intersections supported by the literature review. Introducing the application of jerk for quantifying safety, which has never been done before for cyclists and moped users. Finally, the research is concluded by proposing descriptive policy measures, implications and recommendations with the use of the lane markings to influence the behaviour and safety of cyclist at T-Intersections. Additionally, a brief literature review is conducted to verify if the lane marking nudge is ready for drafting policy actions by reviewing the general systematic frameworks available for implementing behavioural change intervention similar to the lane marking nudges implemented in this research. This section concludes by presenting a descriptive research overview and presenting the connections between the various sections of this report. An elaborate structure and contents of the report are presented at the end of this section following the main goals and research questions.

1.1 Research Goals and Objectives

The main goals of this master thesis are, to explore if there is a significant influence on the cyclists' and the mopeds users' speeding behaviour and safety criticality with and without a lane marking nudge at cyclists T-Intersection. So, one of the key aims is also to check if the transverse lane markings help to reduce the speed with cyclists & mopeds along with whether it has an impact of the safety criticality of the road users at the shared cyclist T-Intersections. Apart from these, the research explores if all the elements for the lane marking nudge implementation are incorporated in the existing generic frameworks for the behavioural change interventions to support the various policy categories and suggest some actions to be taken for its successful implementation in the future. Finally, this research aims to come up with some concrete policy recommendations and improvements with the use of the transverse lane marking nudge in the cycling infrastructure, i.e. the T-Intersection.

1.2 Main-Research Questions

To achieve the research goals, the three main research questions to be answered in this study are mentioned below.

- *Q1: "What are the effects of the transverse lane marking nudge on the speed behaviour with the road users at a cyclists T-Intersection?"*

- *Q2: "What are the effects of the transverse lane marking nudge on the safety criticality of road users at a cyclists T-Intersection?"*

- *Q3: "How can the transverse lane marking nudge can be translated as an effective behavioural change intervention policy in the future?"*

1.3 Sub-Research Questions

To answer all the main research question several sub-research questions have to the answered for each of the main research question. This provides an overall idea about the behavioural changes and the safety effects with and without the transverse lane marking nudge at the T-Intersections. The first three sub-research questions are used to answer the 1^{st} and 2^{nd} main research question. Similarly, the last three sub-research questions are framed to answer the 3^{rd} main research question. So, for answering the main research questions, the following sub-research question has to be answered:

1. **What are the relevant performance indicators needed to quantify the speed behaviour and safety criticality at T-intersections?**

   This question focuses on the various performance indicators necessary to quantify the speed behaviour and safety criticality at the T-Intersection. These are obtained from a detailed literature review. The objective of this question is also to identify and calculate the relevant performance indicators. Apart from this, it also aims to develop a detailed conceptual model to show how certain characteristics of the road infrastructure with and without a nudge influences the speed and safety of the individual road users, linking to all the performance indicators necessary to quantify them.

2. **What are the various factors which affect the performance indicators of the road users directly or indirectly?**

   This question focuses on understanding the state-of-the-art on what factors would affect the performance indicators. It also aims to understand what factors the lane marking nudges could have different variations in the performance indicators. It also helps understand the dependent and independent variables which influence the performance indicators.

3. **What are the data requirements to calculate all the performance indicators?**

   This question helps to give better understanding and connection between the identified performance indicators and factors affecting them from the literature review and the data needed to obtain them. It also assists with what filtering and pre-processing have to be performed with the collected raw data. Eventually, this question assists to obtain the necessary data sub-groups based on the factors influencing the performance indicators.

4. **What are the suitable policy implications with the application of lane marking nudges, based on the empirical analysis with the performance indicators?**

   This question focuses on drafting a list of policy implications solely with respect to the result and statistical inferences based on the empirical analysis with the use of the transverse lane marking nudges. It mainly focuses on whether the transverse lane marking nudge could be used as a traffic calming measure or not and whether it has an improved effect on the safety criticality of the road users using the T-intersection.

5. **What are the changes or additions which could be incorporated with the implementation of the lane marking nudges for improved effectiveness in the future?**

   This sub-research question deals with few of the existing frameworks for a structure implementation of a behavioural change intervention in the road infrastructure to be successful and has a positive impact among the road users eventually resulting with an improvement in road safety. So, these frameworks are used to check whether the factors explored in these successful frameworks are also incorporated with the lane marking nudges used in this research and conclude what all elements could be included with the nudges to have better and improved effectiveness of the nudges as traffic calming measure and improving the safety of the road infrastructure.

6. **What are the suitable policy recommendations with the application of lane marking nudges in the future?**

   This question focuses on drafting a list of policy recommendations for improvements in the application of nudge theory. It is based on understanding when the nudges were successful and effective using the sate-of-the arts, existing generic behavioural change interventions frameworks to improve the certainly and probability of bringing the intended behavioural changes with improved effectiveness.

1.4 Thesis Report Overview

This sub-section explains the various elements of the entire research to give an outline of all the major sections and their connections with all the other sections which are inter-related. The flowchart presented in figure 1 represents the relation between the elements starting from the research goals (including the questions to be answered) till the conclusions of the report along with the feed backs required to achieve the objectives of this research. Based on the research goals and objectives (section 1.1) an extensive literature review was performed (section 2). This is then followed by describing the study location, data collection for the case study in section 3. Then an elaborate conceptual model is created for the main purpose of understanding which performance indicators are relevant and necessary for answering the research questions about the speeds and the safety criticality assessment (section 4.1). Once it is clear what indicators and required, an exhaustive list of hypotheses is tested with the application of the transverse lane marking nudge (based on various expectations presented in section 4.2), elaborating on the data requirements and all the elements related to the handling the data is explained more in detail focusing on the data description (section 3) and data analysis methodology (section 4). The results then summarised (section 5) from the data analysis, then checked with the hypotheses tested (feedback) and based on the outcome, detailed interpretations and statistical inferences (section 5.1) are presented with the implementation of the lane marking nudge.

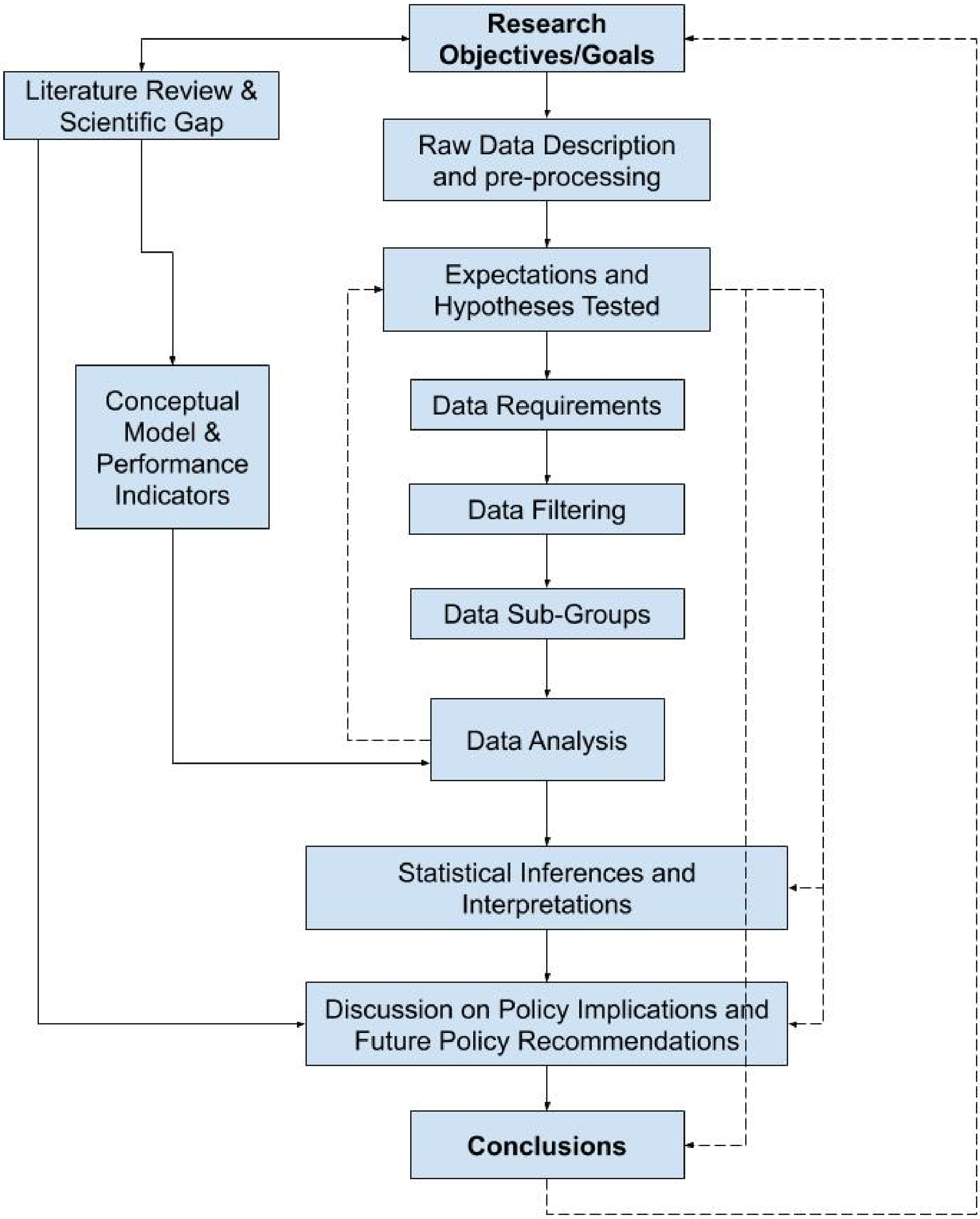

Figure 1. Thesis Report Overview
(Note: The solid lines in this figure represent the direct connect and the dotted line represents the feed-backs or the application of the output information obtained in one section which is used in another section of the report)

This is then followed by a detailed discussion on policy implications (section 6.5) supported with (separate dedicated state-of-the-arts) literature, also to strengthen the societal relevance of this research. Finally, the conclusions (section 7) are drafted answering all the research questions which meet the research goals and objectives along with the exhaustive list research limitations (section 7.4) and future recommendations (section 7.5) to continue exploring the application of lane marking nudges.

2 Literature Review

The section creates a wide context on elaborating on the penetration and usage of cycles and mopeds, along with the necessity of improving their safety in general. Then this section shifts to dealing with the relevant topics to provide a deeper background for the necessity of improvements at the T-Intersections. The aim of this section is to shed light on the state-of-the-arts beginning with cyclists and moped users(or light moped users) facts and safety in the Netherlands and its relevance, the influence of road marking techniques & lane markings as one of the way of nudging road user behaviour, and few measures used to quantify the road user behaviour and safety at the shared cycling T-Intersection.

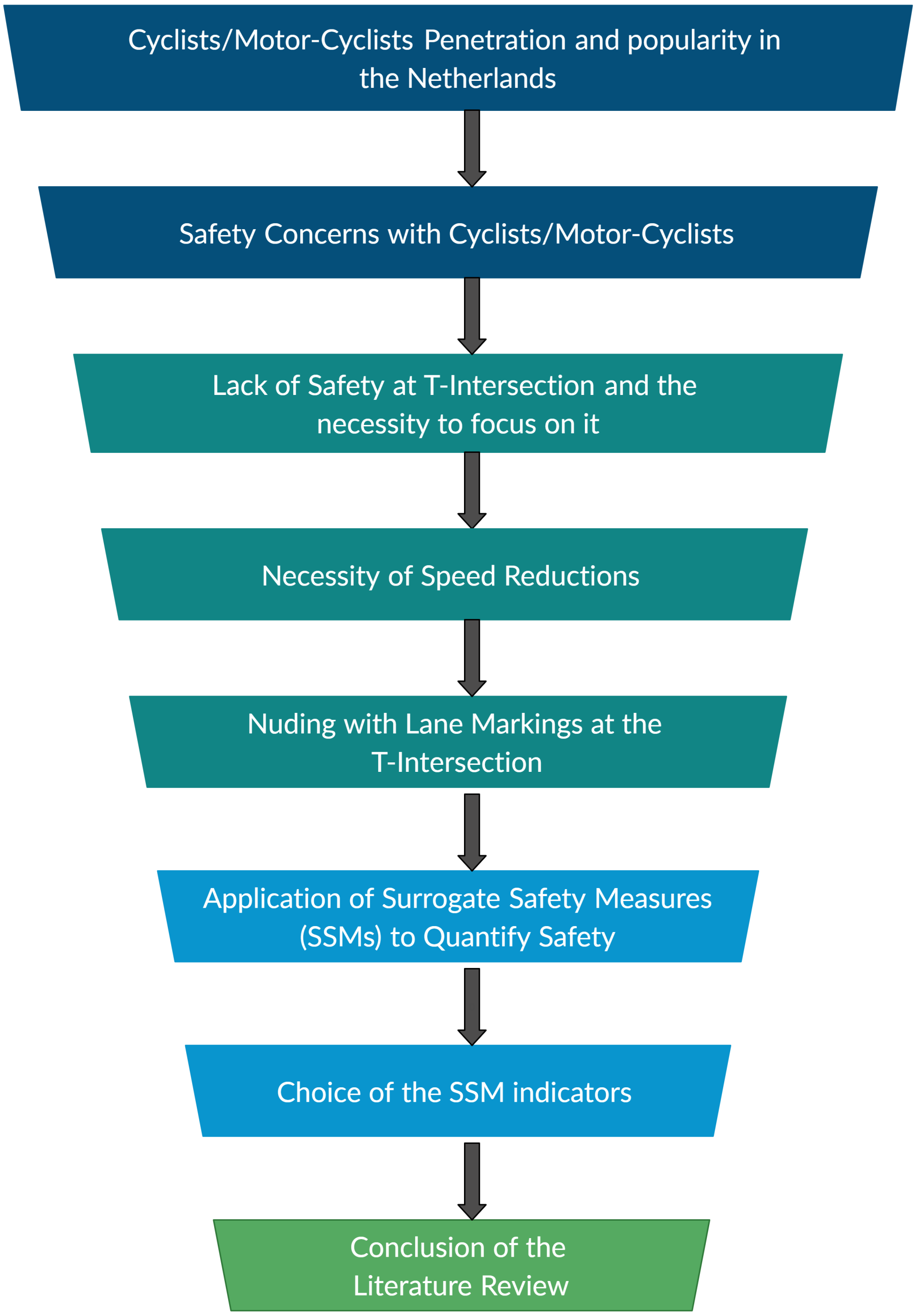

Figure 3. Contents of the Literature Review

The order of topics covered in the literature review is depicted in figure 3 for the convenience of the reader. Each subsection in this chapter shows the necessity for achieving the research goals along with the specific scientific gap addressed. It also helps identify the type of data required, a conceptual model for deriving the relevant performance indicators based on the available data and the proposed data analysis methodology to answer all the research questions.

2.1 Safety of Cyclists and Mopeds

From the Cycling Fact sheet published by the Ministry of Infrastructure and Water Management (KiM, 2018), the Netherlands has a total population of over 17 million with over 23 million bicycles. Apart from the high number of bikes, more than one-quarter of all trips made by Dutch residents are performed using a cycle. In the year 2016, 4.5 billion bicycle trips, covering 15.5 billion bicycle kilometres. More than one-third of all bicycle kilometres are travelled for leisure purposes, and one-quarter involve work-related trips (KiM, 2018). Moreover, the Netherlands has the largest proportion of bicycle use as a percentage of the total number of trips compared to the other countries in the world (KiM, 2018).

Apart from cycling, the use of mopeds is also becoming common with a lot of European countries, especially the light moped has a higher penetration in the Netherlands (R. J. Davidse et al., 2017). In the Netherlands along with a lot of other countries the light mopeds (or mopeds with speeds lower than 25 kmph, (Wagenbuur, 2013)) are popular. Due to various reasons including the relatively less travel time (compared to cycles), and comfort the mopeds are pretty common across all the age groups (Statistics Netherlands). Within a span of 10 years, the total number of light mopeds increased from 304,816 in 2007 to 680,563 in 2017. This eventually brings up higher traffic density in the bicycle infrastructure and a more serious concern with respect to the safety of both the road users (Methorst, Schepers, & Vermeulen, 2011).

Even though, cycling and mopeds are popular in the Netherlands, among all road fatalities in 2019, more than one-third of the victims were cyclists (31%), which is depicted in figure 4. Apart from the high amount of cyclist fatalities, cyclists account for the highest proportion of serious injuries among all the other modes, which is around 52% (cyclists without mopeds) shown in figure 5. These figures and numbers assist to realise the severity of the issue related to cycling safety in the Netherlands. Previous studies also show that more than 80% of the seriously injured cyclists were involved in single-bicycle crashes or crashes between two or more bicycles (Reurings, Vlakveld, Twisk, Dijkstra, and Wijnen (2012); P. Schepers and Klein Wolt (2012)). Hence, although most studies focus on car crashes with cyclists, it is also crucial to investigate and reduce bicycle casualties.

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. There is a lot of literature which sheds light on the mopeds who are allowed to ride till 45 kmph and share the infrastructure with the car users for understanding their behaviour and safety but very few studies elaborate on the consequences of sharing the mopeds and light mopeds with

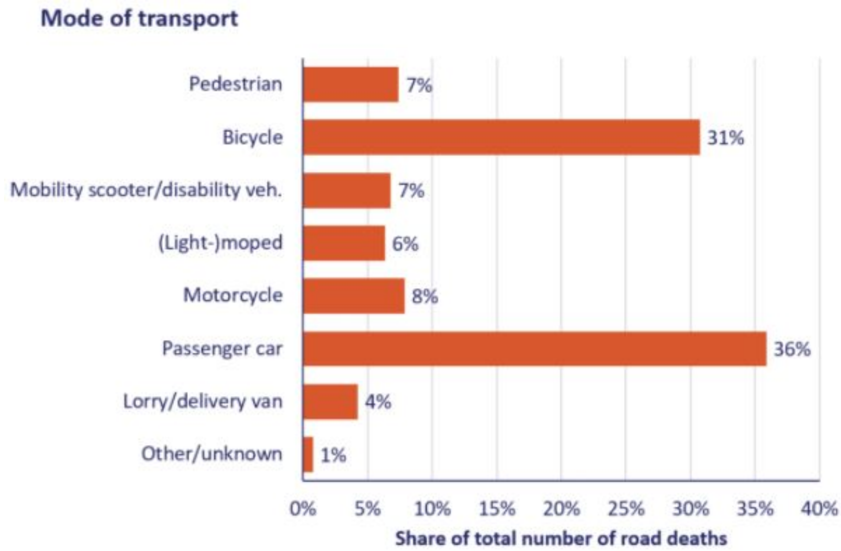

Figure 4. Road deaths 2019 in the Netherlands by various transport modes (CBS, 2019)

the cyclist's infrastructure. On top of that the few studies which experiments only on the light moped road users (Craen et al. (2013); Kuhn, Lang, Priester, and Wilhelm (2013); Methorst et al. (2011); Moller and Haustein (2016)) did not focus on the safety criticality of the light mopeds sharing the bicycle infrastructure, which is analysed in this research.

Even though there is a significant decrease in the overall number of road fatalities, the cyclists' and mopeds' fatalities reduce at a much slower rate compared to the other vehicles (SWOV, 2020). In the research conducted by R. Davidse et al. (2019), 36 light moped crashes were empirically analysed, which took place on an urban cycling path. The course of the events along with the causes, was elaborated in detail for every crash and possible injuries with consequences. They concluded that other road users behaviour such as not yielding forces the moped users to react abnormally (evasive braking) to avoid a collision. The results also show that among all the crashes, more than 70% of the crashes took place on an intersection shared with the cyclists, showing a higher degree of safety issues to be addressed at intersections.

The signalised intersections including the motorised vehicles have been identified as risk locations for cyclist (Schleinitz, Petzoldt, Krems, and Gehlert (1994); Guo, Harvey, and Edwards (2016); Buch and Jensen (2017)). The research conducted by Buch and Jensen (2017) at a signalised intersections, analysed the number of observed conflicts if one road user reacted with an avoidance maneuver. Their results showed that cyclists travelling with high-speed cyclists have increased chances of being in conflict with vehicles that were turning. Similarly, The results from Dozza and Werneke (2014) show that cycling near an intersection increased the chances of experiencing a safety critical event by 400% with mixed traffic of cyclists and motorised vehicles. Additionally the results also indicated that, if there is an intersection near building and hedges (i.e. with some form of visual occlusion) the risk increases up to 12 times.

Since the intersections with motorised vehicles are so unsafe, ideally we should avoid the cyclist-car interaction when designing a bicycle network and cyclists should only intersect with other

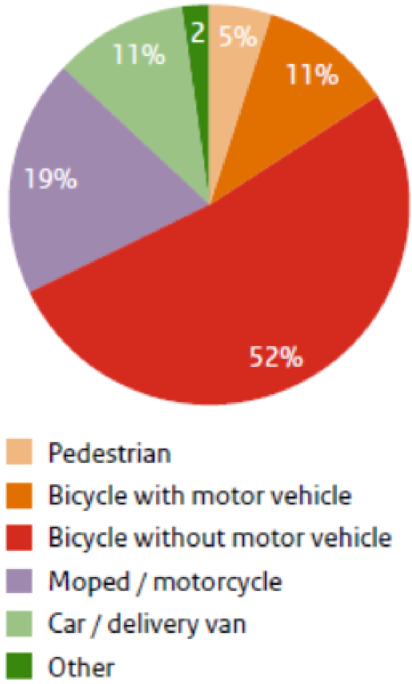

Figure 5. Proportion of serious injuries by mode of travel (KiM, 2018).

cycling streams, where ever possible. But in reality, there might not be enough space in a city to create a fully separate network for cyclists. 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 high speeds than cyclists, leading to more individual safety-critical instances. Also, there are not many studies which focus specifically on the individual safety of cyclists and mopeds at the T-intersections. Especially concerning the through and turning movements types leading to the increased safety-critical instances for individual road users.

2.2 Necessity of Speed Reductions

In general high speeds are considered to be unsafe for all the road users. The results from Siegrist and Roskova (2001), strongly suggests that high speeds have a negative effect on road users, efficiency of the traffic system and the environment, if a crash occurs. The speed of the road users has a high influence on the probability of crash occurrence and the severity of the injury when the crash occurs (Elvik et al., 2004). In fact, the research from Bonanomi (1990) concludes that the probability of death is inversely proportional to the speed of collision. So, reducing the speed of road users is always beneficial for improving the safety of road users. It is also proven in lots of researchers, that, the severity of crash largely depends on the speed of the colliding vehicle (Rosen and Sander (2009); Rosen, Stigson, and Sander (2011); Tefft (2013); Kroyer, Jonsson, and Varhelyi (2014)). Apart from improving safety, reduced speeds are also responsible for creating a "low-stress" cycling environment for all the road users (Furth, Mekuria, & Nixon, 2016) using a shared infrastructure. So, measures should be taken to assist all the road users using the unsupervised shared cyclists T-Intersection with complex movements to improve the safety.

Apart from the improvement in safety and reducing stress of all the road users, another reason for the necessity of the speed reduction is the priority perception of the road users at the T-Intersection. J. P. Schepers, Kroeze, Sweers, and Wust (2011) reported that 95% of the bicycle–motor vehicle crashes in the Netherlands that took place at unsignalized priority intersections were because of the failure-to-yield by the cyclists. In the studies involving car drivers, it has been found that uncontrolled T-junctions 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 (Helmers & Aberg, 1978). Priority perception is very crucial for the type of interactions that occur. When priority perception is high, drivers, as well as cyclists, tend to have high speeds and minimal head movements to observe their surroundings, which can result in unsafe interactions (Costa, Bichicchi, M. Nese, Vignali, & Simone, 2019).

All these studies, however, investigated either only car traffic or mixed car-bicycle flows, where the priority was indicated by road signs. All the differences between affordance, expectations, yielding and actual rules were also analysed by Bjorklund and Aberg (2005). This study was performed with a sample of 1276 Swedish drivers using a questionnaire on how frequently the road users would yield to another driver in different hypothetical scenarios involving crossing. In all different scenarios the priority was given to the right. The results indicated that at a T-Intersection where a road user was approaching along the straight road, 40% of the respondents answered that they would never give way to a vehicle approaching from the right (intersecting arm). Almost half of the participants (49%) also reported that they would highly prefer yield to a vehicle approaching the intersection from the left along the straight road, even if they had the right of way (Bjorklund & Aberg, 2005).

So, in this research, to compensate the inverted priority perception of through road user at the cyclist T-intersection, their speed behaviour and the safety criticality were explored. This is performed by introducing the concept of "Nudging" at the T-Intersection which is elaborated in the subsection 2.3 on what is a nudge, it's advantages and the type of nudge used in this research. The following sub-section on "Nudging" also elaborates more on its ideology, relevance and importance over other measures which could be incorporated to alter the behaviour and safety at the T-Intersection.

2.3 Nudging

Various approaches have been used to motivate, accomplish, cultivate and "nudge" road users to behave in ways that are better for a personal and a societal benefit (Avineri, 2014). Nudge is a concept which can be applied in various fields including the behavioural science, political theory and behavioural economics that tries to bring a positive reinforcement as ways to change or alter the behaviour of the individuals. Nudging contrasts with other ways to achieve the change, such as education, legislation or enforcement. It should be noted that nudging has a clear difference from the other concepts for achieving compliance.

The nudge concept, which was initially developed by Thaler and Sunstein (2008) has turned out to have many benefits. According to them, one of the terms most associated with behavioural economics, and its application to influence behaviour, is the concept of "Nudge", and they 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."

Another similar definition was provided by Hausman and Welch (2010) state that,

"Nudges are ways of influencing choice without limiting the choice set or making alternatives appreciably more costly in terms of time, trouble, social sanctions, and so forth. They are called for because of flaws in individual decision-making, and they work by making use of those flaws."

Berry (2011) concluded that, in describing the existence of behavioural barriers, researchers and policymakers have focused on how people can be 'nudged' into making better decisions through interventions that eliminate the behavioural barriers. Especially in the field of transportation, the policy nudging has been adopted to make the older drivers (more than 70 years old) perform more effectively with their driving habits as they age (Berry, 2011). The importance of this concept is indicated in a study published in the year 2014, reports that "136 countries around the world have incorporated behavioural sciences in some aspects of public policy" (Thaler, 2015). Several of these policy initiatives have used the applications of nudges or nudge-like governmental interventions for making the people behave safety (Tomer, 2018). It is still debatable whether the "nudge theory" is a recent discovery in behavioural science or just a new term for one of already existing methods for influencing behaviour, investigated in the science of behaviour analysis (Marco and Carsta (2018); Mols, Haslam, Jetten, and Steffens (2015)).

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 improve the safety and influence the road user behaviour in a positive way, and this research will help to fill that gap by implementing lane markings as an infrastructural nudge at cyclists T-Intersection, assuming that it was effective of reducing speeds and increasing safety of motorised vehicles. Clearly, the two essential objectives of the conventional infrastructure urban road is "efficient vehicle flow" and "adequate safety" for all road users (Khisty and Lall (2003); Baillie (2008)). Many cities have undertaken traffic calming efforts including several shared space design principles to achieve those goals (SvR-Company, 2014). The subcommittee of the Institute of Transportation Engineering defines traffic calming as: "Traffic calming is the combination of mainly physical measures that reduce the negative effects of vehicle use, alter driver behavior and improve conditions for the road users" (Lockwood, 1997). There are many solutions to incorporate an improved behaviour with the road users to attain traffic calming, which includes road markings, traffic signs, signalised intersections, rumbles, reflectors etc. For this research, the lane markings are chosen (because of the relative economic benefit) as a measure to check whether it alters the behaviour of cyclists in a safer way or not. A general idea, benefit and relevance about the road markings and the different types are briefed in sub-section 2.4.

2.4 Road Marking and Lane Marking Nudges

Road markings have the ability to satisfy the expectations of the different road users. Also, they provide visual cues to detect and classify the different elements of the road infrastructure and its purpose properly (SWOV, 2006). Generally, the road designs based on road markings enforce self-explaining roads and provoke the road users to adapt their speed accordingly (Charman et al., 2010). In 2007, the Road Safety Markings Association (RSMA) published the report stating, ‘White Lines Save Lives’, which, amongst others measures, provided a cost-effectiveness analysis of the performance of new road markings in few of the selected counties (RSMA, 2010).

Among the different road markings, lane markings are one of the common types of road marking. In a cyclist only T-Intersection it is generally expected to have a continuous flow of cyclists rather than a voluntary interruption such a signal to alter the cyclist behaviour and speed which is an advantage with lane markings. Apart from this benefit, lane markings are not only a relatively cheaper and efficient alternative, but it is also clearly visible and audible (Dind, Zhao, Rong, & Ma, 2013b) and relatively non-intrusive compared to rumbles placed in the road sections. All these advantages make it attractive and easier to apply and study their impacts on road users in general.

There are few kinds of research in the past which used the transverse lane markings (as shown in figure 6) 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 resulting in a safer interaction at intersections (Denton (1973); Godley (2000)). This speed reduction marking (SRM) is an example of non-intrusive traffic calming measure that is predominately implemented on highways and urban expressways due to the benefit of not only warning drivers to slow down, but also induces less negative effects on the road users (Godley, 2000).

Gates and Qin (2008) investigated the application of an experimental transverse-bar pavement marking as a traffic calming measure on freeway curves. Considering the vehicle speed as a key performance indicator, a before and after the analysis was performed to determine the short-and long-term effects of this type of road marking. The results of the analysis showed that curve speeds significantly reduced after installation of the road markings which was replicated in the future. In the studies conducted by Dind et al. (2013a), transverse speed reduction markings proved to significantly have a positive effect on the subjects’ speed choice and maneuver compared to the ’no-markings’ and ’longitudinal-marking’ scenarios as depicted in figure 7.

Figure 6. Transverse Lane Markings (Source: Google)

In the research by Arnold and Lantz (2007), they concluded that the optical bars (similar to the Transverse Lane markings) are highly effective in decreasing the speeds of the vehicles approaching a hazardous roadway section, a reduced speed zone, or even a roadways/travel change area but the reductions in the magnitude of speed may be smaller. They also concluded that these transverse lane markings had increased effectiveness in reducing speeds if they extend across the travel lane than those that just extend a short distance from the centre-line or edge line. Compared to the thermoplastic tape markings, the rumbles are more pronounced and relatively noisier. These experiences make the lane markings are better and economical cheaper alternatives compared to the rumble strips. This kinds of lane markings are also audible and vibratory as well (Dind et al., 2013b). In the view of the Chinese national standard Road Traffic Signs and Markings, the Transverse Lane Markings are generally used to effectively warn drivers of the need to reduce their speed (Standardization Administration of the People's Republic of China, 2009). These kinds of lane markings can be placed in advance of different road sections such as the horizontal or vertical curves, tunnels, or other featured roads where drivers need to slow down in advance.

Even though many studies have analysed the influence of the transverse lane marking as an infrastructural nudge for cars and motorised vehicles (excluding light mopeds and mopeds), the influence of transverse lane markings with the cyclists and mopeds has not been explored, the necessity that it has to be studied in detail with the cyclist is mainly that they encounter more uncertain situations than the car drivers would face at signalised intersection and this eventually lead to much more safety-critical instances at the unsignalised cyclists T-Intersection.

Figure 7. Longitudinal speed reduction markings (LSRMs) in China (Ding et al. (2017))

2.5 Factors Affecting the Behaviour of Road users

This sub-section help to understand that, the time of day and the traffic flow variations during within a day has an influence on the behaviour and safety of the road users. So, to understand the behavioural changes, few important factors have to be considered which could influences the way the road users use a road infrastructure (T-Intersection in this research). Lord, Manar, and Vizioli (2005) in their research analysed the accident-flow relationships by using predictive models. They found that the accidents increased at a decreasing rate as flow increases. The study by Martin (2002), also explored the proportionality between accidents and traffic flow and how they are related to each other with the peak and off-peak flow within the day and found that it was directly proportional. Golob, Recker, and Alvarez (2004) also demonstrated a positive correlation between traffic flow conditions and accidents with the objective of providing a real-time assessment of the level of safety. So, all these studies show there is a clear relation between traffic flow (peak or off-peak variations) and the safety of road users at an infrastructure. So, the level of safety criticality is influenced by the variation with the traffic flow or the time of day as well.

A recent study by Kononov, Bailey, and Allery (2008) analysed the association between traffic congestion and crash rates on urban freeways. The results showed that the total as well as fatal and injury accident rates are directly proportional to the traffic congestion. Shinar and Compton (2004) explored the crash occurrence in relation to the drivers' behaviour. They established a linear relationship between the aggressive behaviour counts and traffic congestion, which may subsequently influence road safety. In pursuit of the same goal as the case study used in this research, Balde and Dissanayake (2013) applied three types of road markings (optical speed bars at the edge of center line, full-width transverse lanes and peripheral transverse lanes on two-lane) in a divided rural highway entering small communities. The results this study had a significant reduction of mean speed and speed variance, with the amount of reduction being high during daytime and weekdays compared to the weekends. So, all these studies show there is a clear relation between traffic flow and congestion with the safety of road users.

2.6 Surrogate Safety Measures

The road user injury data is a conventional way of describing the safety effects with the cyclists' behaviour and their effect of cycling tracks and intersections. There are many studies in the past which used the historical data of the injured cyclist to interpret the safety effects on the interactions with motorised vehicles (Thomas and De Robertis (2013); Reynolds and et al (2009); Lusk and et al (2011); Teschke and et al. (2012)). However, studying the crash data is a reactive approach and also the crash data is limited at these locations, and this is one of the major disadvantages of using the crash data or similar reactive approaches like the police or hospital records. So, given the limitations of the crash data, this technique cannot be used to look at the cyclists' behaviour and safety, focusing on the interactions within the cyclists at T-Junctions. This indicates the necessity of using a proactive approach instead of a reactive approach for the understanding of the road user behaviour and safety effects at the shared bicycle infrastructure.

Surrogate Safety Measure (SSM) is an example of a proactive approach (which are not based on the accidents) to study the safety of the cyclists' interaction without accident or injury data. The SSMs has multiple benefits for its appreciations and further development measures (Laureshyn, 2010). Few of the important advantages are:

- It becomes difficult to have a sufficient number of casualties for making a definitive study or conclude with the casualty data.
- The crash data are generally under-reported, especially the crashes dealing with vulnerable users such as cyclists.
- The accurate or descriptive information about the casualty and the setting in which it took place is generally limited and scarce.
- Waiting for a crash or casualty is treated as unethical to come up with some interpretation about the (un)safety of a particular measure.
- SSMs is a quicker alternative for studying safety in an efficient and ethical way.

But it is also important to notify the reader that, despite the abundance benefits of the SSMs, it does have few limitations, firstly, the severity of the crash. That is even though they assist to find the number of potential safety critical instances, the magnitude or the level of the potential injury of the road user is not explicit with the SSMs. The potential crash severity with the application of nudge is not focused in this research. Secondly, the conventional SSMs also do not consider the road-side objects or obstacle. But the cyclists move in proximity of the dangerous road-side objects or obstacles and can also move in proximity of the cyclists suddenly entering the road infrastructure, for instance from the parking space. In these circumstances a slight modification in the road user trajectory might translate into a serious crash. So, all the existing SSMs are reviewed and suitable SSMs are chosen to over come the second limitation.

In literature, the most common surrogate safety measure include the time-to-collision (TTC), post-encroachment-time (PET), gap time (GT) as well as deceleration ranges (DR) (Ismail, 2010). More focused on the intersections and road users, the additional surrogate safety measures include approach speed as well as the speed and deceleration distributions. Conventionally, for the past few decades, capturing the abnormal behaviours has been an important factor to reduce the conflicts between the road users (Sabey and Staughton (1975); Treat, Tumbas, and McDonald (1979)). Research has been performed by analysing drivers' deceleration and jerk behaviour to identify possible conflicts and abnormalities in the behaviour to estimate their severity to reflect on the abnormal behaviours (Hagelin, 2012). The state of arts focusing on the deceleration and jerk has been focused more in the rest of this sub-section, explaining clearly the need and advantage for its application in this research, as well as mentioning the disadvantages and irrelevance of the other conventional safety indicators.

For thoroughly assessing a single road user's behaviour and the safety criticality, it is important that only specific events are analysed. Otherwise, it is highly possible that other road users behaviour might be incorrectly superimposed onto the original road user's assessment (Dingus, Klauer, Neale, & Petersen, 2006). They concluded that, applying only the near-crashes as a SSM for safety criticality does not completely fulfil this requirement. Since, a near-crash is defined as, "Any circumstance that requires a rapid, evasive manoeuvre by the subject vehicle, or by any other vehicle, pedestrian, cyclist, or animal, to avoid a crash. A rapid, evasive manoeuvre is defined as steering, braking, accelerating, or any combination of control inputs that approaches the limits of the vehicle capabilities" (Dingus et al., 2006). This definition clearly shows that it is sufficient that any road user, or animal, performs an evasive action in order for the event to be classified as a near-crash, superimposing the occurrence of a near-crash on the road user under observation. Thus, a surrogate measure for the quantifying the individual safety criticality, i.e. the safety-critical braking event, which 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" (Bagdadi, 2013). This was also strengthened by the research performed by Tageldin, Sayed, and Wang (2015), in which the various traffic conflict indicators, chosen to quantify the evasive actions namely, the sudden speed changes (deceleration and jerk) and swerving behavior (yaw rate) of motorcycles were found to be better at capturing the motorcycle conflicts compared to the individual time-proximity measures, such as time-to collision (TTC).

Furthermore, at T-Intersections, the conventional SSMs like the TTC and PET are of lesser relevance since the conventional SSMs considers that the vehicle (cyclists and moped users in this case) would continue the similar unchanged trajectory or go straight and ignores the turning movements. In more technical terms, with the conventional SSM, the collision course (Svensson,

1998) only takes into account the unchanged cyclists movements (that is the trajectory is considered without the intervention of the other cyclists). The crucial elements in all the safety-critical situations are the "collision courses". A collision course can be defined as a situation in which a couple of road users or also an obstacle and a road user would have collided if they continue in the unchanged movements. Even if some methods such as the dutch conflict technique (DOCTOR) allow for "small disturbances" to account for situations of near-collision course, a general framework for safety analysis should consider all possible paths that may lead two road users to collide or unsafe actions, which is incorporated by the deceleration ranges and jerks since irrespective of the movement or maneuver type, if the individual road user goes beyond a certain threshold it is considered as a safety-critical situation which might lead to a potential conflict which is not safe.

Longitudinal acceleration 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 (Mclaughlin, Hankey, and Dingus (2008); Nishimoto, Arai, Nishida, and Yoshimoto (2001); Van Winsum and Brouwer (1997); Van Winsum and Heino (1996); Yan, AbdelAty, Radwan, Wang, and Chilakapati (2008)) and is thus considered to be a valid measure for comparison. Braking is generally captured through inspection of the acceleration profiles. From the studies performed by Balasha, Hakkert, and Livneh (1980), if a road user applies brakes (beyond a certain threshold), it indicates a potential sign of conflict and can be used as a surrogate safety measure. It is evident that hard braking is an evasive action which might lead to a crash or conflict if it is not performed which in turn could be applied to quantify the safety of the individual road users (Wahlberg, 2000). So, it has to be highlighted that, the lane markings are expected to slow down the road users and may brake, but decelerating beyond a particular threshold is safety critical and that is unsafe. So, deceleration in general is not considered unsafe, deceleration beyond a critical threshold is considered unsafe and safety critical.

So, from this literature one of the straight forward ways of studying the critical braking manoeuvres to quantify the safety criticality is by examining the cyclists' or the mopeds users' deceleration and determining whether it is within the normal range. If the deceleration is below, then the behaviours could be considered as a safety-critical event and assumed a potential conflict might occur or a possibility of a crash when the road user is abnormally deviating from the expected performance (Aronsson (2003); Othman and Zhang (2008)). Similarly, Smith et al. (2003) also concludes that severe deceleration is considered abnormal mainly because the road user try to reduce the collision risk in advance based on anticipation and altering the rate of change of their velocity.

In the similar lines, Dingus et al. (2006) and Lee, Llaneras, Klauer, and Sudweeks (2007) proved that the severe deceleration occurs when the road user has failed to detect the dangerous behaviours of their heading road user or when the road user has failed to adjust their speed in a timely manner which reduced the safety of the respective road users. 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 (AASTHO, 1999). Another research found this value to be 3.4 m/s^2 (Pein, 2004), for quantifying the safety critical events.

Apart from deceleration ranges, jerk could also be used to quantify the safety critically, which has started to gain familiarity a few years back. In research conducted by Wahlberg (2000) related to the effects of braking on safety, the evasive manoeuvres were described in terms of the g-force defining the lateral and longitudinal acceleration variations (Wahlberg, 2000). In a few studies involving car users, the jerk data collected from drivers were statistically analysed against their collision history as a measure to identify risky drivers. Most of the research has relied on capturing the road user data, which is extracted from movement sensors over a long period of time. The results for the studies showed a positive relationship between the frequency of critical jerks and collisions (Hagelin, 2012). This result was further extended to identify traffic conflicts as well (Bagdadi, 2013). The process and development for jerk analysis were broadly explained by Bagdadi and Várhelyi (2011) for the car users.However, there was no studies in the literature which used Jerk as a SSM for cyclists' and mopeds', so this research explores the application of jerk as a SSM apart from the deceleration ranges, since the shared cyclist T-Intersection have complex maneuvers and sudden (or even rapid) changes with the road user behaviour and movements which may not be captured as a safety critical instance with the deceleration as a SSM alone.

The research performed by Bagdadi (2013) developed and validated a new method for quantifying safety criticality, which involved critical jerk in identifying the safety-critical braking events during car driving events. This new method was also compared the critical jerks with one of the currently used indicators, i.e. the longitudinal acceleration for addressing the criticality in braking. These two indicators were then applied on the near-crash data from the 100-car naturalistic driving study previously carried out by the Virginia Tech Transportation Institute (VTTI), to analyse their relationship and for validation of jerk and deceleration as a safety-critical indicator. One of the main objectives of the study by Bagdadi (2013) was to validate the previously developed method (Bagdadi & Várhelyi, 2011) that uses jerk, i.e. the rate of change of acceleration, as the primary measure for detecting safety critical brake events where the driver had performed an evasive maneuver with the car drivers. Bagdadi and Várhelyi (2011) illustrated that the proposed method was sensitive enough to distinguish between brake responses in situations with different severity grades.

The results of Bagdadi (2013) proved that the critical jerk method had approximately 1.6 times higher overall success rate compared to the method based on the longitudinal acceleration measure. Besides, a positive relation was established between the road user's safety-critical braking event and crash involvement. So, clearly the critical jerk method is capable of detecting safety critical braking events and may also be used for assessing high-risk drivers. However, these values (threshold and critical jerk for indicators) vary depending on the observation site, because low average velocity (especially for cyclists) leads to low deceleration which increases the sensitivity of jerk requirements in critical situations. Also, another similar research suggested that the bottom 1% of the cumulative distribution of jerk is considered as the severe evasive action (K. Lee, 2005), for quantifying the safety critical threshold.

Even though jerk as a SSM, is used to quantify critical unsafe braking and evasive maneuvers, performs better with car users, it is not necessary that it would have a similar effect with the cyclists and mopeds who have completely different behaviour and speeds with different complex turning movements (through, slight turn or sharp turn) at the bi-directional cyclists T-Intersections, which is not the same with the cars on the motorways. Additionally, the deceleration and jerk as a SSM implicitly consider the effect of the presence of an object or an obstacle for the individual road user as well, since the road user brakes or performs an evasive action in the presence of an obstacle. So, this advantages of using these two indicators as SSMs, helps over come the limitation using TTC or PET as a SSM apart from the other advantages benefits mentioned in the literature concerning the selection SSM for this research in this section. So, in this research, the deceleration and jerk as a surrogate safety measure to analyse the safety critically of the single cyclists and mopeds at the T-Junctions and check for the differences in safety critically with and without the transverse road markings as well.

2.7 Conclusion

This literature study shows the concerns with the safety of cyclists sharing the infrastructure with the mopeds along with explaining the complexity and uncertainty in the movements at the T-intersections shared with these two road users. This literature also focuses on the need to focus on the unsignalised cyclists T-Intersection, due to the inverted priority perception of the through road users which would make them to speed more and yield less, eventually increasing the safety criticality. Despite few of the researches in the past showing that the policy nudges have an incredible impact on positively altering the human behaviour, there are not many studies focusing on the infrastructural nudging to improve the safety and influence the road user behaviour in a positive way. So, the transverse lane marking as an infrastructural nudge is chosen as a traffic calming measure, especially for the through cyclists, eventually improving the safety of all the road users.

Even though few studies have analysed the positive influence of the transverse lane marking as an infrastructural nudge for cars and motorised vehicles, the influence of transverse lane markings with the road users at the shared cyclist T-Intersection have not been explored. The nudging influences with the cyclist might vastly differ mainly because of the differences in speeds, and the cyclists encounter more uncertain situations than the car-users would face, which result in much more safety-critical instances relatively. From literature it could also be understood that, the speed behaviour and the safety critically also depends on the time of day and trip purpose. That is whether it is a peak or off-peak period or also whether it is a weekday or a weekend. So, these independent factors influence the speed behaviour and safety criticality of the road users. Finally, in order to thoroughly assess a single road user's behaviour and the safety criticality, the

SSMs like deceleration and jerk are used for the quantifying the individual safety criticality, i.e. the safety-critical braking events. It should be noted that since, the actual crash data or hospital data is not available, in this research only the correlation between declaration and jerk as a SSM is checked, and will not focus on validating these two SSMs with the actual crash data.

3 Road-User Trajectory Data

This section contains a descriptive information about the field study location, the data collection technique and its elements. Even though these are not a part of this research it gives a better understanding and structure to the reader about the road user data. It illustrates the application of video camera surveillance to capture all the road user trajectories, which is used as the initial input in the methodological framework to analyse the indicators and assess the performance of the transverse lane marking nudge.

3.1 Data Collection at the T-Intersection

This sub-section elaborates on the collected data used as well as various crucial elements of the raw data set collected from the video recordings before extracting the performance indicators. The study area is the T-intersection located on the field at Kruisstraat-tunnel and Fellenoord intersection in Eindhoven. It is a dedicated cycling infrastructure at Eindhoven, located near the railway station with a large cycle parking facility for the convenience of the cyclists to transfer to public transport. This cyclists T-Intersection is also shared with the moped users. So, the decision of the selection was based on few factors such as the bi-directionality of the cycle path which introduces more complex movements and critical maneuvers resulting in more unsafe maneuvers, heavy cycling traffic (since it is located close to a railway station) and might have a variety of trip purposes. It also had a possibility to mount or install a video camera(s) for surveillance to obtain an unobstructed observation of the all the road users using the nudge. Most of these requirements were met at the chosen study area at the T-Intersection in Eindhoven, except that there was a tunnel present as shown is figure 10, over the intersection arm of the T-Intersection.

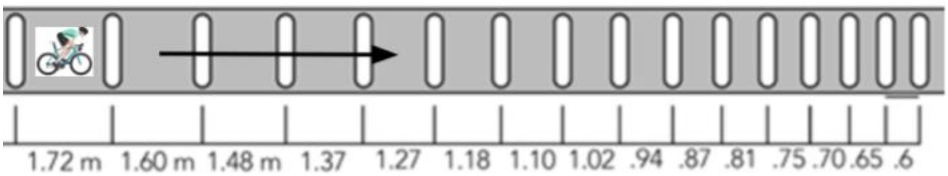

Figure 8. 2D representation of the Transverse Lane Marking Nudge

The lane marking nudge was applied on this T-intersection which is 16.06 meters in length measured from the first line to the last line, as shown in the figure 8. 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 8 along with a cyclist representing the direction of movement with respect to the lane marking nudge. The entire width of the cyclist (bi-directional) lane was 4.9m and the width of the applied transverse lane marking nudge was 2.45m (which is half the width of the bi-directional lane) as shown in figure 10. Also, in the figure 10 the distance 3.08m represents the length of the curvature from the end of the nudge (this distance is actually the length of the road where the curvature of the turn begins and connects with the other arm (tunnel) in the T-Intersection) as shown in figure 10. Finally, it should be noted that, apart from the transverse strips there is also a center line at the end of the nudge as shown in figures 9 and 10.

Figure 9. Transverse Lane marking Nudge at the T-Intersection

It has to be noted that the site selection and the video data collection, placing of the surveillance camera and implementing the transverse lane marking nudge at the T-Intersection was performed by TNO and Connections Systems (refereed as the third party is the rest of the report). Since the trajectories are needed to be highly accurate, overhead cameras are selected by the third party to capture the trajectory movements. For privacy reasons of the collected video of all the road users, the third party extracted the global coordinates of the positional data, i.e. the latitudes and longitudes, along with the time stamp for each road user with a recording speed of 25 frames/second. The trajectories for all the road users sharing the T-Intersection is the raw data set for this research, with separate distinction between the cyclists and moped users. Three cameras were used to observe the road users at the T-Intersection, the actual views from these cameras are shown in figures 11, 12 and 14 along with the position of the nudge. The nudge representation is approximate in these three figures, since the pictures were taken without the transverse lane markings. Each road user has multiple frames from the point of entry into the camera till he/she leaves the camera view. More details on the three camera views and the relevant movement or maneuver types for answering all the research questions as explained in the following paragraph.

Out of these three cameras, camera 1 (Cam 1) as shown in the figure 11, captures all road users approaching the T-Intersection only on the right lane, i.e. the lane of the application of the lane marking nudge, because the road users going in the other direction were not monitored by the third party during the video collection, covering only the upstream road users approaching the T-Intersection. Camera 2 (Cam 2) captures all the roads users crossing the junction, i.e. through traffic and turning traffic as shown in the figure 12. Finally, camera 3 (Cam 3) is clearly facing the tunnel to observe only the road users coming out from the tunnel from the right lane, as shown in figure 14).

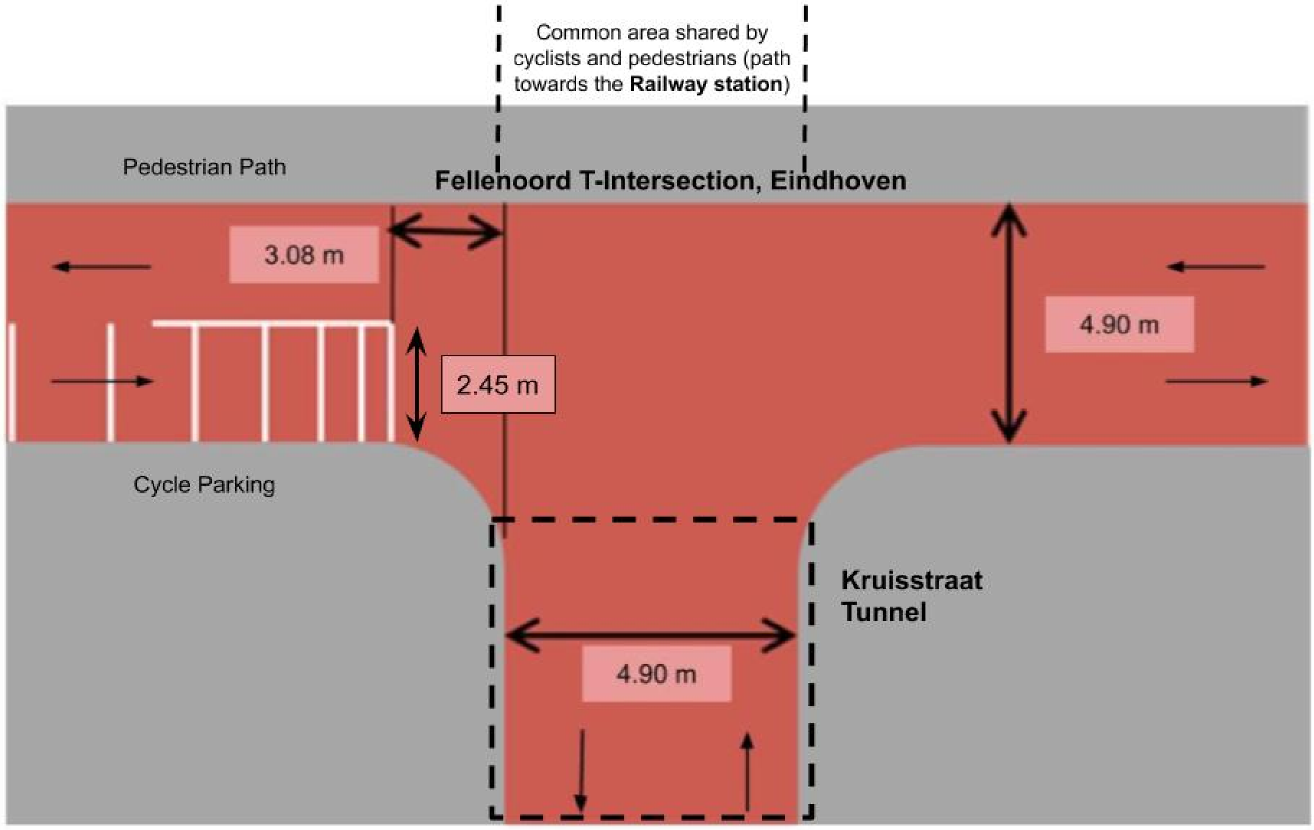

Figure 10. 2D representation of T-Intersection with the measurements

In this research the trajectories obtained only from cameras C1 and C2 will be used separately for analysis, since was a gap with the camera coverage. With respect to the nudge implemented location, Camera 1 is capturing the road users before approaching the junction till the start of the lane markings (as shown in figure 11). With the use of camera 2, all the road user behaviour at the junction (through and turning movements) and the post road user behaviours after crossing the nudge implemented location. Since, the interactions are explicitly not considered in this research, the trajectories from camera 3 will not be considered for further analysis. Here and in the rest of the report, the nudge implemented location means the 16.06m strength at the T-Intersection.

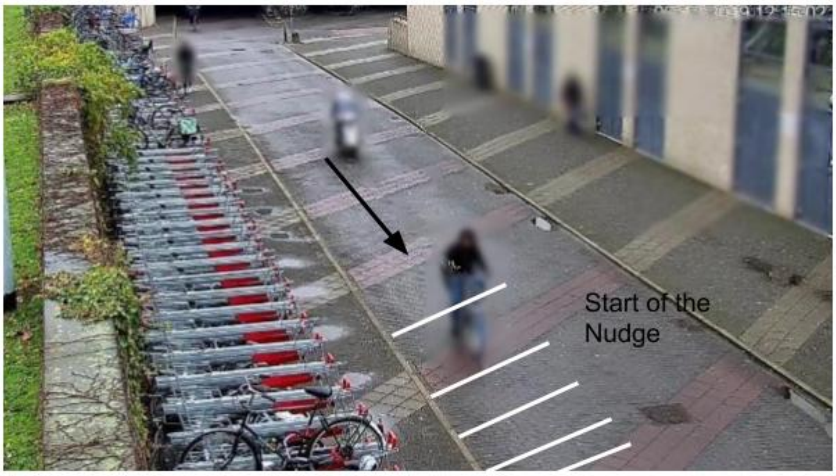

Figure 11. Actual view from Camera 1

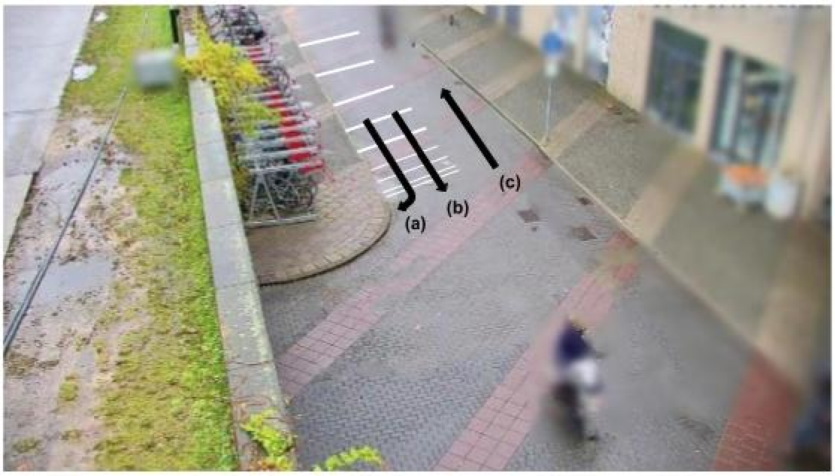

Figure 12. Actual view from Camera 2
(a)Turning (b) Through (c) Opposite-Through Movements

Figure 14. Actual view from Camera 3

Based on the actual views, an overall idea of the all camera view at the T-Intersection is shown in figure 15, approximately. There was a gap with the video surveillance coverage from camera 1 and camera 2. The gap is found to be 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 as represented with figure 15. It has to be highlighted that the camera coverage is approximated to rectangles covering the arms of the T-Intersection, just to give an idea to the reader, representing all the camera views in a single figure.

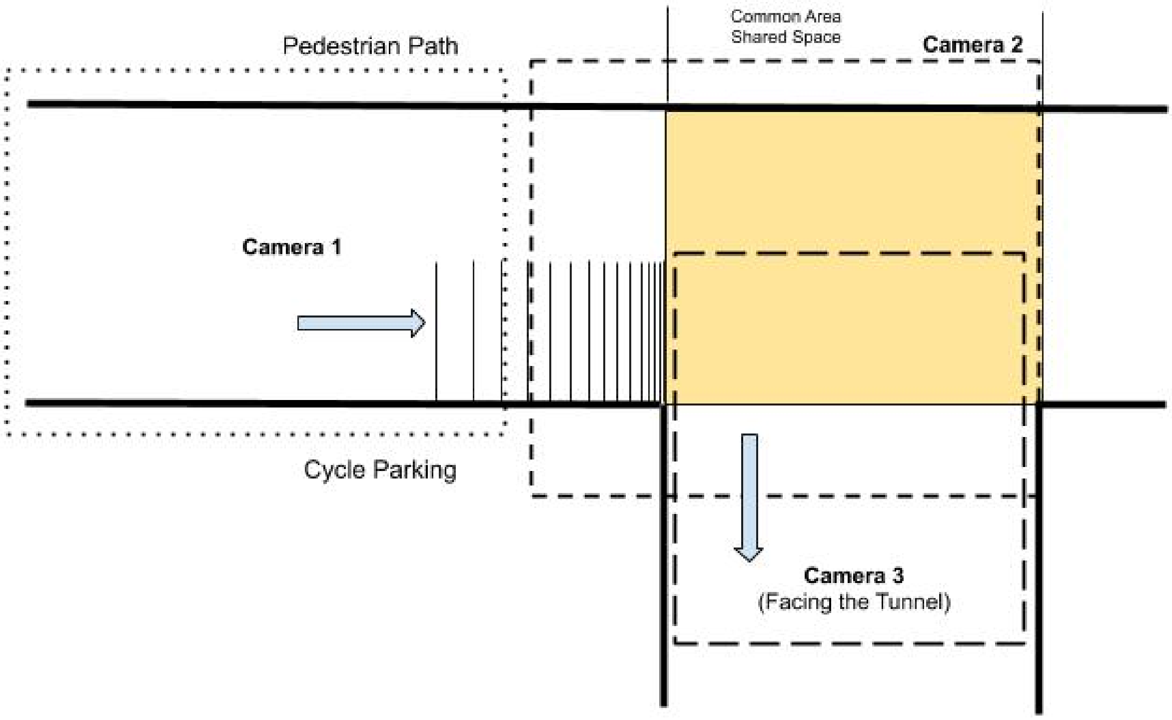

Figure 15. All the Camera view coverage at the T-Intersection
(Note: The dotted line represents the three cameras used for the data collection, with approximate rectangles to represent all of them in the same figure)

Data collection and the implementations of the transverse lane marking nudge for this study was planned and initiated in two scenarios (or phases) such a way that, the video is captured with and without the transverse lane marking nudge. During these two scenarios, camera footage is continuously being recorded from the cyclist intersection at Eindhoven. The camera data is processed by using cyclist-detection-algorithm which is elaborated in the last part of this section. It was predicted that there is a high chance to rain during the second week of December 2019. So, based on this predicted weather forecast and to collect the data during the nudge scenario without the rain, it was decided to switch the measurement period from the conventional way to collect the observations initially with the nudge in the first phase and then without the nudge in the second phase. Hence, the data is collected with the nudge applied initially, so that the application of the transverse strips is not affected with the presence of the rain, and then it was removed for the second phase of the measurement period of video recording, without the nudge scenario.

As predicted, on 8th of December (Sunday), it was raining in the morning in a few intervals from 7:00 am till afternoon and on the 9th of December (Monday MP and EP) as well. This was the period of the second phase of the field study without the lane marking nudge. Apart from this, the temperature in the nudge scenario varied from -1*C to 4*C (with fog in few time intervals) most of the time, whereas the temperature without the nudge scenario was high and varied from 7*C to 10*C throughout the data collection period with the presence of the transverse lane marking. The exact measurement period of the initial phase of the raw data with the transverse lane marking nudge was from 12:00 AM CET (Central European Time) on 1st of December 2019 for a continuous-time till 10:00 AM CET on 3rd December 2019 and then two weeks of continuous video data collected for the no nudge scenario in the second phase. The reason for the reduced measurement period (with the nudge scenario) is because after 10:00 AM CET on 3rd December, the video recording system got overheated and stopped working. After which it eventually failed to collect and store the video data. (So, it was repaired to collect the data for the no nudge scenario, as planned).

To give a context on the video extraction, the Connection Systems used the ViSense Mobility-Dynamics system that analyses the video images using automatic image recognition technique. The system uses an object detector and tracker that localizes objects in the scene and then tracks them over time until they leave the video scene. The object detection generates a location of the object by localizing its upper body (head+shoulders roughly). Connection Systems extrapolated this region to the ground plane location using an average object height assumption, which was not revealed. That point is then used as the true object position on the road (bottom centre of the extrapolated box). Since the detection algorithms and tracking algorithms are the core product and intellectual property of ViNotion, the details regarding the internal working of the code and the corresponding algorithms were not revealed.

Connection Systems also have an internal evaluation data set on which they evaluate the detection subsystem and a separate data set on which they evaluate the end-to-end performance of the tool they used. They have an end-to-end performance of around 95% accuracy (so recognizing between 95 and 105% of all objects). Since this same technique and principle (for video recording) is used by them for earlier projects, the raw positional data of the GPS coordinates and the time stamps (the road user trajectories) are accurate (as informed by the third party who collected the data) for processing the further analysis in this research. But, still data cleaning, sanity checks and pre-processing were performed presented later within this section. Apart from the position and temporal data, the raw data also contained the road user classification for cyclists and moped, with respective unique user IDs, distinguishing the two road users. Additionally, even though same road users are captured by camera 1 and 2, they had different unique use IDs in both these two cameras. The next sub-section presents the road user counts and flows with different movement types and relevant time of days based on the conclusions from the literature review. It should be noted that few of the actual trajectories are shown later in section 4.3, which have more relevance for the trajectories to be visualised.

3.2 Road User Counts and Flows

This sub-section presents the road user counts and flows of the upstream users captured using Camera 1 approaching the nudge. Additionally, it also indicates the counts and flows of all the through and turning road users using the nudges implemented location captured from Camera 2. It should be noted that the counts and flows are presented for the road users separately on Sunday, Monday MP and Monday EP only. The reason behind choosing these three time of day has already been supported with the literature in section 2.5. But, other reasons will also be presented with the generated conceptual model and data sub-groups discussed in the next section elaborating the Methodology for assessing the performance indicators.

It can be clearly seen that from all the tables from table 1 to table 6, the traffic flows on Sunday is relative less than Monday MP and EP. Another point to be highlighted, is that it can also be seen that, the traffic flows during the nudge scenario is more than the no-nudge scenario, due to varying weather conditions with slight rains which reduced the flows in the no-nudge scenario, as explained earlier in this section. It should also be highlighted that apart from the cyclists and moped, there was also a lot of pedestrian movements using the side walk. To give an overall idea there were more than 1000 pedestrian movements on all the different time of days chosen. It includes the pedestrians movements after parking the cycle in the parking facility at the T-Intersection, along with other pedestrians walking in the side walk.

Table 1

Counts and Flow of Upstream Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Road User Count		Flow (users/hr)	
			Nudge	No-Nudge	Nudge	No-Nudge
Upstream Cyclists	Sun	Before Start	2558	2349	106.6	97.9
	Mon MP	Before Start	1029	726	411.6	290.4
	Mon EP	Before Start	1601	1174	640.4	469.6

Table 2

Counts and Flow of Upstream moped users

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Road User Count		Flow (users/hr)	
			Nudge	No-Nudge	Nudge	No-Nudge
Upstream Mopeds	Sun	Before Start	359	339	15.0	14.1
	Mon MP	Before Start	196	137	78.4	54.8
	Mon EP	Before Start	138	119	55.2	47.6

Table 3

Counts and Flow of Through Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Road User Count		Flow (users/hr)	
			Nudge	No-Nudge	Nudge	No-Nudge
Through Cyclist	Sun	Middle End After	1478	1313	61.6	54.7
	Mon MP	Middle End After	738	473	295.2	189.2
	Mon EP	Middle End After	1297	914	518.8	365.6

Table 4

Counts and Flow of Through Mopeds

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Road User Count		Flow (users/hr)	
			Nudge	No-Nudge	Nudge	No-Nudge
Through Mopeds	Sun	Middle End After	214	159	8.9	6.6
	Mon MP	Middle End After	121	91	48.4	36.4
	Mon EP	Middle End After	120	92	48	36.8

Table 5

Counts and Flow of Turning Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Road User Count		Flow (users/hr)	
			Nudge	No-Nudge	Nudge	No-Nudge
Turning Cyclist	Sun	Middle End After	1080	1036	45.0	43.2
	Mon MP	Middle End After	291	253	116.4	101.2
	Mon EP	Middle End After	304	260	121.6	104.0

Table 6

Counts and Flow of Turning Mopeds

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Road User Count		Flow (users/hr)	
			Nudge	No-Nudge	Nudge	No-Nudge
Turning Mopeds	Sun	Middle End After	145	180	6.0	7.5
	Mon MP	Middle End After	75	46	30.0	18.4
	Mon EP	Middle End After	18	27	7.2	10.8

3.3 Data Pre-Processing

Assuming that the road users behaviour depends on the days of the week and in order to have a good comparative interpretation of the lane marking nudge, the second phase of the scenario without the lane marking nudge was chosen from 12:00 AM CET on 8th December 2019 for a continuous-time till 10:00 AM CET on 10th December 2019. This exactly matched the time period of the time of day of the nudge scenario during the first phase of the data collection from 12:00 AM CET (Central European Time) on 1st of December 2019 for a continuous-time till 10:00 AM CET on 3rd December 2019. So, these two scenarios are then pre-processed to understand the raw data in both these two scenarios.

So initially, the global coordinates from the raw trajectory data are converted to local coordinates for each of the road users. Then the trajectory data was plotted to have visual checks of the entire trajectories with the camera 1 and camera 2, separately. It was checked whether, all the trajectories are within the T-Intersection , whether all the trajectories are complete without any gaps or interruptions for the trajectory for both the cameras, separately. Since, all the trajectories were without discontinuities in both the cameras, it was suitable to obtain the relevant performance indicators to achieve the goals of this research.

Then the data was cleaned by detecting and removing inaccurate trajectories from the raw database. The cleaning was done by obtaining the average speed of all the road users (over their whole trajectory) and all the trajectories with and without the nudge scenarios. There were two of the trajectories had their average speed higher than 100 kmph and those trajectories were removed, since it is not possible for a cyclist or a moped user to move at 100 kmph. Also, to have sanity checks (that is the average speed for each road users was rational or not), the limits of the speeds for both cyclists and mopeds were checked. As a matter of fact, the mopeds using the shared cycle at the T-Intersection should be less than 25 kmph, but typically there will be few users who cross this speed limit of 25 kmph (and this has become controversial (Wagenbuur, 2013)). Also, sometimes the mopeds users riding in the motorways could also use the cyclists T-Intersection, so they will probably not remember the different speed limits or ignore that the speed limit in shared cyclists T-Intersection is 25 kmph. So, it is expected for the road users to have the nominal speed ranges and it is reasonable and conservative to check that the speeds of all the road users to be less than 45 kmph since that is the speed limit of mopeds in motorways. As expected the mean speeds of all road users were less than 45 kmph, and also the cyclists or mopeds with speeds were expected or logical to be greater than zero and all the average speeds for each of the trajectory was found to be positive as well. So, in this way, the data was found to be clean and also logical with respect to the average speed of each of the road user over the whole trajectories just to check its rationality. It should be highlighted that, more sanity checks were performed when calculating all the relevant performance indicators, to check and verify if they are within logical limits.

3.4 Speed and Acceleration Plots

To get an overall idea on the speeds of the road users and how the road users accelerate, few histograms are shown in this sub-section. The aim of these plots is to understand the general variations of average speed and acceleration magnitudes within a particular trajectory stretch. This also helps to identify the extreme values of the average speeds and accelerations as well to get an idea before using these attributes to proceed further in the research and data analysis.

Figure 17, shows the average speed histograms of the upstream cyclists and mopeds, along the entire stretch of trajectory captured using the camera 1. Similarly, figure 18, shows the average acceleration histograms of the upstream cyclists and mopeds, along the entire stretch of trajectory captured using the camera 1. Similar plots were visualised for all other movement types and chosen time of day, but only these two are presented to keep it concise and to provide a basic understanding of the variations in speeds and accelerations of the field study at the T-Intersection.

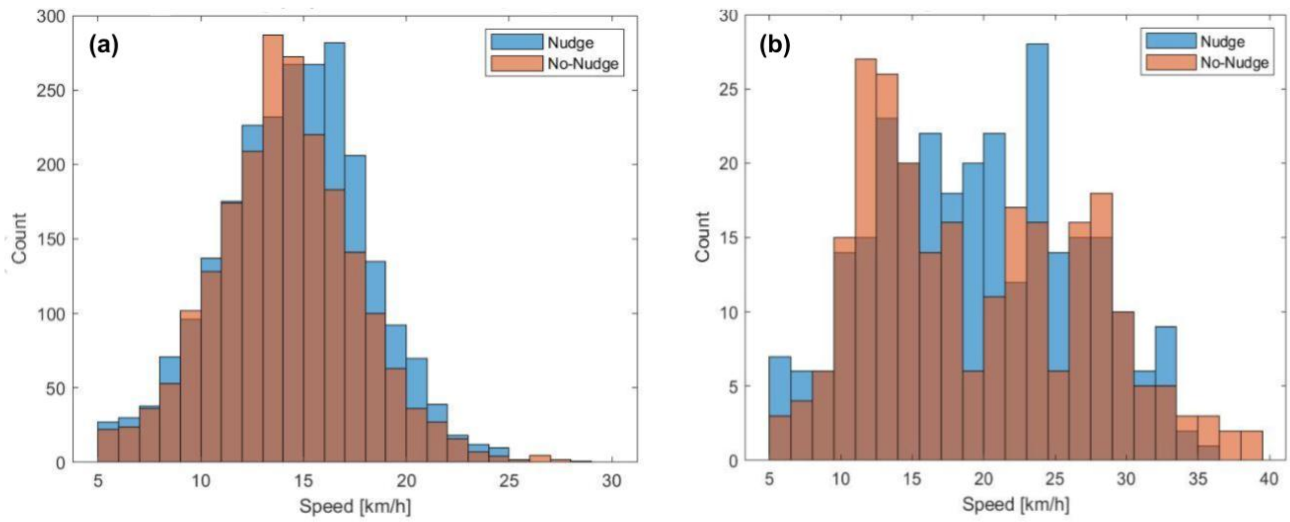

Figure 17. Average Speed Histograms of Upstream (a) Cyclists and (b) Mopeds on Sunday

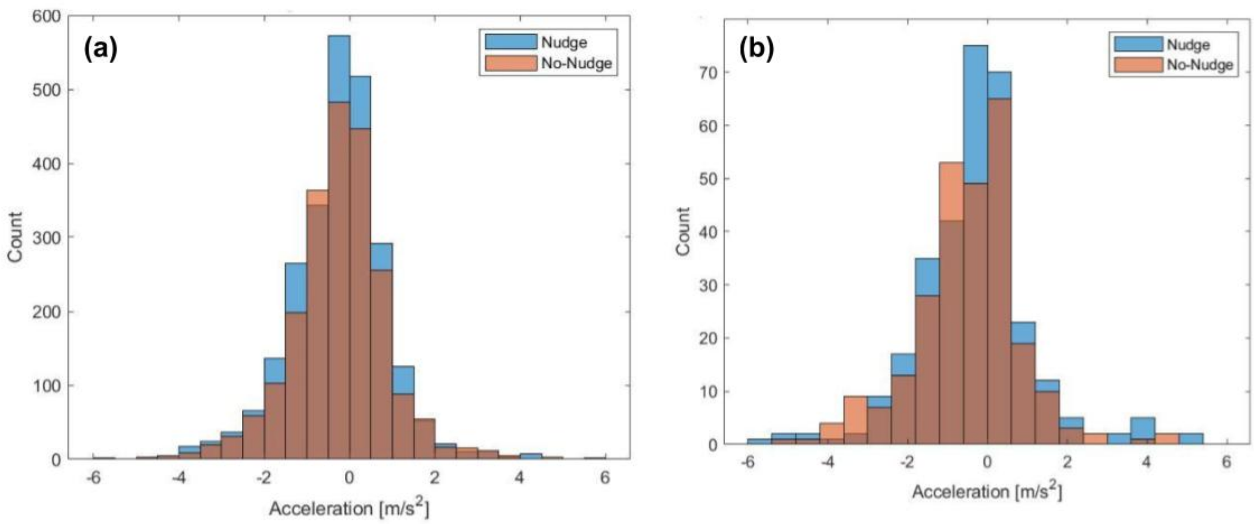

Figure 18. Average Acceleration Histograms of Upstream (a) Cyclists and (b) Mopeds on Sunday

4 Methodology-Assessing the Performance of the Nudge

After getting an overall idea about the raw data (road user trajectories), counts and flows across movement types in various time of days necessary, this sections shed light on the different steps and elements dealing with the road user trajectory data. along with an extensive methodological as shown in figure 19 is used to assess the performance of the lane marking nudges.

A conceptual model is developed in section 4.1, to capture the behavioural and safety differences with and without the lane marking nudge, with respect to the available data. Then a comprehensive list of expectations along with the list of hypotheses is formulated and based on that the data filtered/sub-grouped to answer all of them, after cleaning the data with necessary sanity checks. After filtering the data, obtaining the subgroups and choosing the various relevant cross sectional bands, all the hypotheses are tested. A “cross-sectional band” is a sectional area within a lane in which all the performance indicators are calculated based on the trajectory captured within the band, which will be elaborated later. All the calculations of the performance indicators are separately presented in section 4.6, for the road users trajectory within the chosen cross-sectional bands.

Finally, statistical tests are performed to check the normality of the mean speeds and acceleration, using Kolmogorov-Smirnov test for normality. Then independent 2-sample standard t-tests are performed to check the differences in their mean if they have a normal distribution. Mann Whitney U-tests are used to check the differences in their means if the samples are not found to be normal. Finally, a 2-sample Kolmogorov Smirnov tests are used to check the differences with the distributions of critical declaration and jerks for all the results presented in section (5)) to draw statistical inferences on the implementation of the transverse lane marking nudges. So, all the following subsections will elaborately explain each action step and the corresponding outcome from the framework represented in figure 19, covering all the necessary elements and its needs in a structured way. All the outputs from the big rectangular box is used for interpretation on the effects of the transverse lane marking nudges.

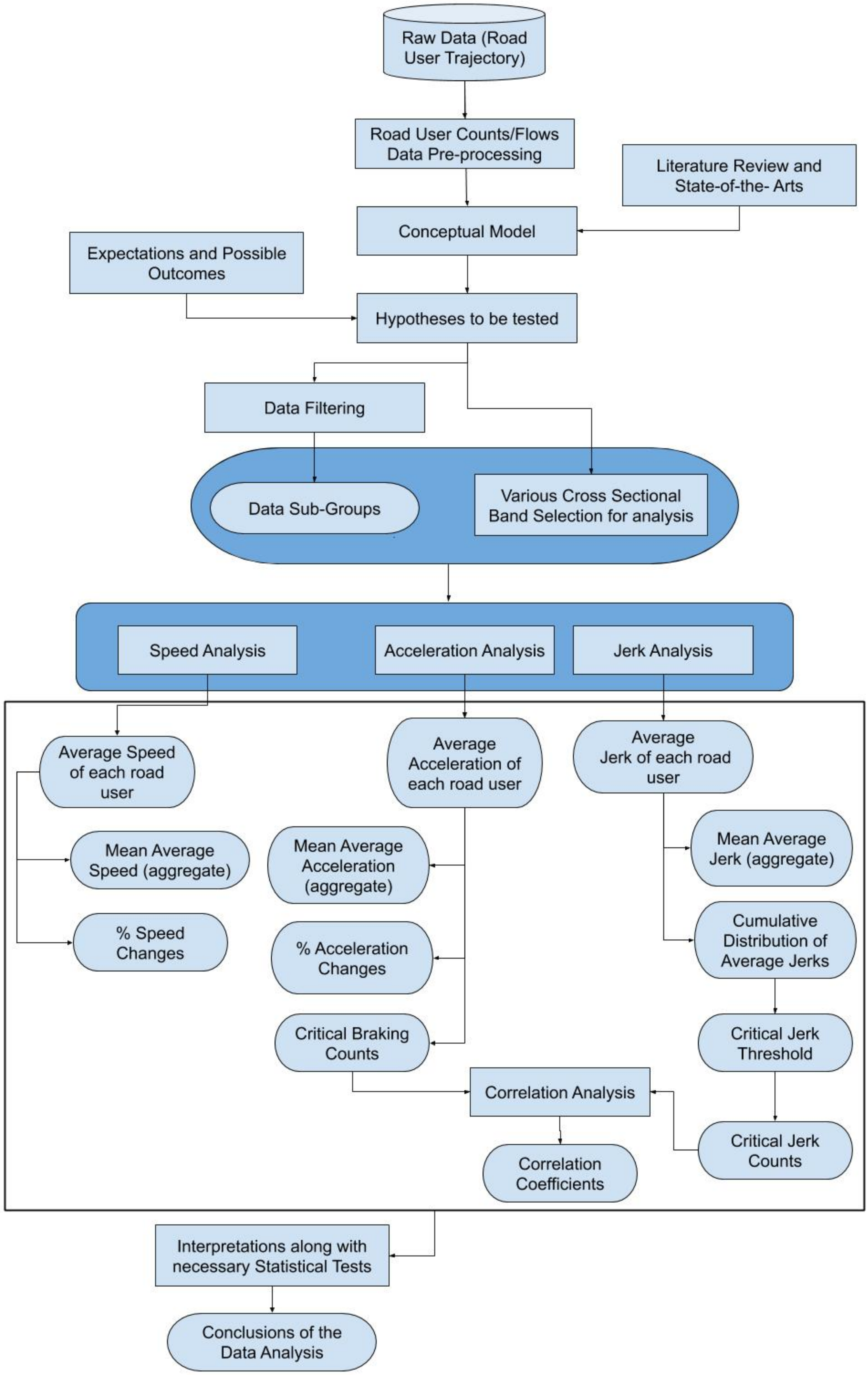

Figure 19. Methodological for Data Analysis
(**Rectangular Box**: Action Steps & **Rectangular Capsules**: Output of an Action Step)

4.1 Conceptual Model of Performance Indicators

With the support of the literature review from section 2, this section elaborates on the relationship (using the individual and aggregate attributes) necessary to obtain the performance indicators and help to answer the main and sub-research questions related to understanding the speed and safety of the road users with and without the transverse lane marking nudge. The figure 21 broadly depicts how certain characteristics (or factors) of the Road Infrastructure (the presence and the position of transverse lane marking nudge at the T-Intersection in this research) influences the speed and safety of the individual road users (considering cyclists and mopeds) along with the indicators necessary to quantify them. It also helps to understand how the indicators influenced by the other factors needed for obtaining them. The details about the arrows and the different types of lines are explained at the end of the following paragraph.

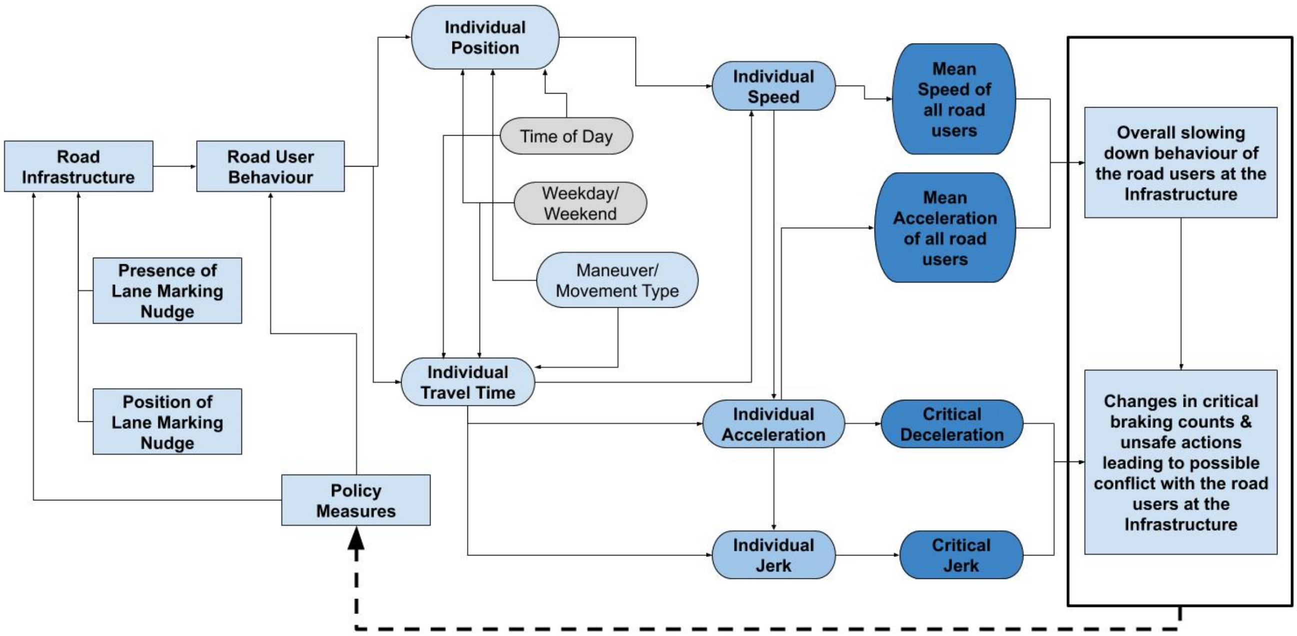

Figure 21. Conceptual Model for assessing the Performance of the Nudge
(**Note 1** : The solid line represents the direct relation and dependence between all the elements and the dotted lines represent the feedback loop based on the outputs, to draft the policy measures.
Note 2: Grey cells are independent variables and the Dark Blue cells are the performance indicators)

Usually, an "attributes" provides a piece of information which determines the properties of an object under study. Similarly, various attributes are needed for extracting the performance indicators of the road users involved in this research and to quantify the behaviour and safety criticality at the road infrastructure used by them. The individual attributes (position, travel time, speed, acceleration and jerk) and aggregate attributes of all the road users (mean speed and mean acceleration) are elaborated more in detail with figure 21.

As shown in figure 21, the road users speed and safety are influenced by various attributes and elements (like the time of day, movement or maneuver type). It is obvious that the individual attributes such as the position and travel time for each road user are used for obtaining the speed of the corresponding road user. The elements like time of day (like whether it is 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 21, 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 (highlighted with grey cell in the figure 21). The importance of these variables is already indicated in the literature studies in section 2.5.

As depicted in figure 21, the mean of the velocities and accelerations (aggregate attributes) of the road users serve as the indicators (highlighted with dark blue cells) to check the slowing down behaviour at a particular road infrastructure. The acceleration and the jerk of the individual road users are used to obtain the critical deceleration counts and the critical jerk counts of unsafe (safety critical) actions performed by the road user using appropriate thresholds, which describes the safety critical instances. As indicated in the literature dedicated for the SSMs in the section 2.6, the critical deceleration counts will help identify the unsafe braking situation encountered by a particular road user and similarly the critical jerk also assists to identify if a road user encounters a safety critical situation. So, the critical deceleration counts and critical jerk counts (highlighted with dark blue cells, in figure 21) are the two safety performance indicators used to quantify the safety criticality of the road users using a particular infrastructure (T-Intersection in this research).

A feedback loop is also used based on the output quantifying the speed and safety effects of the road users on the necessity to draft the policy measures (whether to use/implement the transverse lane marking nudge in the future or not, what additional improvements needed for the infrastructure, which is discussed more in the policy contribution section 6.5) and road infrastructure changes with the use of the transverse lane marking nudge. Finally, the two elements within the dotted rectangle of figure 21 (end of the right side), along with the two surrogate safety measure indicators within the green box which are all needed to achieve the research objectives related to safety performance indicators of this research and specifically concerning the data obtained from the field study.

4.2 Expectations and Hypotheses to be tested

It is important to understand what changes are expected from the lane marking nudge and at what locations with respect to the lane marking are these changes or influences are expected. This will give a clear idea on the list of hypotheses to be tested and the various needs for filtering and grouping the data, accordingly. So, this sub-section elaborates in detail, what might be the expected behavioural and safety outcomes with respect to the application of the transverse lane marking nudge.

It is important for the reader to note that, in this section, initially it is focused to have a generic expectations with time of day, the road user type and movement types in sections 4.2.1, 4.2.2

and 4.2.3, respectively. Finally, in section 4.2.4, all the expectation are liked with the possible outcomes within different parts of the nudge stretch to also come up with the corresponding hypotheses to be tested.

4.2.1 Expectations with the Time of Day

Clearly, the traffic flows on the weekend is less compared to that of a weekday (with the reason being the necessity of work trips). The road user counts and the corresponding flows on Sunday, Monday MP and Monday EP are tabulated in section 3.2 for all the cases. So, with this field study along with the support of literature presented in section 2.5, high flows might result in congestion and thereby decreasing the overall speed of the road users, with or without the nudge. So, it can also be expected that with the relatively less flow on weekends (as presented in section 3.2), 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. This can be distinguished by separately analysing the effect of the nudge on a weekend and a weekday.

Similarly, the flow changes at the T-Intersection would also result in different safety criticality changes with and without the nudge. A general expectation is that, with high flows, there is more congestion, which would result in a less reduction of these braking instance with the nudge, because the congestion might be already responsible for slowing down and braking in both the scenarios on a weekday, which might make the nudge a little less useful. On the other hand, with lower flows (less congestion), resulting in a high speed and less braking instances in both scenarios. But the presence of the nudge with less flow, might make the road users slow down more (creating a significant speeding illusion) and create more critical instances with the lane markings which would make them brake.

With a similar line of reasoning and the use of the literature mentioned in section 2.5, there could a different influence on the lane markings for the road users with the nudge implementation in the morning peak and evening peak within a weekday. This is due to the variations with the home to work trips (Morning peak) and the work to home trips to understand if the nudge has similar effects based on the trip purpose (i.e. work-based or home-based trips). Here, the assumption is that the road users on the Monday morning peak are heading to work from home and the road users on the Monday evening peak is returning home from work. It is expected that the road users in the morning peak might have a necessity to catch the train or reach to the workplace in time (the location of the railway station is indicated in the figure 10). So, the road users might sub-consciously (think about the work or to catch the train in time or reach the workplace in time) speed-up in the morning peak even with the influence of nudge compared to the road users in the evening peak, where they are a little more relaxed or tired after work. But on the other hand, it is also possible that the road users in the morning peak if going fast, would bring a better illusion with the transverse lane marking nudges and would make them slow down with the presence of the nudge. At the same time it is also possible that, with the work trip or catching the train on time in the morning peak, the road users go at a high speed which would help to create the intended speeding illusion.

But one could also argue that, with the road users in the evening peak with the tiredness due to the whole workday, they might still miss the cognitive change in behaviours due to the presence of the nudge, even though they are going fast. With the same line of reasoning, it could also be expected that with the morning peak there could be high critical braking instances or safety-critical events compared to the evening peak. Because of the necessity to be on time or catch the train, the road users might (approaching at high speed) also encounter more braking or speed changes in the morning peak, which is not the same in the evening peak for reaching home. So, all these reasons and expectations show that the differences in the performance indicators would be probably different with Sunday, Monday MP and Monday EP and will be tested separately. It should be highlighted to the reader that, the off-peak road users on Monday are not considered since they are less safety-critical compared to the road users in the peak hour (with a high traffic density and flow) and at the same time since the whole of Sunday could be considered as off-peak including the leisure trips like groceries shopping or visiting a friend.

4.2.2 Expectations with the road user type

A generic and an overall expectation is, with different, the influence of nudge will vary. This is clearly, due to the fact the speeding illusion directly depends on the sped at which the lane marking nudges are approached by the road users (which was also explained in detail with the trip purpose). So, it is also obvious to expect a variation in the behaviour and safety with and without the lane marking nudge for the different road users (i.e cyclists and mopeds). 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, the speed changes (of the nudge scenario with respect to the no-nudge scenario) with the cyclists and mopeds are also expected to have different effects in the presence of the nudge, due to the expected differences in their mean speeds.

Considering the high speed of mopeds users, it is expected to have high safety-critical counts compared to cyclists. This does not ignore the fact that the heterogeneity (with two road users sharing the T-Intersection with different speeds) might also be the reason for safety critical situations, but it is assumed to be same with and without the nudge scenario. Given the fact that it is easier to speed up and accelerate by the mopeds, they might result with the high increase in safety-critical instance compared to that of the cyclists who obviously takes slightly more time to speed up or accelerate after crossing the nudge implemented location.

4.2.3 Expectations with the movement types

There are different expectation based on whether the cyclists passing the nudge implemented location is going straight or taking a right turn into the tunnel. The key expectations are that the through road users 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 variations and reduced critical braking instances with the presence of the nudge. On the other hand, the turning cyclists may not have relatively high speeds changes with the nudge scenario compared to the through cyclists, they might not have any significant difference with and without the nudge. Also, the turning road users are anyway going to slow down expecting an uncertain movement at the junction. Also, due to the tunnel, there is a lack of visibility for the turning cyclists, which would eventually make them slow with and without the presence of the lane marking nudge resulting with no differences with the means speeds or acceleration for the turning road users. In a similar way, 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.

On the other hand it can also be argued that through cyclists might also not have a significant change with the speed due to the fact that they might still have a stronger false perception of the right of way as well (but with the dutch regulations and in this field study, the road users coming from the right have a higher priority at intersections). This is one of the reasons for the necessity of trying to achieve a speed reduction with the use of the nudge. But this false perception (presented in the literature in section 2.2) might still not be able to overcome the speeding illusion intended to be created by the lane marking nudge.

4.2.4 Expectations within the Nudge Stretch

It is important to highlight to the reader that, in this sub-section, the various expectations within the different sections of the nudge implemented location will also be linked with the time of day, road users and the movement types to give a comprehensive idea of all the list of hypothesis listed following this section (connecting the previous three sub-sections). The expectations in this sub-section are discussed for five sectional areas to be checked for the differences in behaviour and safety, in relation to the other generic expectations explained earlier in this section. Also, the "percentage changes" mentioned in this sub-section means the increase or decrease of the performance indicator of the nudge scenario with respect to the no-nudge scenario. These percentage changes gives the reader a quick idea of whether the absolute values of the performance indicators increase or decrease in the nudge scenario with respect to the no-nudge scenario. The five sectional areas are, well 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.

It is logical to expect that there will not be any difference with the road users well before the nudge implemented location. This is because, they would have not reached the transverse lane marking lines. But there are chances that the mopeds (which have relatively high speeds compared to cyclists) might try to be more cautious and reduce the speeds after noticing the lane markings, since in general they are expected to be more cautious, especially when using a shared cycle infrastructure, where cyclist are more vulnerable. But it can also be argued that, the mopeds might be surprised to suddenly see some lines which would make them curious to reach the location to see what it is. This reason could actually make them to have high mean speeds even before reaching the nudge implemented location, with the nudge scenario. Similarly, cyclists may not have differences with the sudden speed changes in both scenarios, but the mopeds might brake due to the fact that they are expected to be cautious. Based of these expectations the hypotheses which will be tested are:

- Mean Speeds of the cyclists with and without the application of the traverse lane marking nudge is the same before reaching the nudge implemented location. This hypothesis will also be tested with the mean accelerations, critical deceleration counts and critical jerk counts, with the expectations of all these indicators to be same as well.

- Mean Speeds of the mopeds are less with the application of the traverse lane marking nudge before reaching the nudge implemented location. This hypothesis will also be tested with the mean accelerations, critical deceleration counts and critical jerk counts, with the expectations that the moped could decelerate more, which might eventually result in high safety critical instances in the presence of the nudge.

Considering the starting sectional area of the nudge implemented location, the cyclists still might not have differences with the performance indicators. This is because, with just a few lines of lane markings (will mention the exact numbers with the section elaborating the data sub-groups and the chosen cross-sectional areas for testing all the hypotheses) may not be enough to create a speeding illusion for the cyclists. But this may not be the same case with the moped when entering the lane marking nudge. With mopeds, the mean accelerations are expected to be lower at the start, because the lane markings might be seen as an obstacle on the lane or the moped users might be surprised as well. This might make the moped users to brake, eventually raising the safety critical instances with the nudge scenario. So, these based on these expectations the hypotheses which will be tested are:

- Mean Speeds of the cyclists with and without the application of the traverse lane marking nudge is the same at the start of the nudge implemented location. This hypothesis will also be tested with the mean accelerations, critical deceleration counts and critical jerk counts, with the expectations of all these indicators to be same as well.

- Mean Accelerations of the mopeds are less with the application of the traverse lane marking nudge at the start of the nudge implemented location. This hypothesis will also be tested with the mean speeds, critical deceleration counts and critical jerk counts, with the expectations that the moped could slow down or decelerate more, eventually have a high safety critical instances in the presence of the nudge.

Unlike the start of the cross-sectional nudge, the cyclists might have differences with the performance indicators at the middle sectional area. It is expected that the cyclists would have got the illusion of speeding up (more with the through cyclists than the turning cyclists as explained before with the expectations of the various movement types). The same line of expectations also goes for the moped users going through the middle of the nudge stretch. Because of the speeding illusion, both the road users are expected to slow down and also have differences in their speed changes. There are high chances that both the cyclists and moped users might brake, eventually increasing the number of safety critical instances with the nudge scenario at the middle of the nudge implemented location. So, these expectations rises the following hypothesis to be tested:

- Mean Accelerations of the cyclists are less with the application of the transverse lane marking nudge at the middle of the nudge implemented location. This hypothesis will also be tested with the mean speeds, critical deceleration counts and critical jerk counts, with the expectations of all these indicators to be high with the nudge scenario as well.

- Mean Accelerations of the mopeds are less with the application of the transverse lane marking nudge at the middle of the nudge implemented location. This hypothesis will also be tested with the mean speeds, critical deceleration counts and critical jerk counts, with the expectations of all these indicators to be different (high) as well. Also, the magnitude of percentage changes to be almost similar for both the road users.

Both of these above mentioned hypotheses will also be tested with the mean speeds, critical deceleration counts and critical jerk counts, with the expectations that the road users would have reduced mean speeds along with decelerating, eventually have a high safety critical instances in the presence of the nudge. But it could also be argued that, at the middle of the nudge implemented location, the speeds of the road users (especially cyclists) might also not be too high to achieve the illusion of speeding up. Since they are approaching the T-Intersection and that could also be a reason for slowing down. And especially the tuning traffic (right turning traffic into the tunnel), would already approach the T-intersection at lower seed compared to the through cyclists. So, this brings the necessity of all the hypotheses to be tested for difference in the performance indicators with the through cyclists and the turning cyclists.

When the road users reach the end of the nudge implemented location, they are again expected to have reduced mean speeds with the nudge implemented location. Since, when reaching the end of the nudge implemented location, there are high chances for the speed illusion created compared to the middle sectional area. So, similar hypotheses could be expected, but the percentage changes with the nudge and the nudge scenario would be high with the road users at the end of the cross sectional area. But the cyclists and mopeds are tested separately because they have different braking capacity, meaning that the moped can brake easily and quickly compared to the cyclists. So, these expectations give rise to the following hypothesis to be tested:

- Mean Accelerations of the cyclists are less with the application of the transverse lane marking nudge at the end of the nudge implemented location. This hypothesis will also be tested with the mean speeds, critical deceleration counts and critical jerk counts, with the expectations of all these indicators to be different (high) as well.

- Mean Accelerations of the mopeds are less with the application of the transverse lane marking nudge at the end of the nudge implemented location. This hypothesis will also be tested with the mean speeds, critical deceleration counts and critical jerk counts, with the expectations of all these indicators to be high in the nudge scenario as well. Also, the magnitude of percentage changes of mopeds to be high compared to the percentage changes with the cyclists.

But it should also be kept in mind that, if in case the road user slow down (reduce their speeds or decelerate) at the middle area, to compensate the lost time, the road users might accelerate or speed up while crossing the end of the nudge implemented location. So, this will make the road users to have high mean speeds and reduced critical deceleration and critical jerk counts in the presence of the lane marking at the end of the nudge implemented location.

Finally, once the road users cross the lane marking nudge, it is reasonable to expect that there will not be any changes in their mean speeds or mean accelerations, since the road users will not have any sort of speeding illusion from the lane marking nudges. This is also a similar line of reasoning compared to the road users before approaching the lane marking implemented location. So, the hypotheses based on these expectations are:

- Mean Accelerations of the cyclists with and without the application of the transverse lane marking nudge is same after crossing the nudge implemented location. This hypothesis will also be tested with the mean speeds, critical deceleration counts and critical jerk counts, with the expectations of all these indicators to be same as well.
- Mean Accelerations of the mopeds with and without the application of the transverse lane marking nudge is same after crossing the nudge implemented location. This hypothesis will also be tested with the mean speeds, critical deceleration counts and critical jerk counts, with the expectations of all these indicators to be same as well. Also, the magnitude of percentage changes is expected to be similar for both the road users.

But again, it could also be argued that if in case there is a speed reduction and deceleration observed at the end of the nudge implemented location with the presence of the lane markings, the road users in the nudge scenario will try to speed up or accelerate to compensate the time lost at the end of the lane markings. So, this could be a reason to believe that there are also changes for bot these road users to speed up and accelerate after crossing the nudge implemented location in the presence of the transverse lane markings.

4.2.5 Expectations with the road users not using the nudge

Obviously, there are few road users who have no direct or indirect effect due to the implementation of the transverse lane marking nudges, like the road users using the adjacent lane, next to the lane where the nudge is implemented. These road users move in the opposite direction relative to the upstream and through road users. These road users are termed as the Control Group road users. So, apart from the through and turning cyclists using the nudge implemented lane, it is also 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, these road users 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. That is, it is expected that their speeds, accelerations and safety criticality, do not differ with and without the presence of the transverse lane marking nudges. The purpose of the control group road users is that, all the differences found with the road users using the nudge can be strengthened further. So, a separate hypothesis used for cyclists and mopeds to test this expectation with the control group road users.

- Mean Speeds of the road users with and without the application of the transverse lane marking nudge is same at the middle of the nudge implemented location in the adjacent lane, moving in the opposite direction relative to the through road users. This hypothesis will also be tested with the mean speeds, critical deceleration counts and critical jerk counts, with the expectations of all these indicators to be same as well.

So, to conclude this section, the elaborate set of expectation and assumptions in section 4.2, all the corresponding hypotheses will be tested to check how the cyclists and mopeds (together called as road users if necessary) are influenced with the application of the Transverse Lane marking Nudge in order to answer the relevant main and sub-research questions. Since the transverse lane marking nudge is very recently started to be researched on cyclists, it is important to know that, all these hypotheses are framed to give a broad picture possible on the influence of transverse lane marking nudge. So, the reader should also be highlighted that, in order to keep the list of hypotheses concise (and to avoid difficulties for the reader), all the above mentioned hypothesis is separately tested on Sunday, Monday MP and Monday EP explicitly for the upstream road users approaching the nudge, through (only) and turning (only) road user movements, based on the extensive expectation and conclusions of the descriptive literature review.

4.3 Data Sub-Groups

This subsection illustrates the necessity of sub-grouping the full data set in order to test all the expectations and hypotheses mentioned in the previous section and eventually answer all the research questions listed in section 1.2 listing the main and sub-research questions. As depicted in figure 23, the basis of the data sub-groups for answering the hypothesises is based on:

- Presence of the Nudge (2 cases)
- Time of day (3 cases)
- Road user type (2 cases)
- Movement/Maneuver type (4)

Each of these four criteria has multiple cases as shown in the in figure 23 just for the purpose of a concise representation of different cases and criteria for sub-grouping the data. So, each sub-group (or a case) always has one of the cases from all 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 with and without the nudge scenarios. Individual analysing each case (with and without the nudge). 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 in section 2.6. So, the individual road user also brakes or does sudden critical maneuver because of the interactions which are captured using the deceleration and jerk as a SSM.

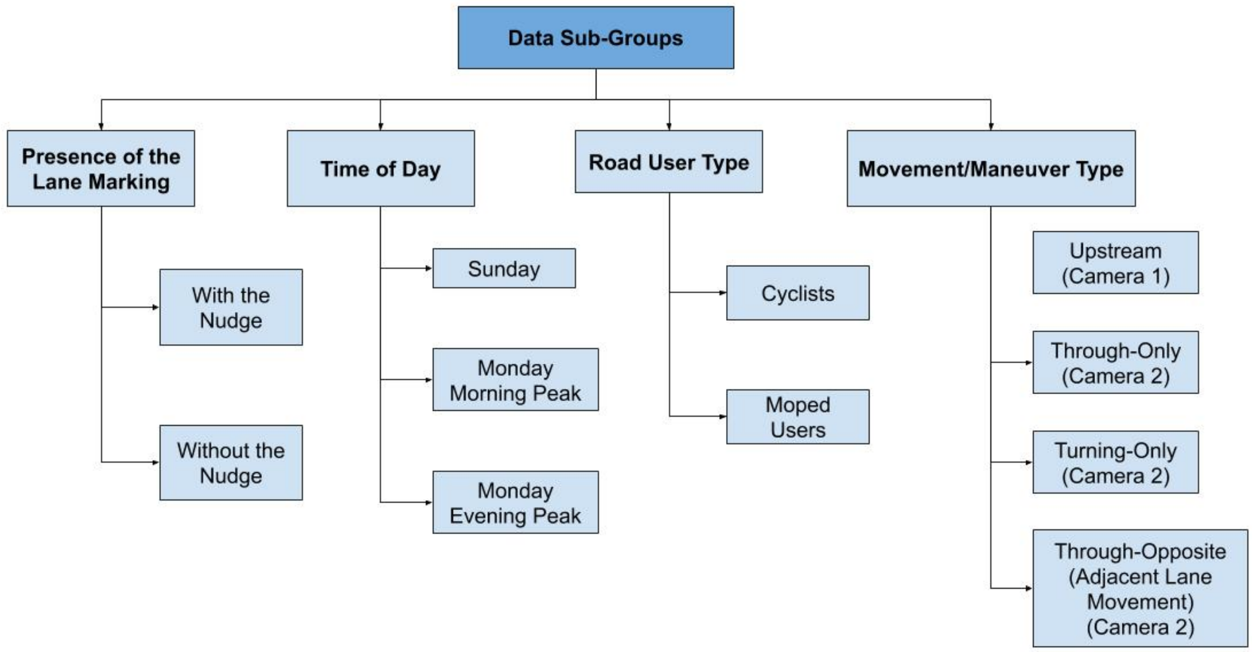

Figure 23. Basis for all the Data Sub-groups

All the various sub-groups are categorised in figure 23 to give a concise idea for the reader. So, based on the necessity to test the various hypothesis listed from the expectations and the need to distinguish between the through and turning cyclists to answer the research question the data is sub-grouped into 4 different movement types and the road user movement opposite the direction of the through road users (control group) approaching the nudge in the adjacent lane as represented in the figure 23 earlier and separately showing the different combinations depicted in figures 24 and 27. The various specific cases are also presented in table 7.

Table 7

All the 48 specific cases

Different Specific Cases for Analysis			
Nudge Scenario		No- Nudge Scenario	
Upstream Cyclists Movement on Sunday	Upstream Mopeds Movement on Sunday	Upstream Cyclists Movement on Sunday	Upstream Mopeds Movement on Sunday
Through Cyclists Movement on Sunday	Through Mopeds Movement on Sunday	Through Cyclists Movement on Sunday	Through Mopeds Movement on Sunday
Turning Cyclists Movement on Sunday	Turning Mopeds Movement on Sunday	Turning Cyclists Movement on Sunday	Turning Mopeds Movement on Sunday
Control Group Cyclists Movement on Sunday	Control Group Mopeds Movement on Sunday	Control Group Cyclists Movement on Sunday	Control Group Mopeds Movement on Sunday
Upstream Cyclists Movement on Monday MP	Upstream Mopeds Movement on Monday MP	Upstream Cyclists Movement on Monday MP	Upstream Mopeds Movement on Monday MP
Through Cyclists Movement on Monday MP	Through Mopeds Movement on Monday MP	Through Cyclists Movement on Monday MP	Through Mopeds Movement on Monday MP
Turning Cyclists Movement on Monday MP	Turning Mopeds Movement on Monday MP	Turning Cyclists Movement on Monday MP	Turning Mopeds Movement on Monday MP
Control Group Cyclists Movement on Monday MP	Control Group Mopeds Movement on Monday MP	Control Group Cyclists Movement on Monday MP	Control Group Mopeds Movement on Monday MP
Upstream Cyclists Movement on Monday EP	Upstream Mopeds Movement on Monday EP	Upstream Cyclists Movement on Monday EP	Upstream Mopeds Movement on Monday EP
Through Cyclists Movement on Monday EP	Through Mopeds Movement on Monday EP	Through Cyclists Movement on Monday EP	Through Mopeds Movement on Monday EP
Turning Cyclists Movement on Monday EP	Turning Mopeds Movement on Monday EP	Turning Cyclists Movement on Monday EP	Turning Mopeds Movement on Monday EP
Control Group Cyclists Movement on Monday EP	Control Group Mopeds Movement on Monday EP	Control Group Cyclists Movement on Monday EP	Control Group Mopeds Movement on Monday EP

All of four movement types different cases will be explained further on how exactly the sub-grouping was specifically performed with each necessary maneuver from the data set. Sub-Grouping the data concerning the specific movement type is done in 4 steps as listed below:

- Plotting all the trajectories.
- Visualising the starting and ending regions (plots with coordinates).
- Plotting the coordinate polygons (boxes) for the trajectories to start, manually from the visualisation.
- Plot the coordinate polygons (boxes) for the trajectories to terminate, manually from the visualisation.

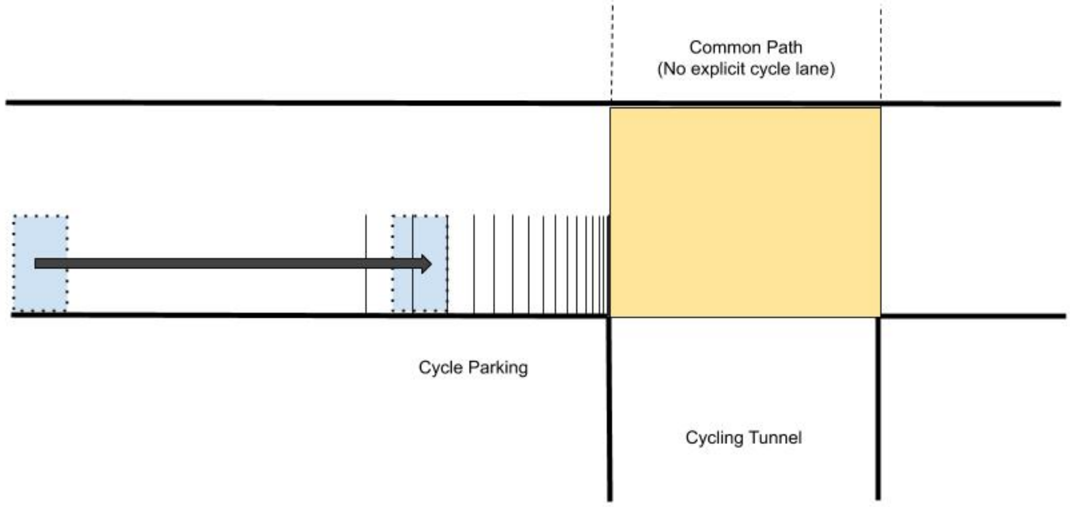

Figure 24. Upstream road users approaching the Intersection (from Camera 1)
(**Note**: The dotted boxes are the coordinate polygons)

So, the trajectories were plotted using their positional and temporal data for visualisation for camera 1 and camera 2 separately. The purpose of visualisation is also to manually fix the position of the coordinate polygon boxes to extract the full trajectory movements. So, using the outputs of the plot, the starting and the ending of the trajectories are inspected. Then a coordinate polygon in the form of a rectangular box is manually fixed in order to extract the necessary full trajectory movement types or maneuvers needed (i.e. from one polygon box to another polygon box within the camera view). Once the polygon boxes are manually fixed, an automated code is used to extract only the trajectories starting and ending within the two polygon boxes. So, the different trajectory movement types were automatically extracted by developing a small code in Python (open source software, version 3.7). Basically, this code captures only the trajectories starting from one polygon box and ending in the other polygon box. So, for the code, the coordinates of the manually plotted polygon boxes are the input (four points, since it is in the form of a rectangle). So, two sets of four coordinates are fed into the code (one set for the trajectory to originate and another set of coordinates for the trajectories to terminate) along with the full trajectory data including all the trajectories, separately with the without the nudge. So, the output would be only the specific movement types of all the trajectories moving from one polygon box to the other. All the other road user trajectories that are not relevant are filtered out.

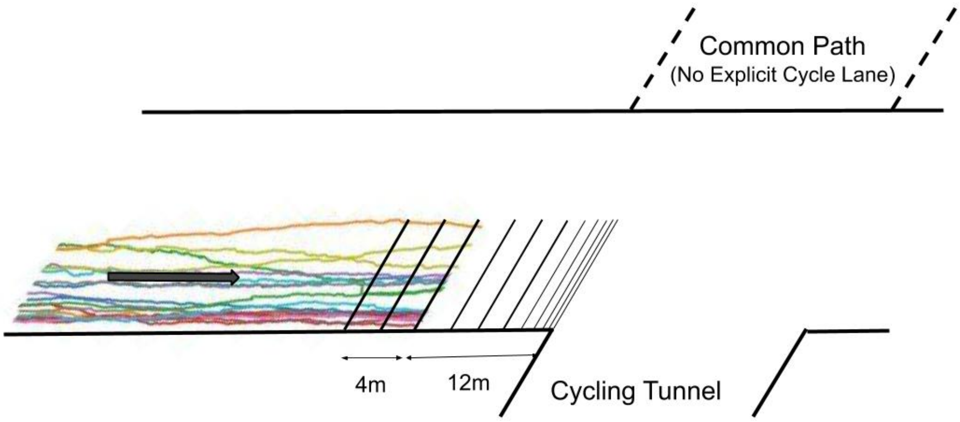

Figure 26. Twenty Upstream Cyclist Trajectories approaching the Intersection (from Camera 1)

All figures shown below have the coordinate boxes from which the trajectories originate (start) and terminate (end) after inspecting their respective raw trajectories from the camera 1 and camera 2 alone used for the video surveillance, Which also filters out all the other movement types which are not necessary. As indicated with the data description section showing the camera view, camera 1 captures only the upstream road users till the start of the nudge using the polygon boxes as shown in figure 24. For better clarity and understanding for the reader, the actual trajectories of 20 upstream cyclists are shown in the figure 26. In a similar way, the trajectories from camera 2, with a clear distinction between through and turning road users from the middle of the nudge implemented location till the road users cross the lane marking captured by the polygon boxes shown in figure 27(a) and 27(b), respectively. It should be noted that the through road user trajectories end just before the common junction area at the T-Intersection, due to the end of the camera 2 coverage. This is the reason for placing the various coordinate polygons, according to the beginning and the ending of the camera 2 coverage.

Finally, the polygon boxes depicted in the figure 27(c) captures all the road users using the adjacent lane with respect to the nudge implemented location in the opposite direction. This control group road users are assumed to have no influence with the presence of the lane marking nudge in the adjacent lane. So, the main aim of the control group road users is to statistically check the expectation that the performance indicators do not significantly differ with and without the nudge.

All the coordinate boxes are 2.45m in length (width of the lane in one direction) in which the trajectories are originating (starting) or terminating (ending) as shown in figures 24 and 27 as well, which is represented in the form of dotted rectangular boxes. These coordinate polygons ensure that all the trajectories are covered for the through and the turning traffic, mainly with respect to the trajectories from camera 2. An additional advantage of the coordinate polygons are it also implicitly considers whether all trajectories originate and terminate and one of them does not lie anywhere else (for instance the starting from the center of the cycle parking area) in the observed location at the T-Intersection. So, the coordinate boxes, help filter out all the trajectories originating from the parking facility. Additionally, with this process, the trajectory which terminates at the parking facility and the pedestrian movements are also filtered out. But it should be reminded to the reader that, the critical braking and evasive maneuvers of the individual road users due to the influence road users going to parking their cycle or road users taking out their cycle from the parking facility or the pedestrian movement is always implicitly taken into account in both the scenarios.

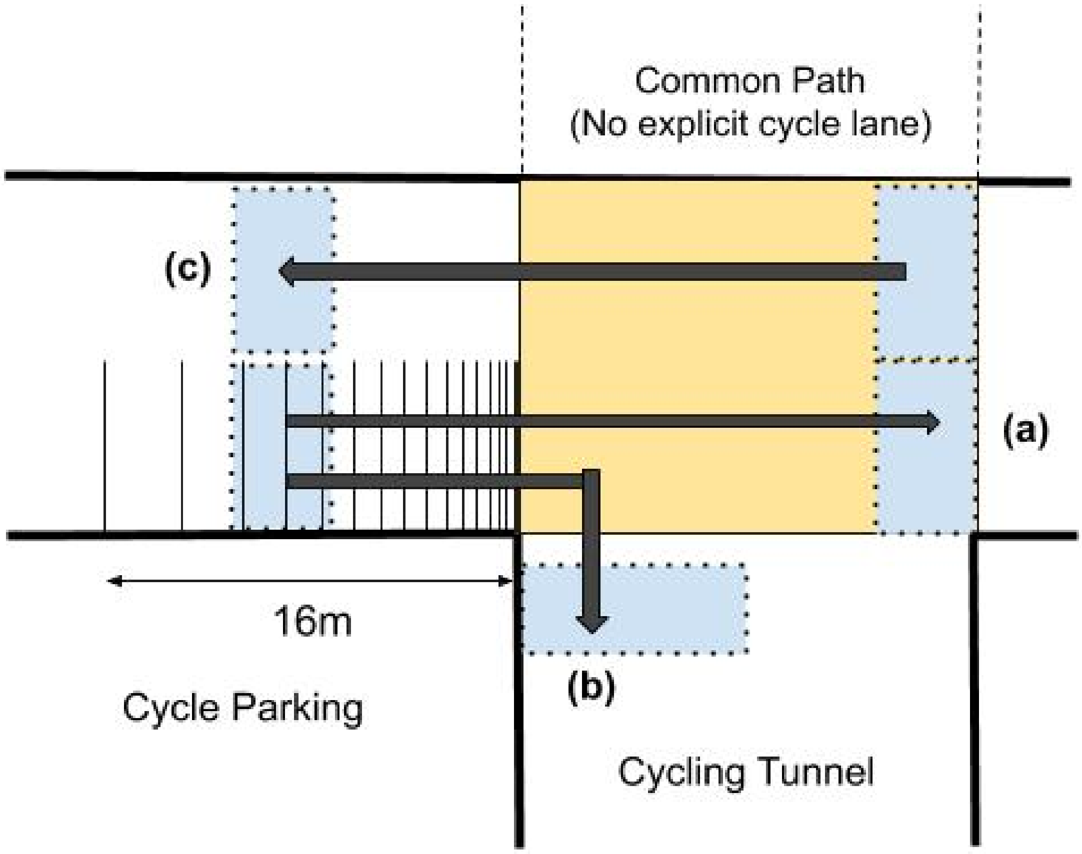

Figure 27. Road User movement (a) Through-Only (b) Turning-Only (c) Through-Opposite (from Camera 2)
(**Note**: The dotted boxes are the coordinate polygons)

4.4 Chosen Cross-Sectional Bands for Analysis

The influence of the transverse lane marking nudge on the speeds and safety criticality is one of the main aims of this research. But the nudge might have a different influence even before reaching the lane marking or it could also have a different variation at the start, middle, end and also after crossing the nudge implemented location elaborately explaining the expectations (as mentioned in section 4.2 and possible differences in behaviour and safety).

It should also be noted that the cross sectional band should not be confused with the coordinate boxes used to divide the different movement types needed. It is also good to know how these cross-sectional bands are formed and how it captures the trajectory data of the road users, within the trajectory band. Whereas the coordinate polygon boxes are to distinguish the various movements of the whole trajectories. This is performed in three steps. The coordinates for the various cross-sectional bands are chosen with respect to the nudge implemented location based on the various expectation and hypothesis to be tested. Since we have multiple frames for each road user, a code is generated to automatically filter only the frames (of each trajectory) which lie within each of the cross-sectional band for each road users separately for various cases (categorised in figure 23) with and without the nudge scenario. So, basically, all the road users trajectories within a particular cross sectional band with respect to the nudge implemented location is used for the analysis.

The different cross-sectional bands which were chosen for the analysis to answer the hypotheses and eventually the research questions are as follows:

- Before approaching the nudge location
- At the start of the nudge location
- In the middle of the nudge location
- At the end of the nudge location
- After leaving the nudge location

The length of each cross-sectional bands for the calculation of all the indicators is chosen to be 3m for various reasons. The purpose of using a 3m cross-sectional band is:

- To obtain the average speed and average acceleration indicators for each road user within the sectional area, based on the conceptual model generated in section 4.1.
- To cover the different areas of the nudge based on the expectations and corresponding hypothesis elaborated in section 4.2.4.
- Especially at the start of the nudge implemented location, just a cross-section may not be enough to create an illusion.
- Finally, a cross-section band greater than 3m cannot be chosen. Since, neither the trajectories from camera 1 nor the trajectories from camera 2, will not be able to exactly cover the middle cross-sectional band (if 4m cross sectional bands are chosen), due to the gap between the coverage in both the cameras.

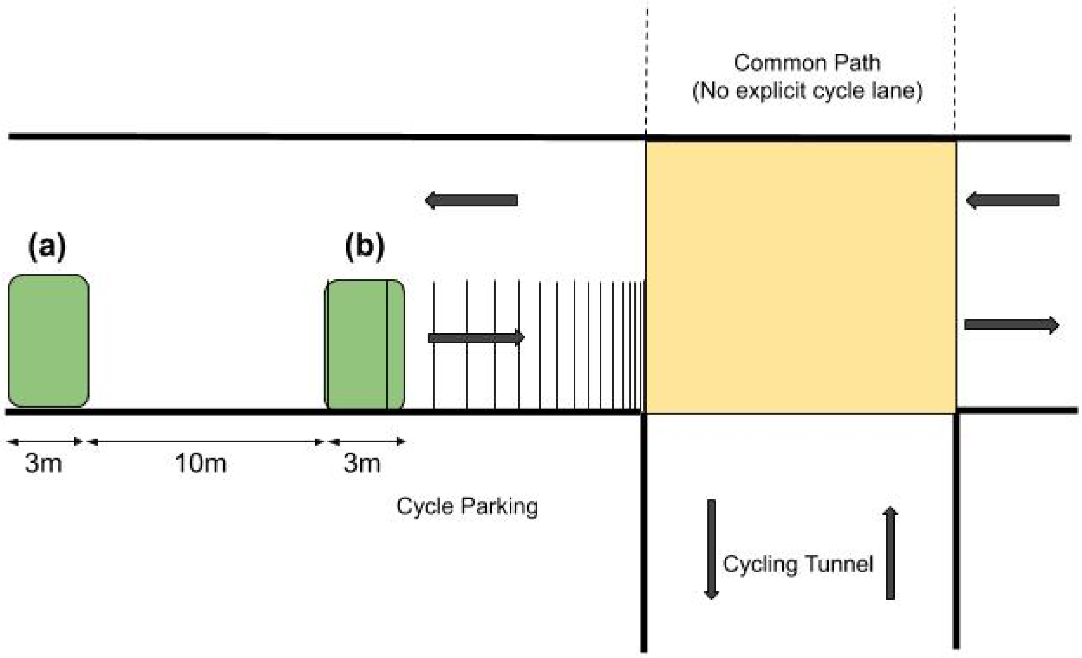

Figure 29. Cross-sectional bands (a) Before and (b) At the start of the nudge (using only the trajectories from camera 1)

The figure 29 is used to capture the behaviour and safety of all the road users 10m before the nudge as depicted. The length of 10m is chosen with respect to the video coverage from camera 1 and will be a considerable distance to observe if there were any changes observed with the line marking nudge before reaching the start of the nudge. It is good to make a distinction, that the cross sectional band before and the start of the nudge (as shown in 29(a) and 29(b), respectively) are formed keeping in mind the view in camera 1 (shown in figure 11). Similarly, the cross-sectional bands at the middle, end and after crossing the nudge implemented location is formed with reference to camera 2 (shown in figure 12), so that both camera capture all the relevant trajectories of the road users. As already mentioned none of the cross sectional bands involves the use of camera 3.

So, in order to test the expectations and hypotheses, figure 30 is used to perform the analysis to check the variations and differences in the behaviour and safety at the middle (figure 30(a)), at the end (figure 30(b)) and after crossing the nudge (figure 30(c) for turning traffic and figure 30(d) for the through traffic after crossing the nudge) implemented locations. Figure 30 also depicts two cross sectional bands after the nudge implemented location (i.e. immediately after the common area of the intersection of all the three arms) which is used for testing if the behaviour and safety of the road users are altered after the road users cross the nudge. For improving the clarity and understanding of the reader, the actual trajectories of 20 Through cyclist within the middle 3m cross sectional band are shown in figure 26.

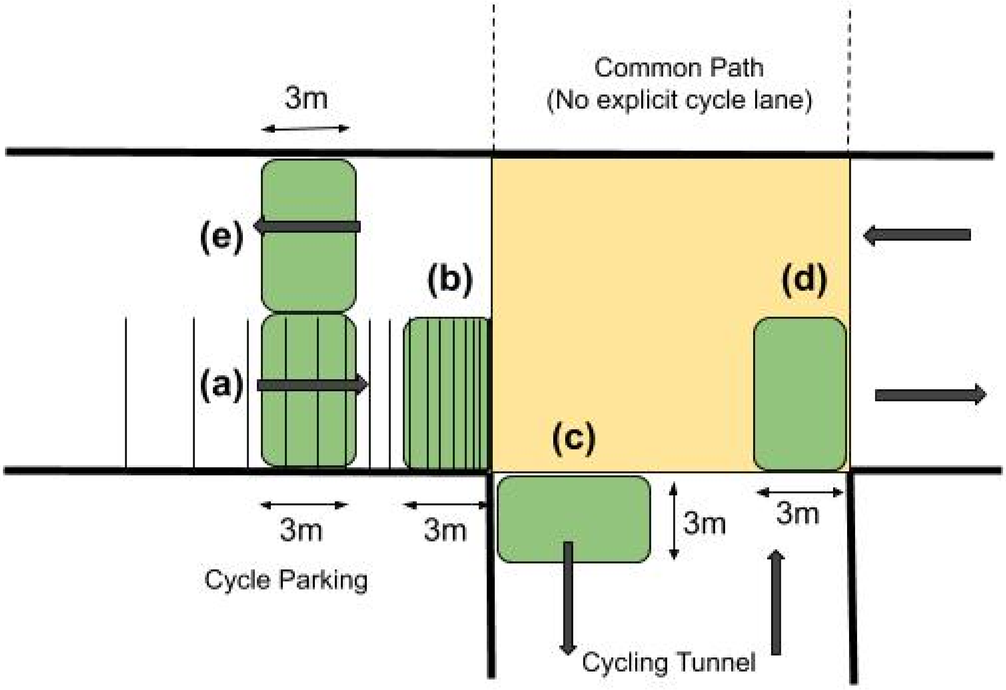

Figure 30. Cross-sectional band at the: (a) Middle (b) End w.r.t. the nudge and the Cross-sectional band after crossing of the nudge: (c) for Turning and (d) for Through road users (e) Adjacent Lane movement (using only trajectories from camera 2)

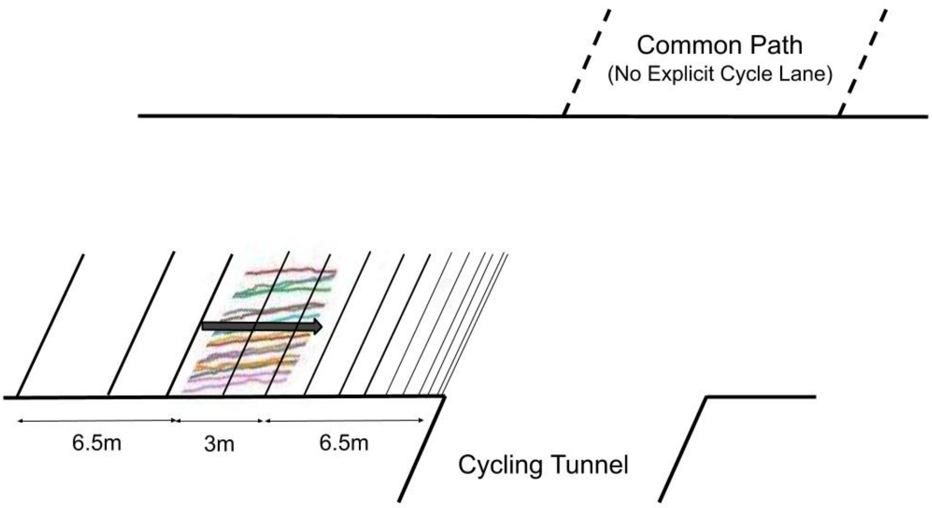

Figure 31. Twenty Through Cyclist Trajectories within the 3m (middle) cross sectional band

It is also crucial to realise that in figure 30 the cross-sectional band (c) is immediately placed after the common area for all the three arms of the T-intersection to capture the turning road users after crossing the nudge location. Also, it is the end of the camera 2 overage. In a similar way, the cross-sectional band (d) in figure 30 is placed at the end of the common area, for the same reason that the coverage from the camera 2 is terminated there, and this is used to understand the performance indicators of the through road users after crossing the nudge implemented location.

4.5 Definitions - Performance Indicator Variables

Before calculating the performance indicators it is important to understand few definitions of the performance indicators with respect to the data (using the frames of each trajectory), to have a clear understanding with all the calculations following this sub-section strengthening consistency between all the calculations for each road user. It should be noted that each frame has a positional data (the x and the y coordinate) and the corresponding timestamp.

- **Frame-Section**: It is the five consecutive frames of a road user trajectory. These are used to calculate the moving averages of the variables. The choice of using 5 frames will be explained later.
- **Instantaneous Speed**: Speed calculated within a frame-section. This can also referred as frame sectional speed or instantaneous frame sectional speed. Measured in m/s.
- **Average Speed**: It is the mean of all the instantaneous speeds calculated or also the mean of all the frame-sectional speeds, within the stretch, using the method of moving averages (Song and Lee (2015); Zhao et al. (2020)). Measured in m/s.
- **Instantaneous Acceleration**: It is the difference between two consecutive frame sectional speeds (which are used in the speed calculations) divided by the corresponding time interval between them. Measured in m/s^2
- **Average Acceleration**: It is the mean of all the instantaneous accelerations calculated within a stretch. Measured in m/s^2
- **Instantaneous Jerk**: It is the difference between two consecutive instantaneous acceleration (which are used in the acceleration calculations) divided by the corresponding time interval between them. Measured in m/s^3
- **Average Jerk**: It is the mean of all the instantaneous jerks calculated within a stretch. Measured in m/s^3

4.6 Performance Indicators Calculations

Once the data is clean and rationality is checked, using the various necessary cross-sectional band (elaborated in section 4.4), the performance indicators are calculated for each road user based on the flowchart depicting the necessary performance indicators presented in section 4.1. This sub-section sheds light on how the speeds, accelerations and jerks are computed with the necessary description for each road user across the relevant case and within a cross-sectional band. In the end, the critical deceleration counts and critical jerk counts are used as a SSMs to quantify the safety criticality for various cases. As defined earlier, a frame section is composed of 5 consecutive frames (also commonly referred as window size in literatures). The reason for this window size is to obtain the variable like speed, acceleration and jerk with better accuracy using the method of moving averages, supported from literatures (Song and Lee (2015); Zhao et al. (2020)). Since the window size of 5 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 (Song & Lee, 2015).

For a better structure and consistency within and between the calculations of speed, acceleration and jerk, frame sections (with 5 frame window size) are used for all the calculations to obtain the instantaneous and average values within the cross sectional band for each road user. So, the next three sub-section will elaborate on how the average speeds, acceleration and the jerk is calculated using the frame sections of the trajectory data within each of the cross sectional band.

4.6.1 Speed Calculations

This sub-section explains in detail how the average speed is computed for each individual road user using the positional and the temporal data (i.e the trajectory data) across each cross-sectional bands. The data for each road user has multiple frames and when the road user goes through each of the cross-sectional band, some frames of his/her trajectory comes within the cross-sectional band. The frame sectional speeds (5 consecutive frames) are calculated using the method of moving averages. That is, calculate the frame-sectional speed within frames 1 to 5 (1^{st} frame section) and then frames 2 to 6 (next consecutive frame section) and so on till the last frame within the cross-sectional band. And finally, the average velocity is calculated by taking the mean of all the instantaneous frame sectional speeds. So, the instantaneous speeds and average speeds are calculated using the equations 1 and 2, respectively.

$$FS_S = (D_{5f} - D_{1f})/(T_{5f} - T_{1f}) \tag{1}$$

$$AverageSpeed = (\sum_{i=1}^{n} FS_S)/n \tag{2}$$

where,
FS_S: *(Instantaneous) Frame-Sectional Speed*
n: Number of frames within the cross sectional band minus 4 (For instance, with 20 frames, 16 instantaneous frame sectional speeds can be calculated, using the window size of 5 frames for implementing the method of moving averages)
D_{5f}: *Local coordinate of the* 5^{th} *frame within the frame-section*
D_{1f}: *Local coordinate of the* 1^{st} *frame within the frame-section*
T_{5f}: *Time-stamp of the* 5^{th} *frame within the frame-section*
T_{1f}: *Time-stamp of the* 1^{st} *frame within the frame-section*

So, each frame sectional speeds calculated, act as the instantaneous speeds within each of the various cross-sectional bands, based on the movement type and necessity. These instantaneous frame sectional speeds are further used for the acceleration and jerk calculations in the following sub-sections using the definitions mentioned earlier in section 4.5 across various cross-sectional bands.

4.6.2 Acceleration Calculations

Acceleration of a road user is defined as the rate of change of speed or the change in speed (instantaneous frame sectional speed) per unit time, represented in m/s^2. In other terms, acceleration is the second-order derivative of the rate of change in the position of an object (road user in this case). The instantaneous acceleration is the difference between the two consecutive instantaneous frame sectional speeds, divided by the corresponding time interval. The same way of calculating the instantaneous acceleration is used in the research of Li, Li, Xu, and Liu (2020). To be more clear to the reader, basically to calculate an instantaneous acceleration, a consecutive pair of frames sections are needed. Sanity checks were performed by plotting the acceleration histogram distributions, similar to the ones depicted in figure 18, explained with the data description. It mainly checked if all the mean accelerations are logical and the extreme values are reasonable. The formulation of instantaneous and average acceleration across the 3m cross-sectional band is presented with equations 3 and 4, respectively.

$$A_{Inst} = (V_2 - V_1)/\Delta T \tag{3}$$

$$A_{Avg} = (\sum_{i=1}^{n} A_{Inst})/n \tag{4}$$

where,
A_{Inst}: *Instantaneous Acceleration using two consecutive frame sections*
A_{Avg}: *Average Acceleration across the cross-sectional band*
V_1: *Instantaneous speed of the first frame section*
V_2: *Instantaneous speed of the next consecutive frame section, (obtained from the speed calculations using the method of moving averages)*
ΔT: *Time difference between the corresponding final and initial instantaneous velocities*

4.6.3 Jerk Calculations

The jerk of a road user is defined as the rate of change of acceleration or the change in acceleration per unit time, usually represented in m/s^3 or g/s (standard gravity's per second), where g is 9.81m/s^2. In other terms, jerk is the third-order derivative of the rate of change in the position of an object (road user in this case). As performed in the calculations of accelerations, even the jerk values for individual road users were calculated in a similar way using the values obtained from the calculations of accelerations in the previous sub-section using the frame sections of the trajectory data. So, the instantaneous jerk is found by taking the difference between the final and initial instantaneous accelerations divided by the corresponding time interval. To be more clear to the reader, basically to calculate an instantaneous jerk, three frames section are needed. First and second frame section to calculate the initial instantaneous acceleration, similarly, the second and third frame section to calculate the final instantaneous acceleration. The instantaneous jerk is calculated using the initial and final instantaneous acceleration (obtained from the acceleration calculations), divided by the corresponding time difference. The formulation of instantaneous and average jerk across a cross-sectional band is shown with equations 5 and 6, respectively.

$$J_{Inst} = (A_2 - A_1)/\Delta T \quad (5)$$

$$J_{Avg} = (\sum_{i=1}^{n} J_{Inst})/n \quad (6)$$

where,
J_{Inst}*: Instantaneous Jerk using two consecutive instantaneous accelerations or four consecutive frame sectional speeds*
J_{Avg}*: Average Jerk across the cross-sectional band*
A_1*: Initial instantaneous Acceleration using first pair of frame sections*
A_2*: Final Instantaneous Acceleration using the next consecutive pair of frame sections*
ΔT*: Time difference between the corresponding final and initial instantaneous acceleration*

4.6.4 Safety Criticality Calculations

After obtaining the mean accelerations and jerk for each of the road users across each sub-grouped data, it is then used to quantify safety criticality at the T-intersection. 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. It is same as having acceleration lower than -3.3 m/s^2, obtained from literature review presented in section 2.6. 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. Then the percentages (% critical counts) of the safety critical instances are calculated by dividing the absolute number of critical instances of each case with the corresponding number of road users with that specific case. Finally, the percentage counts are multiplied by 1000, to represent the safety critical instances for 1000 road users. The reason for performing it for 1000 road users is to magnify the effect, since few percentages safety-critical counts were small, and it might not be easy for the reader to interpret or differentiate between only the normalised safety-critical percentages, with and without the nudge scenarios for all the cases.

Since this research was the first of its kind to use 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 (supported by various literatures in section 2.6) is considered as the critical jerks for the nudge and no-nudge scenario, respectively, for each case. To be conservative and capture the safety criticality for comparison, the high jerk (lower negative jerk) among the two critical jerks is considered as a critical threshold to obtain the number of critical counts for both the nudge and no-nudge scenario for comparison.

The reason why the threshold is used to calculate the number of critical counts and not directly compare the critical threshold values of both the scenarios is that, by just comparing thresholds, it will not be possible to obtain the normalised number of critical jerks. Also, in one of the sub-research question (4th) is also to find the extent of the linear relationship between these two safety critical indicators. So, these are the reasons to apply this technique to obtain the safety critical jerk counts with and without the nudge scenario.

It is logical to say that if the critical (negative) jerk of a case with a particle scenario (nudge or no-nudge) is lower, that is the bottom 1% from the cumulative distribution curve is lower in magnitude, that scenario is safer than the other scenario. Eventually, that scenario with the lower (negative) jerk magnitude will have lower critical counts, since that value is considered as the critical jerk threshold for both the scenarios of the particular case for comparison with and without the nudge.

4.6.5 Correlation Analysis with the SSMs

Once the normalised safety-critical counts are obtained using the deceleration and jerk as a SSM, the correlation is tested between them to understand the relationship with each other. Since critical jerk as a SSM for cyclists is applied for the first time with cyclists, it is correlated to the well established deceleration as SSM to see if see the extent o the linear relationship between each other. It is reminded to the reader that, the correlation of both these SSMs with the actual crash or hospital data is beyond the scope of this research.

So, this correlation analysis is only to give an idea of how the jerk as a SSM is varying with the deceleration as a SSM. It is expected the critical jerk counts will at least have a positive correlation with the critical deceleration counts in most of the cases with the cyclists and mopeds. The reason of this expectations being, both the indicators obviously, represent the safety-critical instances and obviously with both these indicators, high counts imply lower safety at the T-Intersection. The correlation coefficients between the critical deceleration counts and critical jerk counts were performed using the Pearson's Correlation tests to obtain the correlation coefficient with different groups with the Nudge and without the Nudge scenario with a 95% confidence intervals. The results of the correlation coefficients will be presented at the end of the next section elaborating on the results obtained from the calculations of all the performance indicators elaborated in this sub-sections.

5 Results and Interpretations

This section summarises the results obtained from the calculation of the performance indicators in section 4.6. Initially, all the results (before statistical testing) is described to understand the overall variations with the indicators across for the cyclists and mopeds, separately. All the performance indicators with different cases (categorised in the figure 23 and table 7) are presented in Appendix B. Once a general understanding is developed, all the statistical tests are explained which is followed by detailed interpretations and inferences. This section is also the basis for answering all the hypotheses, expectations and eventually the final research goals and objectives. Before addressing all tables shown in this section, it is important for the reader to understand few rows of the table to have a better idea and a clear understanding with the descriptions of all the table elements and for the statistical inferences in the next section as well.

It is obvious that a positive percentage change indicates an increase in the magnitude and the negative percentage change shows that there is a decrease in the magnitudes of the speeds, of nudge scenario compared to the no-nudge scenario. However, considering the percentage changes of the mean accelerations of the road users at a particular cross sectional band, it might not be straight forward like the percentage changes with speeds. This can be illustrated separately,

- If in both the nudge and the no-nudge scenario road users are accelerating. A positive percentage change implies that, the nudge scenario have high acceleration in the nudge than the no-nudge and vice-versa with the percentage change is negative. This is exactly similar to the understanding of the percentage changes with the means of speeds of the road users.

- If in both the nudge and the no-nudge scenario road users are decelerating. A positive percentage change implies that, the nudge scenario have high deceleration magnitude in the nudge than the no-nudge and vice-versa with the percentage change is negative.

To have better clarity and understanding for the reader, an example is considered to elaborate on the percentage changes of mean accelerations.

- If in both the nudge and the no-nudge scenario road users are accelerating. A +20% percentage change implies that, the nudge scenario has high a 20% higher acceleration magnitude in the nudge than the no-nudge and vice-versa with the percentage change is -20%. This is exactly similar to the understanding of the percentage changes with the means of speeds of the road users.

- If in both the nudge and the no-nudge scenario road users are decelerating. A +20% percentage change implies that, the nudge scenario has high deceleration magnitude in the nudge than the no-nudge and vice-versa with the percentage change is -20%.

Finally, before describing the results, it had to be noted that if the there is a change in sign with the mean accelerations between the scenarios, that is, either from acceleration to deceleration or deceleration to acceleration, the percentage changes in the mean acceleration is relatively high. So, those instances are represented as "CD", which means that there is a "Change in Directionality". For these cases, the values of the mean accelerations in both the scenarios are directly interpreted and discussed to obtain inferences.

The percentage changes in mean speeds are positive for the upstream and through cyclists in most of the cases except the cyclists crossing the middle and end part of nudge implemented location on Monday MP and EP, respectively (which is less than 1%). Whereas, the percentage changes in the acceleration, have very mixed results with positive and negative percentage changes. Similarly, with safety performance indicators of upstream and through cyclists, using the critical braking counts and jerk counts per 1000 cyclists, there is a mix of decrease and increase across various cases. Interestingly, three cases on Sunday (middle, end, and after with respect to the nudge implemented location) had an opposite variation with the safety criticality counts obtained from deceleration and jerks. That is if the deceleration counts is less in nudge scenario, the jerk counts in the same case is higher in nudge scenario and vice-versa. This is also same as the cases on Monday EP with the middle and after crossing the nudge implemented location. All these observed changes will be inferred in detail along with the statistical inferences in section 5.1 later.

With respect to the upstream and through mopeds, there is a mixed changes with the percentage speed change (positive and negative changes) unlike with the upstream cyclists which had only positive changes with speed in the nudge scenarios relative to the no-nudge scenario. But the overall acceleration changes were similar to the through cyclists with mixed variation and also with the change in directionality in few cases like the middle, end, and after crossing the nudge implemented location of the Monday MP. Similarly, the changes with safety criticality of the upstream and through mopeds in the nudge/no-nudge scenario have mixed variation similar to the through cyclists. Also, few cases which include the through mopeds have relatively very high critical deceleration counts, compared to the jerk counts as in middle/end nudge implemented location on Monday EP. On the other hand, the upstream mopeds on Monday MP had relatively high jerk counts compared to the decelerations counts.

With respect to the turning cyclists, the overall speeds when coming closer to the T-Intersection was less relative to the through cyclists approaching the nudge, that is in the middle, end and after the nudge implemented location. Similar to the upstream and through cyclists the percentage increase in speeds was positive across all the cases for the turning cyclists, showing that there is an increased mean speed of the turning cyclists as well with the presence of nudge. Also, there was a lot more change in directionality of the mean acceleration with the turning cyclists compared to the upstream and through cyclists. Interestingly as shown in the safety criticality counts of turning cyclists few cases in the no-nudge scenario had no critical deceleration counts (zero) which include the middle and after sections on Monday MP and the end/after sections on Monday EP.

The changes in the percentage speeds and acceleration with and without the nudge scenario had varying effects with the different cases similar to the through mopeds as well. With respect to the safety criticality, the end section on Monday MP had zero critical declaration and jerk counts in the nudge scenario and interestingly both the safety critical counts were zero for the no-nudge scenario after crossing the nudge implemented location. But all these observations have to be statistically testes to draw concrete inferences. Finally, from the results of the control group cyclists, in the nudge scenario, there was a reduction in speeds on Sunday and Monday EP. In these two cases, there ware higher accelerations compared to the no-nudge scenario. With the control group mopeds with the nudge scenario, there was a speed decrease on Sunday and an increase on Monday (both MP and EP). Also, the safety performance indicators were extremely low (less than 1) with all the control group road users. But, the main purpose of the control group road users is to check and verify if there is a significant difference with and without the nudge scenario which is discussed in the sub-section 5.1.1 in detail.

As explained briefly, in the calculations of the correlation coefficient, the relation is divided into three categories. That is a weak, moderate and strong relationship. Overall, with respect to all the road users across all the three-time zones selected, the correlation was found to be positive and weak. It can be seen from the highlighted cells in table 39 presented in Appendix B, that both the road users (cyclists and mopeds) have a moderate relationship with the critical jerk counts and critical braking instances. The relationship between them is stronger with the case considering only mopeds users' criticality with jerk and deceleration as SSM. The Sunday cyclists among all the other group had the highest Pearson's correlation coefficient. As expected, all the correlation coefficients were also found to be positive. The application, statistical inferences and interpretation for these correlation coefficients along with the statistically significant values will be elaborated in the following sections.

From the results obtained with a general understanding of the variations for each of the road users per movement type as briefed in this section, it is very important to check if the all the cases with and without the nudge scenarios have statistical differences or not. This is crucial to present a strong inference from the results obtained. To check the statistical differences in the mean of the average speeds and accelerations of the road users, initially, the normality of the samples with the nudge and no-Nudge is statistically tested using the Kolmogorov Smirnov test for normality. If they found to be normally distributed then an independent 2-sample t-test is applied to draw conclusions and interpretations whether the means of the samples significantly differed or not between the nudge and the no-nudge scenarios for all the cases. If they were not normally distributed (that is if the normality assumption fails) then a non-parametric Mann Whitney U-test is performed between the samples with and without the nudge scenario to check their differences in their means. Both these tests were all done at a standard 5% significance level (p-value < 0.05), which means that if the p-value is less than 0.05, the two samples have a significantly different means.

The critical deceleration counts and critical jerk counts were used to quantifying the safety criticality and statistical tests were performed to check whether the two groups (with & without the nudge scenario) had a difference with their distributions. The difference with the two distributions was checked using the non-parametric Kolmogorov Smirnov tests to check the statistical significance at a standard 5% level (p-value < 0.05, for statistically different distributions). So, all the results with the safety-critical counts using the critical decelerations and jerks were presented while interpreting the results (in section 5.1). It has to be noted that the cases where the nudge and no-nudge scenarios did not differ statistically is also important to be reasoned and were discussed in detail in the next section interpreting the reasons for the indifference. Finally, for identifying the statistical significance with the Pearson's correlation coefficients a 2-tailed test with 95% significance ($p<0.05$) is used to obtain the t-statistic to draw inferences with respect to the relation between the two safety criticality indicators (critical deceleration counts & critical jerk counts). All various observation will be inferred in detail along with the statistical inferences in section 5.1 below.

5.1 Statistical Inferences and Interpretations

This section elaborates on the statistical inferences and detailed interpretations from all the results of this field study explained in the previous sub-section. It has to be highlighted that the behaviour and safety are interpreted only based on information available from this case study and cannot be generalised without further studies and validations. For a better-structured interpretation of the results, the statistical inferences are presented in various sub-sections (with all the corresponding tables in this sub-section showing statistically significant performance indicators and the percentage changes) which separately interprets the influence of the transverse lane marking nudge per road user type with a particular movement type. These are listed below:

- Control Group Road Users,
- Upstream Cyclists,
- Through Cyclists,
- Turning Cyclists,
- Upstream Mopeds,
- Through Mopeds,
- Turning Mopeds,

It has to be highlighted that all tables in this section highlight only for all the cases which have statistical differences among them. But indeed all the results described at the beginning of this section would be interpreted and explanations for why it differs or does not differ with a specific case with and without the nudge scenario, with clear reasoning.

5.1.1 Control Group Inferences

As mentioned earlier, the control group were the road users using the adjacent lane (next to the lane where the transverse lane marking was applied) passing through the middle cross-sectional band with respect to the entire stretch of the nudge, in the opposite direction. It is expected for the control group not to have any differences, but in this empirical research, the control group is found to have statistical differences with the mean speeds, deceleration and jerk count distributions for both the cyclists and mopeds in few cases which will be elaborated in this section. Finally, followed by a list of possible reasons for changes in performance indicators with the control group.

The cyclists in this middle cross-sectional band had different mean speeds on Sunday and Monday MP with a slight decrease in the magnitude with the nudge scenario on the adjacent lane. It had around 6.2% less speeds with the on Sunday and around 2% less on Monday MP with the cyclists compared to the no-nudge scenario. The exact values are presented in table 8. On the other hand, the mean accelerations did not seem to significantly differ with and without the nudge on the cyclists using the adjacent lane. So, the mean acceleration changes with the cyclists and mopeds is mostly due to the presence of the lane marking nudge. All these observations could be due to multiple reasons (mentioned at the end of this sub-section) which are not been incorporated with the data collection.

Table 8
Mean Speed of Control group Cyclists and Mopeds

Control Group		Cyclists		Mopeds
		Sunday	Mon EP	Sunday
Mean Speed (kmph)	Nudge	14.27	15.14	18.61
	No-Nudge	15.20	15.45	19.73
% Change in Mean Speed of Nudge w.r.t to No-Nudge		-6.16	-2.02	-5.71

Considering the safety criticality of these cyclists, both the critical counts obtained using the deceleration counts and the jerks counts had statistical differences but the magnitudes were less than 1 per 1000 road users both with and without the nudge scenario across all the three chosen time of days (i.e. Sunday, Monday MP and Monday EP), as shown in the table 9. This is because these cyclists are moving away from the intersection and obviously will have less braking instances and eventually very less (or negligible) safety criticality compared to the cyclists moving towards the T-Intersection, who have to break and negotiate with other road users crossing the T-Intersection.

Similarly, the means speeds of mopeds on Sunday significantly differed with the control group roughly had a 5.7% per cent decrease with the mean speeds in the presence of the nudge in the adjacent lane. But no statistical difference was found in the mean speeds with the mopeds on Monday MP and EP. Similar to the cyclists, the mean accelerations of the mopeds did not seem to significantly differ with and without the nudge application on the adjacent lane. Even with the mopeds both the critical counts obtained using the deceleration counts and the jerks counts were less than 1 per 1000 road users both with and without the nudge scenario across all the three-time of days chosen (i.e. Sunday, Monday MP and Monday EP), but had statistical differences in the distribution of accelerations. This is also because these mopeds are moving away from the intersection and obviously will have very less (or negligible) safety criticality compared to the mopeds moving towards the T-Intersection, for the same reason mentioned with the cyclists.

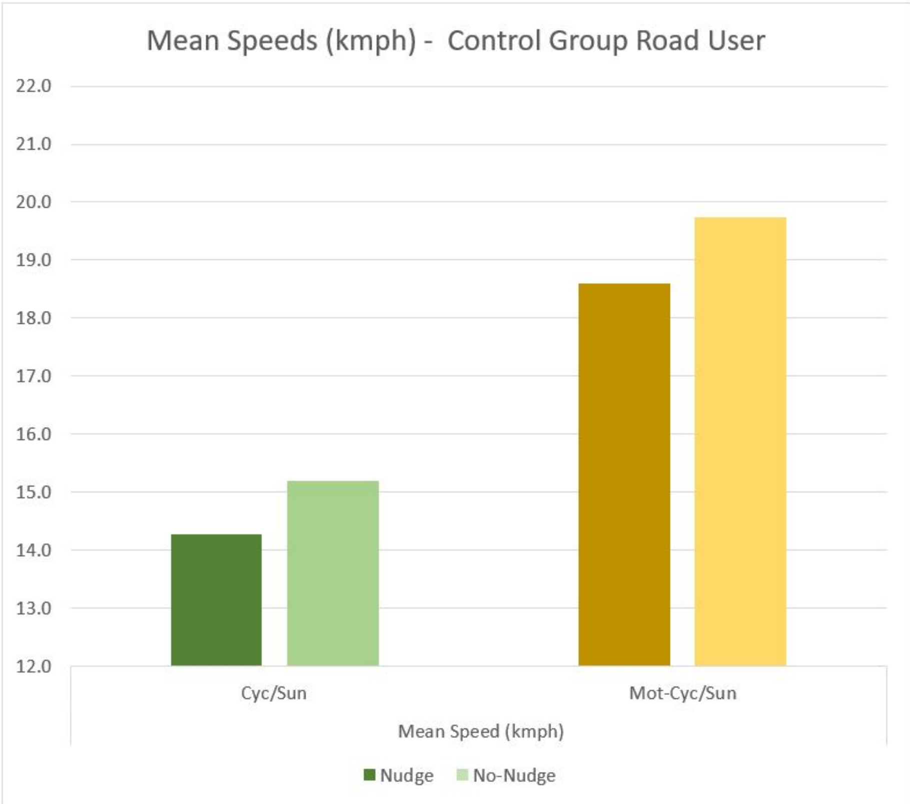

Figure 32. Mean Speed variation of the Control group road users

Table 9

Safety Indicators of Control group Cyclists and Mopeds

Control Group		Cyclists		Mopeds
		Sunday	Mon MP	Mon MP
Relative Critical Dec Count/ 1000 road users	Nudge	0.104	0.135	0.204
	No-Nudge	0.137	0.211	0.224
Relative Critical Jerk Count /1000 road users	Nudge	0.153	0.119	No Statistical Difference
	No-Nudge	0.112	0.188	

The control grouped is assumed to have no influence with or without the nudge, so the statistical differences found in the other cases of through and turning road user movements is due to the presence of another element/factor apart from the lane marking nudge. The reason for the differences with the control group could be due to any of the following:

- Variation with the weather, i.e. presence of the rain during the no-nudge scenario. Rain could have a high influence on the speed behaviour of the road user.
- Demographics of the road users which include, their age, gender, education, employment and income. Except age and gender, the other demographics may not have a high influence on the speed and safety performance indicators. But it has to be noted that, due to privacy reasons, the demographics data was not provided for this research.
- Personality and attitude of the road users. These two are partially depend on the demographics. But within the same age group or gender, there could be differences in openness, conscientiousness, extraversion, agreeableness or neuroticism (the Big-Five personality traits) towards the lane marking nudges and the performance indicators.
- Presence of the tunnel close to the lane where the lane marking nudge was implemented. This would have relatively more influence on the speeding behaviour of the through cyclists due to the obstructed vision of the right turning cyclists coming out the tunnel. Similarly, it might have a less influence with the turning cyclists, considering these road users have already decided to turn and would be prepared to slow down anyway. This could give rise to high safety criticality for all these road users. But, the turning traffic coming out of the tunnel is not considered in this research.

The variation with the control group means that the empirical results and statistical inferences with all the cases using the nudge implemented location (with and without the lane) in this research is not only due to the nudge but also due to the presence of any of the condition of elements mentioned in the above list, which has to be considered in the future researches concerning the implementation of the lane marking nudges since it is out of scope for including in this research. The possible degree of influence with all the different factors is also mentioned to have a better interpretations of the results with the all the other cases, in the rest of this section.

5.1.2 Upstream Cyclists

As opposed to the expectations mentioned earlier, with the upstream cyclists, the mean speeds are high with the nudge scenario. These values are presented in table 10 by the percentage change column with the mean speeds in the nudge scenario in comparison to the no-nudge scenario was positive (more in magnitude) across all the cross-sectional bands. This implies that, the speeding illusion is not created with the upstream cyclists before and at the start of the lane marking nudge on both weekday (MP and EP) and weekend. Another explanation could also be that since the nudge scenario had slight rains, this would have made the road users reduced there speed as well.

So, whether the rainy weather could be an influencing or not could be verified with the variation of the control group cyclists later in this section.

So, it can be inferred that the lane marking nudge implemented in this field study, is not effective in reducing the speeds of the upstream cyclists. So, it is not effective in creating an illusion of the cyclist speeding up. It could also be interpreted that even though the upstream cyclists might have a seeding illusion, they are not slowing down (because of the lack of necessity or motivation to slow down). The changes in the mean speeds of the upstream cyclists are also presented to have a visual understanding in figure 33 using different colours for the chosen three time of days for the analysis.

The mean accelerations of the upstream cyclists did not differ on Monday MP and EP. This implies that they do not change their acceleration well before reaching the nudges or at the start of the lane markings on a weekday (Monday MP and EP). But the mean acceleration significantly differed at the start of the nudge implemented location on Sunday, as shown at the end of table 12. So, on Sunday, the upstream cyclists accelerate less with the nudge compared to the no nudge and this reduction is 12.62% less than the no-nudge scenario. This can imply that, the lane markings might create an illusion of a stop line which would be a reason for the upstream cyclists reducing their acceleration. Also, the lane markings could be seen as an obstacle on the road which could be another reason of the reduced acceleration in the nudge scenario. But it has to noted that none of the road users fully stopped or came to a halt at the start of the nudge implemented location with the lane markings.

Table 10

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

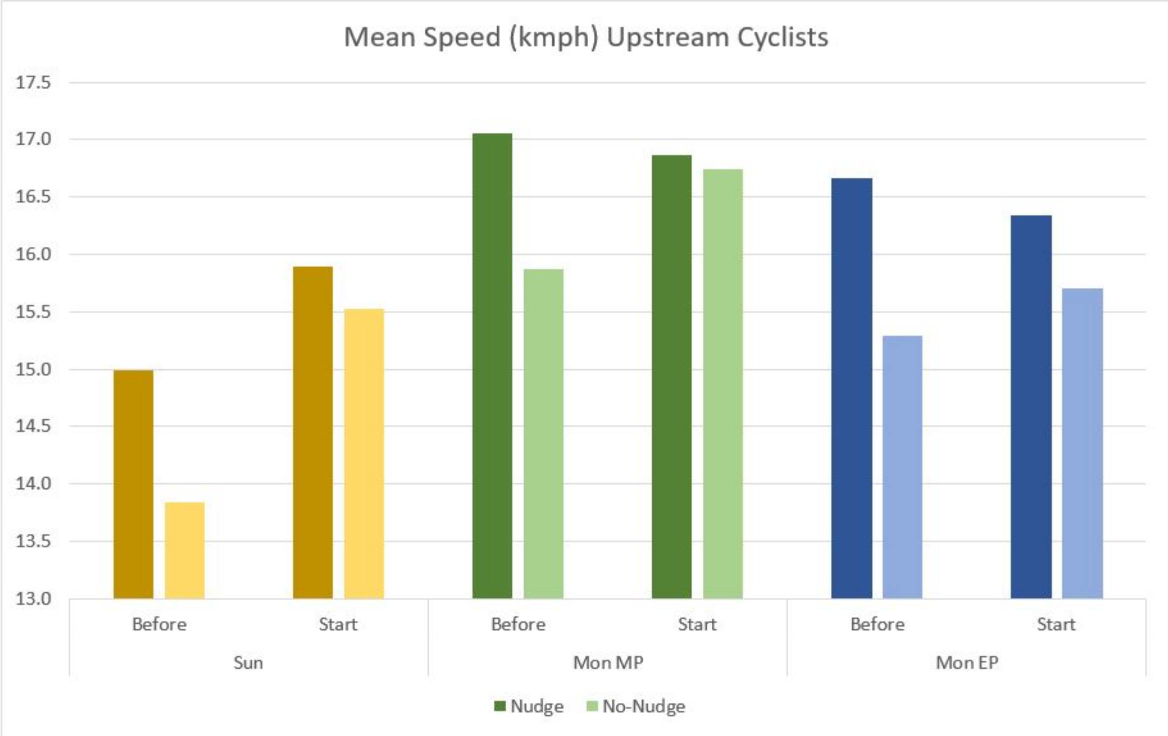

Figure 33. Mean Speeds differences of Upstream Cyclists

Table 11

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

From looking at the safety criticality indicators presented in tables 14 and 17, the nudge scenario have high critical counts compared to the no-nudge scenario. This also strengthens the inference that, the lane markings might create a false perception of a stop line or an obstacle and marking the upstream cyclists undergo more critical braking in the presence of it.

5.1.3 Upstream Mopeds

In a similar way, as opposed to the expectations mentioned earlier, with the upstream mopeds, the mean speeds are high with the nudge scenario. These values are presented in table 10 by the percentage change column with the mean speeds in the nudge scenario in comparison to the no-nudge scenario was positive (more in magnitude) across all the relevant cross-sectional bands. Since, the nudge scenario has slight rains, this could be a reason for the less speed with the rainy no-nudge scenario, compared to the nudge scenario.

So, it can be inferred that the lane marking nudge implemented in this field study, is not effective in reducing the speeds of the upstream mopeds. Additional factors such as the weather (presence of rain or snow) have to be taken into accounts. So, similar to the upstream cyclists, it is also not effective in creating a speeding up illusion for the upstream mopeds users. It could also be interpreted that even though the upstream mopeds might have a seeding illusion, they are not slowing down because of the lack of necessity or motivation to slow down. The changes in the mean speeds of the upstream moped are also presented to have a visual understanding in figure 34 using different colours for the three time of days chosen for the analysis.

Unlike the upstream cyclists, the acceleration significantly differed on Monday EP and found to be negative with and without the nudge. As expected, moped users on an average were decelerating more at the start of the nudge implemented location in the nudge scenario. It can be seen from table 12, that the nudge scenario had a higher magnitude of mean deceleration. Similar to the upstream cyclists, this can also imply that, the lane markings are seen as a stop line which would be a reason of the upstream moped for increased decelerations. Also, the lane markings could be seen as an obstacle on the road which could be a reason for the higher deceleration magnitudes with the nudge scenario. Another reason could also be that, the moped users could have been surprised by the lane markings. So, despite the high speeds in the nudge scenario they decelerate or brake more with the start of the lane markings.

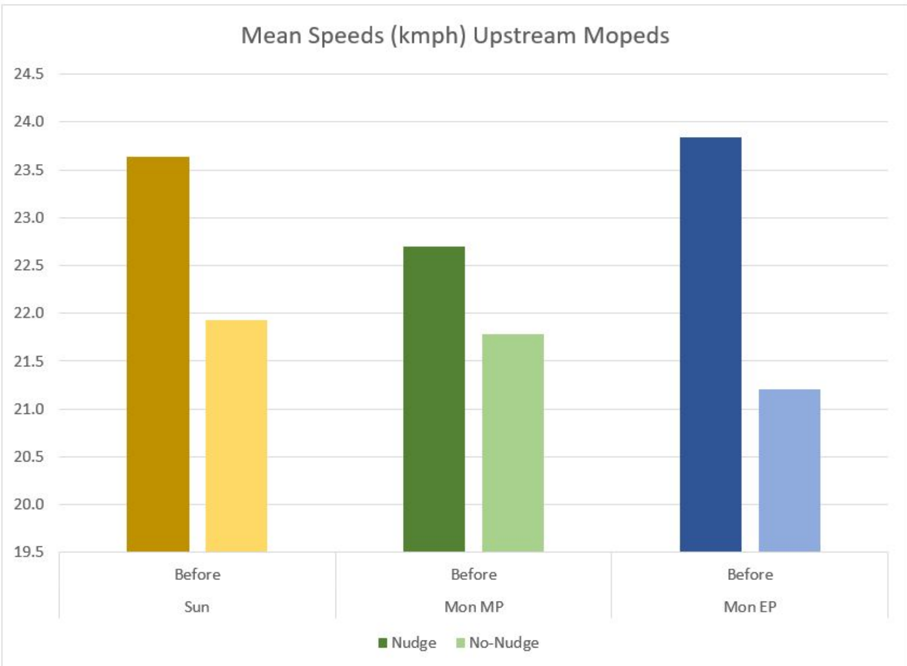

Figure 34. Mean Speeds differences of Upstream Mopeds

The critical deceleration and jerk count did not have a difference on Sunday (weekend). This could be due to the non-work related trip purposes or leisure trips on a Sunday. The safety performance indicator was significantly different only the Monday MP before reaching the nudge implemented location. Interestingly, with the upstream mopeds, the nudge scenario had less critical braking instances before reaching the nudge implemented location on Monday MP, as shown in table 14. But for the same case, the critical jerk counts as shown in table 17 were high compared to the no-nudge scenario. The higher jerk counts in the nudge scenario, strengthens the inference that, the lane markings could be considered as a stop line, an obstacle or as a sudden surprise and marking the upstream moped users higher critical jerk counts in the presence of the nudge.

Table 12

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 13

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

5.1.4 Through Cyclists

As opposed to the expectations with the through cyclists mentioned earlier, the mean speeds are high with the nudge scenario. This is also indicated in table 11 by the percentage change column with the mean speeds in the Nudge scenario in comparison to the no-nudge scenario was positive (more in magnitude) on Sunday across all the cross-sectional bands, which were statistically different. The similar variations were also observed for the upstream cyclists before reaching the nudge and at the start of the nudge for the morning and evening peaks on Monday. So, the reason for the less speed in the nudge scenario due to the rain. Also, the priority inversion (false assumption of the right of way) of the through cyclists is stronger than the speeding illusion is created by the presence of the lane marking nudge. This also indicates that through cyclists do not tend to change their speed when crossing the nudge. The speed differences with and without the nudge scenarios across the three time zones and the cross sectional band is shown in the figure 35, just to have a visual idea of the variation with the mean speeds on all the three chosen time of days with respect to the cross sectional bands, clearly indicting a higher change in speeds (with the upstream cyclists) in the cross sectional band before reaching the nudge implemented location.

So, even though many pieces of research were showing that the transverse lane marking nudge was successful in the reduction of speeds with cars uses, due to the relatively less speeds with cyclists it might not have the same or a desirable effect with them. Another possible reason could also be that, the cyclists might have been surprised or curious with the presence of a difference (lane marking in this case) and might have focused on seeing the road on what it is and eventually forgetting to reduce the speeds when approaching the intersection from the upstream side by focusing on checking the road markings or wondering why there are some lines present in the road. It could also be argued that, due to the improper visibility (for the through cyclists) of the cyclists coming from the tunnel could also be a reason for not slowing down, but this situation is present both with and without the nudge scenarios. So, whether the tunnel could be an influencing or not could be verified with the variation of the control group cyclists later in this section.

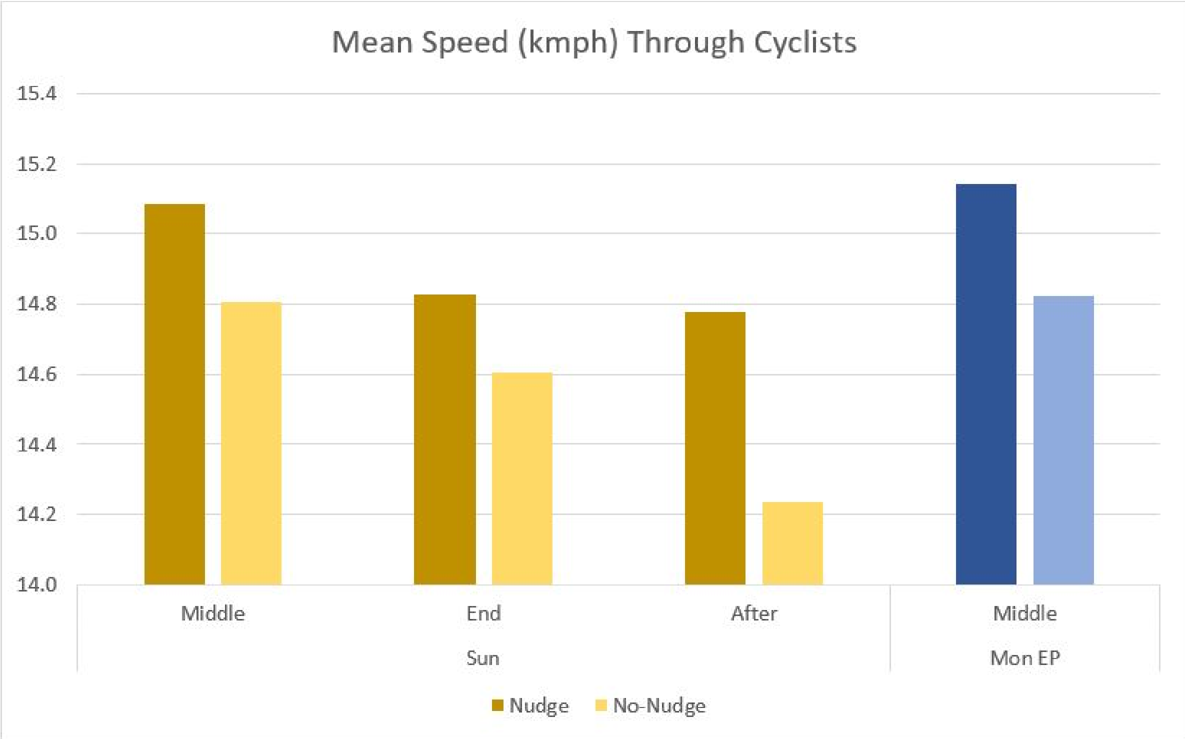

Figure 35. Mean Speeds differences of Through Cyclists

Regarding mean accelerations variation, only the upstream cyclists on Sunday (at the start of the nudge) and through cyclists on Monday evening peak crossing the cross-sectional bands in the middle and the end had a statistically significant difference in the mean accelerations. In all these three cases, the cyclists in the nudge scenario tend to have a reduced acceleration on Sunday and an increased magnitude of deceleration indicating that they tend to reduce their rate of change of velocity at the start of the nudge in the middle and end of the nudge on Monday evening peak. This is in line with the expectations discussed in section 4.2.

So, even though the mean speeds were high (maybe because of the weather and confused why are these lines suddenly originate), their mean accelerations are found to be less. This shows that the transverse lane marking nudge make the user to decrease their accelerations on Sunday and increased deceleration (more braking) on Monday EP and especially the percentage change in the evening peak at the end of the nudge location was significantly higher, as shown in table 12. The reason being the lane markings instead of creating an intended speeding illusion, it is possible creating an illusion of a stop line or as an obstacle, which makes the through cyclists to brake more, eventually increasing the number of safety critical instances with the through cyclists as well.

Table 14

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

Another reason for the higher deceleration and reduced acceleration could be linked to the reason mentioned for not reducing the speeds. It is possible that the cyclists might have been distracted or curious by the lane marking and have forgotten to slow down (maybe by looking at the newly introduced marking on the road) and eventually when they realise that they were reaching the intersection (or a later realisation of another road user in front of them or cyclists coming and merging with them from the cycle parking close to the nudge implemented location) and then they apply brakes in the nudge scenario compared to the no nudge scenario where there was no distraction with the lane marking nudge implementation and the road users might have just focused on reaching and going through the T-intersection rather than looking and maybe puzzled with what was going on with the lane marking implemented without any prior notice or advertising.

Another reason might also be that, the cyclists are subconsciously not being affected by the transverse lane marking nudge due to a much lower speed of cyclists compared to the car user, the perception of speed up with the transverse lane marking might be slower to make them think they are speeding subconsciously and also this late realisation might also be responsible more braking or decelerating with the transverse lane marking nudge. So, some changes have to be made with the length of the transverse lane marking nudge or with the other specifications like the gap between the consecutive transverse lines, to create the intended speeding illusion and avoid the surprise or misinterpretation of the lane marking nudges as a stop line or as an obstacle.

Table 15

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

Considering the critical braking manoeuvres, only the upstream cyclists at the start of the nudge (on Sunday) and the through cyclists crossing the middle and end of the nudge have statistically significant differences. Furthermore, the percentage differences with the nudge scenario with respect to the no-nudge scenario is positive in all these cases. This means in the presence of the nudge the through cyclists in these cases tend to apply brakes more often than the cyclists without the nudge, due to the same reasons mentioned of the reduced acceleration or the increased deceleration of the through cyclists. These changes are shown in tables 14 and 17. The difference with and without the nudge scenario could be visualised in the figure 36, to get an idea of the changes in critical braking instances, with different colours based on the chosen time of days.

However, considering the jerk as a SSM to quantify the safety criticality, it had significant difference with the jerk distributions at different locations compared to the acceleration distributions. They different in 3 cases namely, the through cyclists crossing, the middle and end bands on Sunday, and also after the nudge on Monday (MP). With these cases, the through cyclists have a reduced critical jerk count with the nudge scenario at the end (on Sunday) and after crossing the nudge including interactions on Monday (MP). These are also in line with some of the expectations, since in the middle of the nudge implemented location they tend to have relatively more braking. And then it is possible that the through cyclists want to compensate for the loss of time and then speed up at the end and after crossing the lane marking. So, once they would cross the lane marking nudge the through cyclists are expected to speed up and have a smoother movement after crossing the nudge.

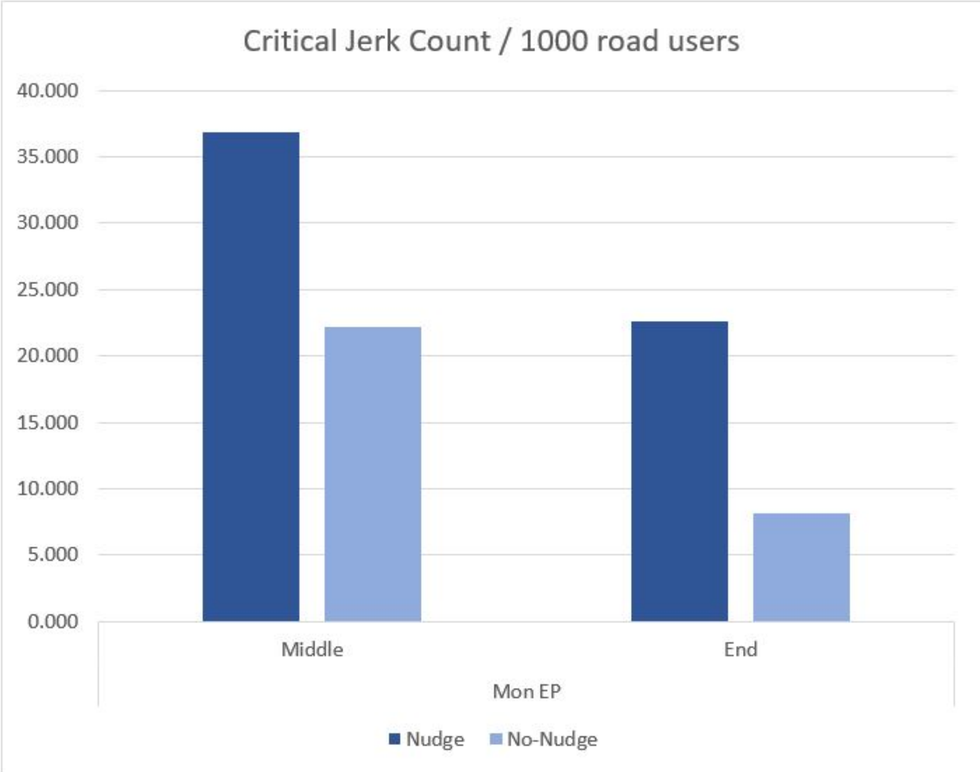

Figure 36. Critical Deceleration Counts of Through Cyclists

5.1.5 Turning Cyclists

Similar to the through cyclists, the mean speeds are higher with the nudge scenario which is also shown by the positive percentage change (increase in magnitude) with the mean speeds in the Nudge scenario relative to the no-nudge scenario, as presented in table 11. The increase in mean speeds (with the lane marking) was seen in all the cases from before the nudge implemented location to the cyclists crossing the nudge on Sunday, Monday (MP) and Monday (EP). All the cases with the three-time of the days have statistically different mean speeds with and without the nudge scenarios. Similar to the through cyclists, this behaviour is also unexpected with the turning cyclists which could be explained using the same reason as well with the presence of the rain in the no-nudge scenario and the lane marking as a cause for a potential cause for distraction, making the turning cyclists not slow down with the presence of the nudge.

The mean accelerations were significantly different in all the cases for the turning cyclists. All the three cross-sectional bands had a deceleration (mean acceleration being negative) with the nudge scenario while the mean acceleration of all the same cases was positive without the nudge scenario. This is shown in table 13. In a similar way, on Monday MP, the turning cyclists tend to have a reduced acceleration in the middle and deceleration in the following sections with the nudge scenario and the same was also observed with the EP on Monday. So, this implies that with the implementation of the lane marking nudge the accelerations of the cyclists are reduced or in other terms they also tend to decelerate compared to the turning cyclists without the nudge scenario. The reason could also be similar to the through cyclists' deceleration changes, considering the transverse lane marking more like a stop line rather than creating a speeding illusion for the turning cyclists as well. So, even though they do not slow down (which could be due to the rain in the no-nudge), they try to decelerate or slow down suddenly rather than the excepted graduate reduction in the speeds, which eventually results in a decrease of overall safety at the T-Intersection as well, explain in the next paragraph.

Table 16

Mean Speed changes in turning cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge
			Nudge	No-Nudge	
Turning Cyclists	Sun	Middle	12.805	10.436	22.700
		End	12.006	10.333	16.198
		After	11.897	11.626	2.334
	Mon MP	Middle	13.463	11.230	19.882
		End	13.164	10.946	20.258
		After	12.997	12.279	5.842
	Mon EP	Middle	13.268	10.730	23.649
		End	11.920	10.928	9.084
		After	11.812	11.569	2.107

With respect to the critical braking instances presented in table 15 with the turning cyclists, on all the three chosen time of days, had significant differences across the three correctional bands. So, it is obvious that with an increase in deceleration magnitude the critical deceleration counts is also higher. It seems that in all the cases which has a significant statistical difference, the number of critical braking instances are more in the nudge scenario. And as expected the critical jerk counts shown in table 18 indicate the same. So, this means that even though turning cyclists seem to have relatively less acceleration or in most cases decelerate more, at the same time they have more critical braking instances or critical jerk counts with the nudge scenarios, which is not the actual intention or expectations with the lane marking nudge. The variation of the critical jerk counts and the differences with the nudge and no-nudge scenario could be visualised with the figure 36. The figure also shows that the introduction of the nudge seems to have introduced a lot more safety critical movements compared to the scenarios without the nudge which is less than 20 critical jerks per 1000 road users across all the cases.

Table 17

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

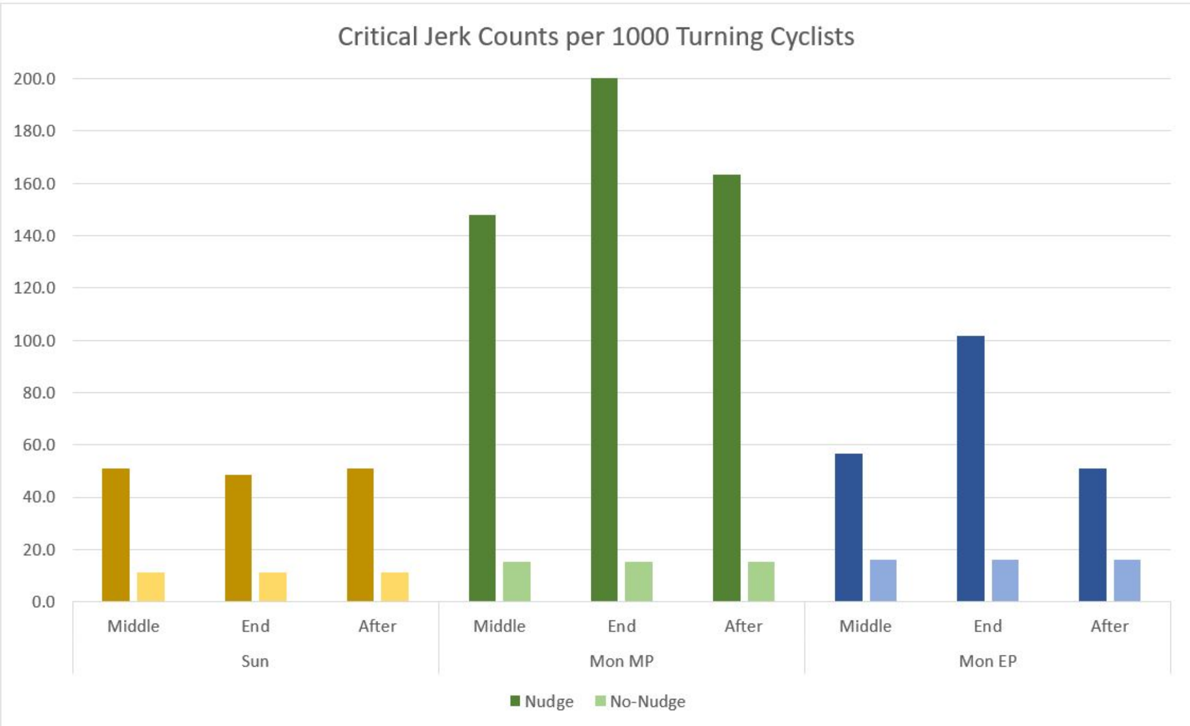

Figure 37. Critical Jerk Counts of Turning cyclists

Table 18

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

5.1.6 Turning Mopeds

There were no significant differences in the mean speeds for the turning mopeds from the middle of the nudge implementation location till the end and even after crossing the nudge. So, as expected the mean speeds of the turning moped did not differ with and without the nudge. This is clearly because in both the scenario they slow down for turning. Especially with the presence of tunnel the mopeds might tend to be cautious irrespective of the presence of the lane markings.

But, the means of the acceleration significantly differ with the tuning mopeds at the middle of the nudge implemented location on Monday MP, as shown in table 12. Here the turning mopeds had a less acceleration with the presence of the nudge compared to the scenario without the transverse lane markings. As mentions many time, this behaviour is due to the possibility that the lane marking lines resemble the stop lane and give rise to the reduced accelerations with the nudge.

The distributions of the mean accelerations had statistical differences with the turning mopeds cross the middle of the nudge location on Monday MP (unlike the through mopeds) as shown in table 14. With the case on Monday MP, there were much higher critical braking instances with the presence of the nudge. This is also straight forward since with the lane marking creating a stop line illusion or act as an obstacle for the turning moped at the middle of the nudge as well. At the end and after crossing the lane marking implemented location did not significantly differ as expected. Since the turning mopeds were probably already would have made the choice to turn. Similarly, the statistical stets also prove that the means speed and mean deceleration do not differ at the end and after crossing nudge location in both the scenarios.

5.2 Inferences on the Correlation between the SSMs

It is found that all the groups which had a moderate linear relationship with the deceleration and jerk counts were statistically significant. The statistically significant groups, along with their t-statistic and the corresponding p-value are presented in table 19. The highlighted colour intensity indicates the relationship between the deceleration and jerk counts, 'all road user' group has a lighter colour indicating a weaker relation, whereas all the other groups have a moderate relation between both the safety performance indicators are relatively highlighted with a darker colour.

Table 19

Pearson's Correlation Coefficients with test statistics

Group/Category	Statistically Significant ($p < 0.05$) Pearson's Correlation Coefficient	t-statistic	p-value
All Road Users	0.268	3.085	0.003
Cyclists	0.313	2.478	0.018
Motor-Cyclists	0.310	2.581	0.014
Monday Morning Peak Road Users	0.452	3.189	0.003
Sunday Cyclists	0.585	3.224	0.005
Monday Morning Peak Motor-Cyclists	0.429	2.144	0.047

The main inference from Pearson's correlation coefficients from table 19 is that both the critical jerk counts and the braking instance are proportional to each other. But the degree of proportionality varies between various groups as shown in table 19. Both the cyclists and mopeds road user group almost has the same level of relationship between the indicators. So, assuming a well-established correlation between the declaration and the actual crash data or the hospital records, it can be inferred even the jerk as a SSM would be a good indicator for quantifying the safety criticality in the road infrastructure, especially the T-Intersection with a lot of bi-directional complex movements. But it is crucial and important to check the validity of both the safety performance indicators for the road users using the shared cycling infrastructure in order to evaluate which indicator is performing better or worse reactive to each other in the future researches.

5.3 Overall Interpretations Summary

This section summarises all the hypotheses mentioned with the six broad groups earlier this section into overall inferences which will make it easier to answer all the hypotheses mentioned in section 4.2 and to answer all the main and sub-research questions. It also gives more clarity for further discussion in the next section followed by the final conclusions of this research. But importantly, as explained with the finding with the control group, the variations of all the performance indicators with and without the nudge scenario for all the cases was not only due to the presence of the lane marking nudge at the T-Intersections, so the other factors are also included with the interpretations summarised below. So, based on the detailed results and interpretations the summary of all the key findings are:

- The mean speeds of upstream cyclists and upstream mopeds before and at the start of the nudge implemented location was high in the nudge scenario compared to the no-nudge scenario, which had statistical differences. Similarly, the mean speeds of cyclists and mopeds at the middle, end, and after the of the nudge implemented location was also high in the nudge scenario compared to the no-nudge scenario, which had statistical differences. 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, who did not use the lane with the nudge implementation. 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 compared to the nudge scenario.
- The mean accelerations of the upstream cyclists 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 had a higher magnitude of deceleration before reaching the nudge implemented location (only on Monday MP). This implies that, the upstream moped have noticed the lane marking and have higher 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 braking.
- In all the cases with significantly different mean acceleration, the nudge scenario had a higher 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,
  - 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.

  Moreover, the control group road users no differences with the mean acceleration, which strengthens these inferences with the variation of the mean accelerations with the presence of the nudge. So, all these inferences with the changes in the mean acceleration had a high chances that it is because of the presence of the lane marking nudge. So, 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 tend to decelerate at the start, middle and end of the nudge implemented location on all three times of days chosen, i.e. on Sunday, Monday MP an on Monday EP. The same was with the case of turning mopeds in the middle of nudge implemented location on Monday MP, with a relatively high deceleration in the nudge scenario. Also, the turning cyclists were deceleration with the nudge scenario and accelerating without the nudge scenario, after crossing the nudge implemented location (on Sunday, Monday MP and Monday EP).

- On the other hand, the mean accelerations of the through cyclists and mopeds did not have any differences in their means, after crossing the nudge implemented location, as expected. Since 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 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. So, probably the tuning 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 gives rise to increased critical braking instances and high jerk counts. It is same with all the corresponding cases where there was a higher 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.

- Finally, it should also be highlighted that relatively very few cases had reduced safety critical instance with the presence of the lane markings. One of two cases in which the critical deceleration counts were less is, with the turning cyclists (on Monday MP at the middle of the nudge stretch). From this, it could be inferred that, the turning cyclists increased braking (more deceleration and critical braking instances) at the start tend to accelerate which shows a reduced critical jerk counts in the presence of the lane marking nudge at the middle of the nudge implemented location. The other case was with upstream moped (on Monday MP before reaching the nudge stretch). This could imply that, even though the moped users seem to treat the lane marking as a stop line or a sudden obstacle from the start of the nudge, they are more prepared to encounter the lane marking well before reaching the nudge in the presence of it, compared to the no-nudge scenario to avoid the safety critical instances. Similarly, the only two cases where the critical jerk counts were less in the nudge scenario was the through cyclists (at the end of the nudge on Sunday and after crossing the nudge on Monday MP). It both these cases it could be inferred that, the through cyclists due to the increased braking (more deceleration and critical braking instances) at the start and the middle of the nudge stretch, tend to compensate the loss of time or compensate the perceived delay due to the brakings. So, they tend to accelerate which shows reduced critical jerk counts in the presence of the lane marking nudge in these two cases.

- Also, as expected, the deceleration and jerk as a SSM have a positive correlation between them. So, the next step in the future is to validate these two indicators and check which of these two indicators performs better in predicting an actual safety critical situation. The idea is elaborated more in the future recommendation regarding the application and validation of jerk as a SSM. Finally, it also important to highlight that, many cases with the mopeds did not have statistically significant different due to the fact that the moped users were relatively very less. So, more moped user data is needed to have strong inferences to test the influence of the lane marking nudges on them.

6 Discussions on Policy Implications

This chapter to entirely dedicated only to the future policy recommendations formulated based on the empirical research and analysis performed and an explicit literature review. This list is presented in the section 6.1. To have a better understanding and reasoning from the inferences presented with the empirical analysis, it is important to understand when was the nudges implemented in the past were successful and not successful (this is presented in sections 6.2 and 6.3). For the benefit of the reader and policymakers, the literature corresponding to behavioural interventions is presented within the various sub-sections for better structure. The literature also covers a brief discussion focusing on how the lane marking nudge implementations could be improved based on literature and existing theoretical frameworks to bring a successful behavioural change intervention for the lane marking nudge studies which also strengthens the societal relevance this research. This is presented in section 6.4 highlighting two generic theoretical frameworks "MINDSPACE" and "Behavioral Change Wheel" to recommend what steps could be added or adopted for the successful implementation of lane marking nudes in the future as a traffic calming measure improving the safety of the infrastructure in which it is applied.

Finally, all the state of arts along with the two generic frameworks are considered as a motivation for the key improvements (presented in section 6.5) to assist the implementation of nudges in the future studies. The overview of the contents in this section with relation to the empirical analysis is shown in figure 38.

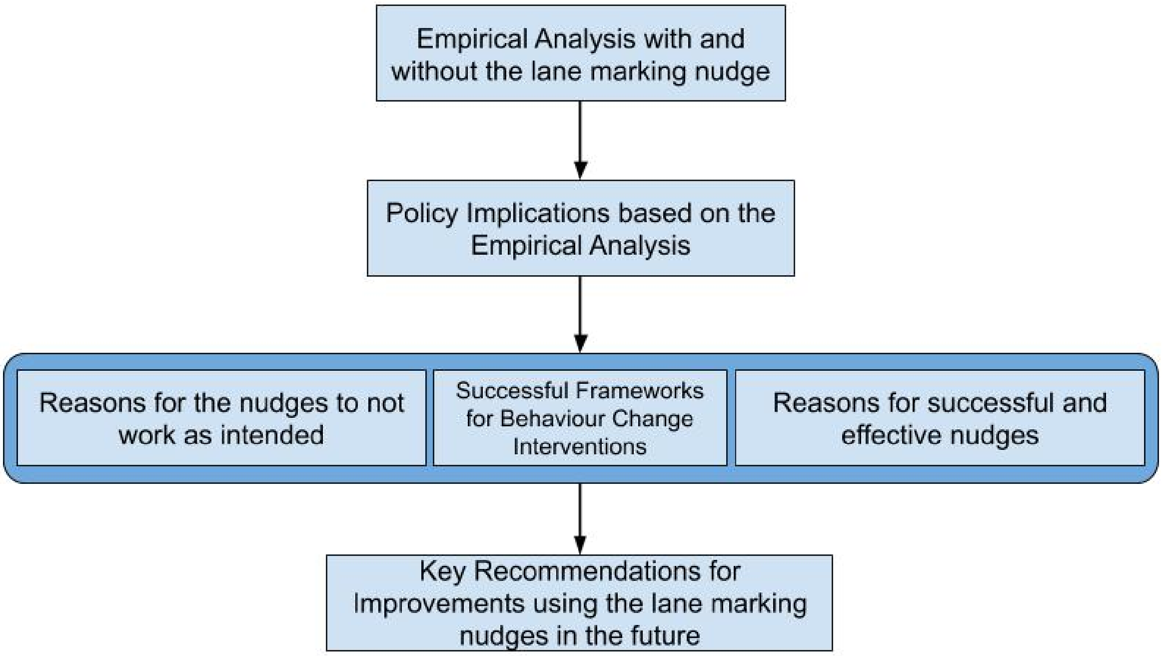

Figure 38. Overview of Discussions on Policy Implications

6.1 Policy Implications

Based on the results and inferences from this research, a generic set of policy implications and recommendations are drafted, which have to be supported with other similar researches or field studies in the future, especially the safety criticality obtained from Surrogate Safety Measure (SSM) have to be validated in the further upcoming researchers in this field. It has to be highlighted that these recommendations and implications are solely based on the results from the empirical field study, which took place in T-Intersection at Eindhoven.

- Transverse lane marking nudge used in this research is not making the road users perform the way it was intended to. Overall, in most of the cases (categorised in figure 23) with the cyclists and mopeds and on all the three-time of days like Sunday, Monday MP and Monday EP, do not tend to reduce their speeds in the presence of the transverse lane marking nudge applied in this case study.

- So, if the transverse lane marking nudge with a similar specification of the length and the infrastructure is implemented, it would not result with a decrease in mean speeds and the safety-critical situations of both cyclists and mopeds is also not proved to decrease with the use of the lane markings. That is there is no statistical evidence from this case study for the reduction with the critical braking instances and critical jerk counts at the T-Intersection in the presence of the transverse lane marking nudge for all the road users sharing the bicycle T-Intersection.

- Further studies have to be performed especially with different specifications of lane marking, in terms of length (increase), the spacing between the transverse lines or another orientation different from the transverse lane marking used in this field study for bringing the expected changes (speeding illusion) with the road users and for the nudge to serve as a traffic calming measure. Clearly, literature suggests that, an increased length of road markings are more effective and are successful when placed for a longer duration of time.

- A more systematic and structured approach should be incorporated for the implementations and design of nudges, with the use of successfully established generic frameworks for a behavioural change intervention (similar to the transverse lane marking nudge implemented in this research) in the road infrastructure.

So, a dedicated discussion is necessary which deals about, (a) what are the reasons for the nudge (used in this research) not to work as intended, supported with existing literature on the nudge theory implementations, (b) the factors necessary for a successful behavioural change intervention using the existing theoretical frameworks on behavioural change interventions and then finally (c) what & how the nudges (in the future) can be improved. All these three are discussed elaborately in the following sub-sections for improvements in the future with the similar application of lane marking nudges.

6.2 Reasons for the nudge not to work as intended

There can be many reasons for the nudge (as a behavioural change intervention) to not work as intended. Even though there might be many interventions which are straight forward in bringing a change, for example, a speed bump or a speed breaker (to have a significant reduction in speed as traffic calming measure), on the other hand, there are also many interventions or measures which are hoped that it would be effective but were not found to be beneficial in few of the previous researches (Grimshaw et al. (2001); Summerbell et al. (2005); Coleman (2010)). Even in the field study conducted with this research, the implemented transverse lane marking nudge did not perform the way it was intended to, and the remaining part of this section would help understand why is that.

Grimshaw et al. (2001), in his research, reviewed forty-one different studies which implemented a wide range of interventions and behaviours. He generalised that, "passive approaches are generally ineffective and unlikely to result in behaviour change". Similarly, Ajzen (2019) concluded that the interventions will be not be effective, however, unless the road users are capable of carrying out their newly formed intentions (Ajzen, 2019). This shows that, it is incumbent on the investigator (or the researcher) to check that there is a significant connection from the intentions to behaviour. If in case this relation is weak, appropriate actions must be taken to improve it. One of the effective ways is to induce the individuals to form an implementation intention, i.e. to form a specific plan detailing, when, where and how the desired behaviour will be performed (Gollwitzer, 1999). So, formulations of these plans will help and assist people to carry out their intended action.

Avineri and Goodwin (2010) highlighted that one of the disadvantaged of the 'nudge' strategy is that, "it is being designed to influence individuals' behaviour through intuitive and impulsive processes of the automatic system they do not address the fundamental problem of behavioural change". They concluded that, nudges are more effective with unintentional/automatic behaviours within a controlled context, but, they are not designed to alter the decision making the process of the reflective system (Avineri and Goodwin, 2010). They also concluded that the nudge theory does not make a significant improvement to the choice set or to the choices' attributes and utilities. Also, unlike some of the conventional measures (such as education), they do not lead directly to a real change to the road user's knowledge, attitudes or values towards the choices and decisions they make. So, all these reasons might thus make it more challenging to maintain and achieve long-term and effective change in the individual's behaviour only by designing measures that are solely based on the nudge strategy. This is because without promoting and maintaining sustainable road safety behaviour through values and attitudes, their effects are likely to get cancelled out (Avineri and Goodwin, 2010). So, it is unlikely to have a control over the general context in which nudge strategies are introduced and changes in the intended behaviour to be achieved might be easily offset by unintended effects or other external factors.

Even though there were few kings of researches in which the nudge did not work as intended, however, there are also a lot of studies which applied the nudge theory and saw significant and successful benefits of the nudge, which will be discussed in the next sub-section. So, all these factors should be taken into account when drafting the improvements for the nudge implementation in the future, which is presented in section 6.5.

6.3 Factors for Effective & Successful Nudge Implementation

A study by Steinmetz, Knappstein, Ajzen, Schmidt, and Kabst (2016) tested the analysed effectiveness of various methods to bring a behavioural change and concluded that motivational appeals, persuasion, and increasing skills were successful. To design an effective intervention (Steinmetz et al., 2016), the policy makers or researcher must initially check whether the road users fail to perform the desired behaviour because they are not motivated to do so (e.g., slowing down at an Intersection), or due to the fact that they are motivated but not capable of carrying out the intended behaviour (e.g., to catch the train at the correct time), or both. For introducing a suitable intention to make the individual perform the expected behaviour, the actions must be focused at behavioural, normative, and control beliefs through which the behaviour of interest is determined (Steinmetz et al., 2016). After this step is achieved, it then important to confirm that the individual would have the means to shift their newly formed intentions into action. All these requires the technique of intervention to be matched with the correct phase of the process (i.e., motivation vs. implementation), supported with the use of intermediate measures of the Theory of Planned Behaviour (TPB) constructs and adaptation of the processes based on the necessity. For example, when the steps taken to change motivation were not effective, continuing with to implementational methods may not be successful. Rather, starting a second cycle of motivational interventions may be more appropriate (Steinmetz et al., 2016).

Various studies of research has identified the effectiveness of theory-based interventions targeting change in modifiable determinants or mechanisms (Abraham (2015); Massey, Decety, Wisner, and Wakschlag (2017); Kok et al. (2016)). Specifically, the interventions based on choice architecture, which is also referred to as 'nudging', have demonstrated effectiveness in changing behaviour in laboratory and field settings (Allais, Bazoche, and Teyssier (2017); Kremers, Eves, and Andersen (2012); Lewis and Eves (2012); Marteau, Ogilvie, Roland, Suhrcke, and Kelly (2011)) in the past. The reason for these nudges implemented to be effective or successful in these studies are discussed further.

The type of nudge used in the studies of Allais et al. (2017), showed that the nudge has an immediate, albeit decaying, peaked effect on individuals' behaviour, with a stronger effect when weak physical effort is made salient. So, it concluded that one option to create effective intended behaviour would be to consider a longer intervention duration. That would allow a sufficient number of behavioural change occurrences and so foster reinforcement and tolerance to make the individuals behave in an intended way for effectiveness. The results from Venema, Kroese, and De Ridder (2017) show that a default nudge can intended increase with the stand-up working rates in offices at least until two months after the nudge intervention. So, both these researchers prove that to create a successful behavioural change a longer intervention duration is necessary. Also apart from the intervention duration, Lewis and Eves (2012) concluded that the traffic flow at the place of the nudge implementation can influence its effectiveness Simple messages appear more suitable for busy sites.

Table 20

List of Do's and Dont's for a Successful and an effective nudge for bringing the intended behavioural change

Do's and Dont's for a Successful and Effective Nudge Implementations		
S.No	**Do's**	**Dont's**
1.	Active approaches to bring a behavioural change	Passive approaches to bring a behavioural change
2.	Coming up with a unique plan detailing, about when, where and how the desired behavioural change will take place	Not checking the capability of the road user for carrying out the newly formed intention
3.	Create a strong link between the intention and the behaviour. That is, to develop an intention to achieve the intended behaviour, the intervention must focus at the behavioral, normative, and control beliefs that eventually determine the behaviour of interest	Forgetting to focus on creating a strong link between the intention and the behaviour
4.	Focus on the fundamental problem of behavioural change, beyond the intuitive and impulsive changes	Only design to alter individuals' behaviour through intuitive and impulsive processes of the automatic system chnages
5.	A design to lead directly to a real change to the individual's knowledge, attitudes or values towards the choices and decisions they make	A design that does not make an objective improvement to the choice set or to the choices, attributes and utilities
6.	Longer intervention duration bring effective and successful intended behavioural changes	A very short intervention duration, not allowing for a sufficient number of behavioral change occurrences and also not fostering reinforcement and tolerance to make the individuals behave in an intended way for effectiveness

The list presented in table 20 summarise all the factors to be considered for a successful and effective nudge implementation and also focusing on all the situations to be avoided which would jeopardise the intended behavioural change with the application of a nudge. Before drafting the key recommendations of the improvements, it would also give a better clarity if the nudge implementation could be modified based on some existing generic frameworks for bringing positive behavioural changes from the literature, which is elaborated in the next sub-section.

6.4 Generic Frameworks for Successful Intervention

To improvise the application of the nudge in the future and understand the shortcomings of the nudges implemented in a field study conducted of this research, a short review of various systematic approaches and key elements involved with the use of a measure (similar transverse lane marking nudge applied in this research) for improved behaviour and safety changes for the road users. For obtaining the relevant literature, "ScienceDirect" search engine was used with keywords or phrases such as, "behavioural economics", "behavioural change interventions" and, "nudge as a safety measure". This section also assists how the implementation of lane marking nudges could be successfully implemented in the future and also be a part of a generic well-structured & a systematic approach for the future field studies and for effective policy measures. It also elaborates on what other elements to be focused more in the future research to give an extensive general overview used to bring policy changes with the successful use and implementation of the nudge as a traffic calming measure or a safety measure.

Nudges could be very well considered as a type of intervention to bring behavioural or safety changes in the road infrastructure with the intention of positively impacting the road user behaviour and eventually improve the safety of the road users as well (Thaler & Sunstein, 2008). The definition of a nudge by Hausman and Welch (2010), also indicates the same idea with respect to the concept of nudging (presented in detail with the literature in section 2.3). These types of behavioural change interventions are crucial for a significant well being of the road users and the safety issues faced by the road users. As mentioned in the study on behavioural change interventions by Michie et al. (2011), a 'Behaviour change interventions' can be defined as coordinated sets of actions formulated to change specified behaviour patterns. In this research, the nudge as a behavioural change intervention is applied to improve the safety critically of the road users at a particular T-Intersection.

So, in order to improve these kinds of situations as in the future research, an improved design, planning and application strategies are necessary to implement these kinds of behavioural change interventions (nudges) leading to a structured policy planning and to have an expected outcome of positive behavioural adaptation and eventually improve safety. Since there is no explicit theoretical framework dealing with the nudges, the general frame works used for any behavioural change intervention is compared to improve the concept of nudging in the future.

There are multiple generic frameworks addressing a systematic, structured approach and theoretical frameworks for any general implementation considering all the relevant policy categories and intervention actions necessary with respect to the successful behavioural changes such as the,

- 'MINDSPACE' an influential report from the UK's Institute of Government, is intended as a checklist for policymakers of the most important influences on behaviour (MINDSPACE, 2010).
- Cochrane Effective Practice and Organisation of Care Review Group (EPOC)'s 2010 taxonomy (EPOC, 2010).
- Behavioural change Wheel (Intervention functions relevant to various policy categories) (Michie et al., 2011).

Each of the frameworks has proposed several steps in order to achieve the intended outcome of a behavioural change intervention. One part which is clear is that there are a lot of diverse factors that explain systematic deviations with the road users' behaviour, from the predictions of rational models to the potential application of contextual design and other insights emerging from nudges to the design of behaviour change measures with relevant policies (Avineri, 2014). Even though it might not be an exclusive framework of behavioural economics applications for designing successful change interventions, the MINDSPACE framework had multiple benefits and effectiveness with its application. To give a brief idea, table 21 give a gist of the nine key elements along with brief descriptions made in a road user behaviour context applying the MINDSPACE framework. A more comprehensive elaborate explanation of the MINDSPACE frame work can be found in the Appendix D.

Out of these 9 elements of the MINDSPACE framework listed in table 21 for bringing a successful change in the behaviour, the nudge strategy incorporates only the "Priming" and does not fully address any of the other elements used in this framework, related to the road users attitude or values, by assuming that the road users might subconsciously change their behaviour, which was not found to be the true from the empirical research, in this study.

So, based on the conclusions of Avineri and Goodwin (2010) and with use of the MINDSPACE framework, it is advisable to also promote the nudges in such a way to incorporate or change the road user values and attitude (maybe by using a suitable "Messenger" as done with the MINDSPACE framework) and not only relying on the fact that the nudge to subconsciously change the road user behaviour. So, it is recommended to incorporate a few more additional elements along with the nudge, such as choosing a correct, "Messenger" inspired from MINDSPACE framework as shown in 21.

It is also a similar case with the application of the "behaviour change wheel" introduced by Michie et al. (2011). The behavioural change wheel as shown in the figure 39 has already incorporated the drawbacks and shortcoming of the framework EPOC's taxonomy frameworks to make it applicable for any kind of successful intervention in the future covering all the necessary policy categories and intervention actions for a successful outcome. So in the rest of this section, the behavioural change wheel will be focused more in detail to check how could it be modified or be used for a successful implementation in case of the transverse lane marking nudge as well as

Table 21

MINDSPACE – the role of context on behaviour (Source: Dolan et al. (2010) and Dolan et al. (2012))

S.No	Key Elements	Brief Description
1.	Messenger	We are heavily influenced by who communicates information.
2.	Incentives	Our responses to incentives are shaped by mental shortcuts.
3.	Norms	We are strongly influenced by what others do.
4.	Defaults	We 'go with the flow' of pre-set options.
5.	Salience	Our attention is drawn to what is novel and seems relevant to us.
6.	Priming	Our acts are often influenced by unconscious cues.
7.	Affect	Our emotional associations can powerfully shape our actions.
8.	Commitments	We seek to be consistent with our public promises and reciprocate acts.
9.	Ego	We act in ways that make us feel better about ourselves.

any type of nudge in the future to have a positive or higher chance of a successful outcome in its implementation.

The research Michie et al. (2011) performed an extensive literature review on different ways to implement behaviour change interventions and summarised seven policy categories, nine intervention functions and three broad sources of behaviour as respected in the figure below, calling it the "behavioural change wheel" applicable to any interventions for the future (1,267 articles were identified from the electronic databases, to come up with the new framework presented with the behavioural change wheel depicted in the figure 39). It is important to note that this behavioural change wheel is a generic framework applicable to all behavioural change measures or interventions. From this behavioural change wheel proposed by Michie et al. (2011), it is checked and verified if the interventions functions and the sources of behaviour relevant factors could help improve the implementations of the nudges in the future.

Out of nine the intervention functions mentioned in the behavioural change wheel the nudge theory does not seem to fully incorporate any of those in order to expect a positive change with the behaviour. Even though the nudge theory is expected to change the behaviour subconsciously, it would be additional support (or make the nudge better) if at least one of the intervention function like the persuasion, education or training is included. This also helps to change the attitude or choices on the top of altering the impacting the behaviour subconsciously.

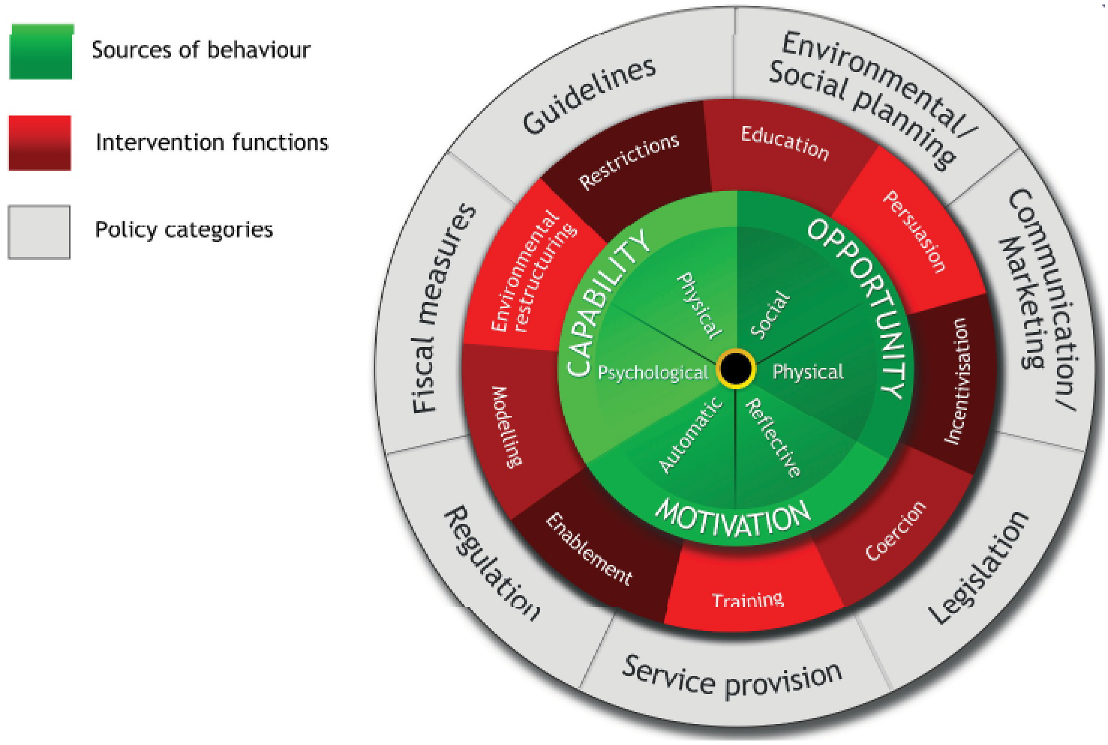

Figure 39. Behaviour Change Wheel (Michie et al., 2011)

Interestingly it is also realised that a policy category focusing on the video/camera surveillance for data collections needed for empirical research or modelling is not explicitly included in this behavioural change wheel and the MINDSPACE framework, which is also a very crucial and necessary addition to this behavioural change wheel especially if applied to test the naturalistic behaviour of the road user (Avineri, 2014). So, apart from the camera or video surveillance, the other interventions function inspired by the behaviour change wheel which could be to be added with the implementations of the nudges are persuasion (i.e. Using communication to induce positive or negative feelings or stimulate action), additional restrictions, detailed environmental restructuring (i.e. changing the physical or including social context) or providing an example for road users to aspire to or imitate. An elaborate definition of all the nine intervention functions are defined with examples in Appendix C.

So, apart from all the do's and dont's for a successful and effective nudge implementation mentioned in the table 20, the crucial leanings from the two generic frames works, MINDSPACE and the behavioural change wheel are:

- Not to only rely on influencing the behaviour sub-consciously, So, additional elements have to be incorporated to achieve the intended behaviour with the nudge.
- Draft an effective and better way of communicating or 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 on 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 helps determine the behaviour of interest.

6.5 Key Recommendations for Future Improvements with Nudge

Since, the transverse lane marking nudge implemented in this case study was proved not to be efficient with the speed reduction of the road users and not recommended in using it as a traffic calming measure at the T-Intersection, in the same way as done with this case study. So, clearly, the lane marking nudge has to be improved or some crucial changes have to be implemented in order to avoid these kinds of unexpected results in the future.

So, based on all the action steps of what to do and what not to do elaborated in sections 6.2 and 6.3, respectively, along with the list of learning from the generic frameworks for successful and effective nudge implementation as a behavioural change interventions in section 6.4, few concrete improvements are recommended for the future nudge implementations are:

- Since, passive approaches are generally ineffective and unlikely to result in behaviour change (Grimshaw et al., 2001), the nudges implemented in the future should involve active changes with the choice architecture (Benjamin, Rainer, and Peter (2010); Larrick and Soll (2008)) made by the road user. More studies and research should be incorporated focusing on understanding the choice architecture by the users with the application of nudges before implementations (Johnson and Goldstein (2003); Cronqvist and Thaler (2004)).

- Ensuring that there is a strong connect from the intentions to behaviour. This could be achieved by inducing the road users to form an implementation intention, i.e. to form a specific plan detailing, when, where and how the desired behaviour will be performed (Gollwitzer, 1999), with respect to the lane marking nudges.

- The nudge intervention must be targeted at behavioural, normative, and control beliefs that ultimately determine the behaviour of interest. So, the lane marking nudges should also include all these three elements in future implementations.

- There has to be a dedicated study to check the steps needed to incorporate the stronger motivation for a safer behaviour of the road users. When the steps taken to change motivation were not effective, the continuing with the implementational methods may not be successful. Instead, starting a second cycle of motivational interventions have greater chances of bringing a successful and intended behavioural change.

- To create effective intended behaviour of nudge is to consider a longer intervention duration to study the intended behaviour. That would allow a sufficient number of behavioural change occurrences and so foster reinforcement and tolerance to make the individuals behave in an intended way for effectiveness.

- Adding or incorporating few of the relevant steps inspired from the "Behavioral change wheel" and "MINDSPACE" frameworks, an effective and successful outcome could be expected with a higher chance of positive behavioural changes along with a structured way (with incorporating more intervention functions or elements) of approaching the implementations of lane marking nudge which could help in drafting more concrete policy recommendations and implications. More details and proof regarding exactly what all intervention function and elements should be adopted or necessarily have to be further researched in the future, but this section mainly concludes that at least few interventions from the MINDSPACE framework (like choosing the correct way of communication) and inspired improvements from the behavioural change wheel (like better persuasion, education or training should be included) have to be considered and definitely not relying only on the fact that the nudge to subconsciously change the road user behaviour. So, the nudging and educating should be treated as complementary to each other and not separately used to bring intended changes for safer road users behaviour.

It should be highlighted that all these suggested recommendations for improvements also make sure that it is not altering the core definition of the nudge (Thaler and Sunstein (2008); Hausman and Welch (2010)) maintaining the core advantages and benefits of the nudge.

7 Conclusions

7.1 Research Objective

The main objective of this master thesis is to explore if there is a significant influence on the cyclists' & the mopeds users' speeding behaviour along with quantifying the safety criticality with and without a lane marking nudge (transverse strips, perpendicular to the movement of the road users) at the T-Intersections. So, one of the key aim is also to check if the transverse lane markings help to reduce the speed with cyclists & mopeds along with whether it has an impact of the safety criticality of the road users at the shared cyclist T-Intersections. In this research, the safety criticality is the safety-critical braking events, to detect evasive actions such as sudden speed changes of individual road users. Apart from these, the research explores if all the elements for the lane marking nudge implementation are incorporated in the existing generic frameworks for the behavioural change interventions to support the various policy categories and suggest some actions to be taken for its successful implementation in the future. Finally, this research aims to come up with some concrete policy recommendations and improvements with the use of the transverse lane marking nudge in the cycling infrastructure, i.e. the T-Intersection.

7.2 Findings from the Empirical Analysis

The speed behaviour is quantified by using the mean speeds and acceleration of the road users. The safety criticality is quantified by using the deceleration and jerk as a Surrogate Safety Measure (SSM). All these necessary performance indicators are analysed as various correctional areas with respect to the nudge stretch. These cross-sectional areas are chosen with respect to the nudge implemented location, which are, before reaching the nudge, at the start, middle and end of the nudge and also after crossing the nudge. The variations (with and without the nudge) in the performance indicators were explicitly analysed on Sunday, Monday morning peak and Monday evening peak, distinguishing the upstream movement (from before reaching the nudge implemented location till the start of it), the through and the turning movement (both from the middle of the nudge implemented location till the road users cross it) for both cyclists and mopeds. The results and interpretations are explained in the following sections within this sub-section.

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 in 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.

Considering the variations within the control group road users, the major findings on the performance indicators from the transverse lane marking nudge ides in this field study are:

- In the nudge scenario, the mean speeds of cyclists before reaching the lane marking implemented location, at the start, middle, end and after crossing the nudge were high compared to the no-nudge scenario. Due to the variations with the mean speeds of the control group, further analysis including the weather conditions have to be analysed to confirm the findings. Since, this field study encountered slight rains during the no-nudge scenario, which could also be a major reason for the variations with the mean speed. Similarly, even with moped users, the mean speeds was high in the nudge scenario across all the cross-sectional bands.

- 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 mopeds after crossing the nudge implemented location.

- 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 be responsible for,

  - creating an illusion of a stop line,
  - 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.

- 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 gives rise to increased critical braking instances and high jerk counts. It is same with all the corresponding cases where there was a higher deceleration with the nudge.

- Few cases had reduced safety critical instance with the presence of the nudge. One of two cases is, with the turning cyclists (on Monday MP at the middle of the nudge stretch). The other case was with upstream moped (on Monday MP before reaching the nudge stretch). This could imply that, even though the moped users seem to treat the lane marking as a stop line or a sudden obstacle from the start of the nudge, they are prepared to encounter the lane marking well before reaching the nudge in the presence of it. Similarly, the only two cases where the critical jerk counts were less in the nudge scenario was the through cyclists (at the end of the nudge on Sunday and after crossing the nudge on Monday MP). It both these cases the through cyclists due to the increased braking (more deceleration and critical braking instances) at the start and the middle of the nudge stretch they tend to compensate the loss of time or compensate the perceived delay due to the brakings. So, they tend to accelerate which shows reduced critical jerk counts in the presence of the lane marking nudge in these two cases.

7.3 Reflection on Policy discussions on Nudge Theory

7.3.1 Policy Implications

Based on the conclusions 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).

7.3.2 Successful and Effective Nudges

The table 22 summaries all the crucial factors which made the nudges successful and effective in the past, along with elaborating what not to do to achieve the intended behavioural change with the nudge implementations in the future.

Table 22

List of Do's and Dont's for a Successful and an effective nudge for bringing the intended behavioural change

Do's and Dont's for a Successful and Effective Nudge Implementations		
S.No	**Do's**	**Dont's**
1.	Active approaches to bring a behavioural change	Passive approaches to bring a behavioural change
2.	Coming up with a unique plan detailing, about when, where and how the desired behavioural change will take place	Not checking the capability of the road user for carrying out the newly formed intention
3.	Create a strong link between the intention and the behaviour. That is, to develop an intention to achieve the intended behaviour, the intervention must focus at the behavioral, normative, and control beliefs that eventually determine the behaviour of interest	Forgetting to focus on creating a strong link between the intention and the behaviour
4.	Focus on the fundamental problem of behavioural change, beyond the intuitive and impulsive changes	Only design to alter individuals' behaviour through intuitive and impulsive processes of the automatic system chnages
5.	A design to lead directly to a real change to the individual's knowledge, attitudes or values towards the choices and decisions they make	A design that does not make an objective improvement to the choice set or to the choices, attributes and utilities
6.	Longer intervention duration bring effective and successful intended behavioural changes	A very short intervention duration, not allowing for a sufficient number of behavioral change occurrences and also not fostering reinforcement and tolerance to make the individuals behave in an intended way for effectiveness

Apart from all the do's and dont's for a successful and effective nudge implementation mentioned in the table 22, the crucial leanings from the two generic frames works, MINDSPACE and the behavioural change wheel are:

- Not to only rely on influencing the behaviour sub-consciously, 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.

7.3.3 Key Recommendations for improvements

Finally, based on all the action steps 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 are:

- 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.
- Should ensure that there is a strong link from the intentions to behaviour by inducing road users to form an implementation intention, i.e. to form a specific plan detailing, when, where and how the desired 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.
- Considering a longer intervention duration to study the intended behaviour.
- Inspired from the generic frameworks on behavioural change interventions, at least few actions from the MINDSPACE framework (like choosing the correct way of communication) and few elements from the behavioural change wheel (like better persuasion, education or training should be included) have to be considered and definitely not relying only on the fact that the nudge to subconsciously change the road user behaviour.

7.4 Research Limitations

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. And it is the same case with this research as well, which are listed and explained briefly.

- **Cycle parking facility at the T-Intersection**: As mentioned earlier in the report that there a large cycle parking facility (in the pedestrian footpath) placed next to the lane marking nudge location, which was much longer than the stretch of the nudge. So, there was also a large number of cyclists parking their cycles in the morning peak or taking back heir cycles in the evening peak. Even though the data was chosen to avoid these instance (using the coordinate boxes for specific movement types and cross-sectional bands to capture the road user movements only with the cross-sectional band) to capture the full influence of the lane marking nudge alone, it might have had an impact with the road users who were not planning to park their cycles. Especially, the mopeds would have probably had an influence on the cyclists' coming out of the parking location. As mentioned earlier, the application of the deceleration and jerk SSM implicitly considers the critical instances due to this situation as well. But, the explicit study of direct influence on the parking behaviour of the cyclists with and without the lane marking nudge is beyond the scope of this research.

- **Weather conditions during the field study:** Unfortunately on 8th of December (Sunday), it was raining in the raining in a few intervals from 7:00 am till afternoon and on the 9th of December (Monday MP and EP) as well. This was the period of the second phase of the field study without the lane marking nudge. So, this definitely would have had an impact on the flow and the wet surface would also have an impact on the speeds and braking of the road users which was not possible to take into account within this research. Apart from this, the temperature in the nudge scenario varied from -1*C to 4*C (with icy fog in few time intervals which was included in the analysis of this research) most of the time, whereas the temperature without the nudge scenario was higher and varied from 7*C to 10*C throughout, which could have also had influence with the results, which was beyond the scope of this research to incorporate in this study.

- **Data collection with and without the nudge scenarios:** The video surveillance of the filed study performed by the third party is done initially with the presence of the nudge and then without the lane morning nudge. This procedure is opposite to the conventional way of testing a measure. Since the scope of this research was not related to the choice of filed study location and collection, this is also a limitation which might have impacted the influence of the behaviour in the scenario without the nudge in the second phase after collecting the data of the road used in the presence of the lane marking nudge. This might be a limitation because, in the no nudge scenario after the collecting the data with the nudge scenario, there will be a possibility of a learning behaviour or behavioural adaptation due to the use of the lane marking nudges. So, if the road users would have already changed or adapted the behaviour with the presence of the lane making, this could have an impact of the road users with the lane marking lanes, which is collected after the data collection phase with the nudge scenario. So, to avoid the chances of a learning effect or behavioural adaptation of the road user, in future studies, it is advised to collect the data with the lane marking implementation and then with the lane markings.

- **Wear-off with the lane marking:** In this research, the length of lane marking nudge was 16m, but actually, it was planned to be 19.6 m, but the lane marking machine got heated up, and it was not possible to place the lane two-line away from the centre of the T-Intersection in the upstream side of the road user approaching the lane marking. The choice of the location of the field study, application of the lane marking and its measurements were also not a part of this research. But with those two extra lines, the nudge stretch would have been extended by a 3.6m which would have had considerable differences with the changes in behaviour and safety critically with the use of the transverse lane marking nudge.

- **Limitations of using the coordinate polygons and cross-sectional bands:** As explained earlier a pair of coordinate polygons are used to filter the different movements types and the cross sectional bands are used to capture the trajectories within the band for obtaining all the performance indicators. One of the limitations of using the technique of coordinate polygon, is that the trajectories who are not starting or ending within these coordinate polygon are not considered. Also, the trajectories outside of the cross-sectional band are not considered. But, usually, it is expected that the road users should use their own lane moving in a particular direction. So, if in case a road user is overtaking, he/she would move to the lane meant for the opposite direction, which might be missed with the use of the cross-sectional bands. Also, in the field, the cyclists T-Intersection did not have a center line in the scenario without the nudge to separate the bi-directionality.

- **Camera overlap with the video surveillance:** A major limitation is that with the video surveillance data, the camera 1 and 2 had a considerable 2.5m gap between the coverage. Also, the IDs of the tracked road users in camera 1 and 2 had totally different and unique IDs even if the same road users are tracked in both the cameras. So, it could still be argued that the time stamps from the data could be used to stitch the road user trajectories from the camera 1 and 2. But, the cycling parking facility placed along the entire stretch of the nudge implemented location and further, introduced high chances of the cyclists starting from the parking at the joining the other road users at the same time stamp (which is the main criteria and assumption that it could be the same road user for for stitching the road user trajectories and avoid the gap) as well. This made it difficult to track the road users approaching the nudge to distinguish if they are going straight (through) or turning at the T-Intersection. But it had a clear coverage and possibility to identify the different movement types from the camera 2 as mentioned earlier from the middle of the nudge implemented location.

- **Interruption with the video recording:** After approximated two and a half days during the nudge scenario, the video recording setup encountered a malfunction and stopped working. Which eventually failed to record the video after that. So, this was the reason the video recording during with the nudge scenario was for 2.5 days and similar time period was chosen for the analysis without the nudge scenario to approximately have a similar road user time frames, for comparison.

7.5 Future Recommendations

To overcome the limitations mentioned in the previous sub-section, a concise list of all the recommendations are elaborated which could be focused in the future research. These are:

- **Explicit interviews or surveys with the road users**: A separate interview or a stated choice survey has to conducted with few of the road users crossing the nudge implemented location. To check if they actually had a speeding illusion or not. And if in case they report that they experienced a speeding illusion, it should further be checked with the road users that, was the speeding illusion enough motivation to make them slow down or not. Additionally, it could also be clarified (if in case they experienced a speeding illusion) how did they slow down, that is, whether they reduced there speed gradually or suddenly. This would definitely help in reconsidering the specification of the transverse lane marking applied in this research.

- **Validation of the SSM indicators**: As already mentioned, both the SSM used in this research has to be validated with the use of other indicators or the use of the hospital data or the crash data at that location in the future. Even though jerk and deceleration as a SSM have a reasonable correlation, it has to be validated that which has a better performance with the conflict deduction with then actual crash data in the future.

- **Explicit inclusion of road user interactions**: A more explicit focus has to given to differentiate between the pedestrian movements, interactions between the various road users (cyclists, moped users and pedestrians) and the cycle parking interaction very close to T-intersection like the one found in the study. Especially since the parking is built very close to the T-Intersection and given there is a tunnel, it might result in a lot of safety-critical conflicts critical to the parking interaction of the cyclists. Also, the conclusions from Dozza and Werneke (2014) indicates that, if there is an intersection near building and hedges (i.e. with some form of visual occlusion) the risk increases up to 12 times. So, it would be a good scientific contribution if these interactions are studies explicitly and separately. This would eventually help to modify the infrastructure, change the design or create a separation between the road and the parking facility, to avoid sudden surprises for the road users from the parking facility.

  Additionally, the presence of lane marking nudge could also influence the pedestrian crossing movement at the T-Junction. The pedestrians might possibly try to avoid the nudge implemented location and would cross either after or before the nudge implemented location in the presence of the lane marking, which could eventually have a different effect on the performance indicators.

- **Influence of Nudge on Demographics data of the road users**: In this research due to privacy reasons, the demographic data of the road users such as the age, gender, occupation and other relevant demographics data were not provided. These demographic factors would have a different impact with the use of the lane marking nudges since the nudge tries to make the road user behave in a safer way, subconsciously. So, the effect in the subconscious changes would depend on the age and gender. Especially the perception with the use of the lane marking nudge would have a high probability for variation with the young-aggressive road users sharing the infrastructure with the old-less aggressive road users.

- **Influence of Nudge on the bi-directionality of the T-Intersection**: As mentioned earlier, apart from the transverse lines there is also a center line which can be seen in the figure 9. So, the effect of this center line is not focused on this research. But it could be possible that this center line could create more separation between the bi-directional road users, reducing the safety critical instances of the road users coming in opposite directions. So, it would be interesting to see, if the center line makes the road users be within their lane and eventually improve the safety of the bi-directional road user interactions.

Figure 40. Peripheral speed reducing lane markings (FHWA, 2015)

- **Impact of lane marking nudges on the peripheral vision**: With the application of speed reducing lane marking nudges for cars, it is sometimes implemented only at the edges of the lane (also called the peripheral lane markings). These also have a reducing spacing in between two consecutive markings similar to the lane marking nudge implemented in this research but not along the entire width if the lane, as shown in figure 40. So, in the future studies, it is also recommended to empirically test if these kinds of peripheral lane marking nudges would have a better impact and influence with reducing speeds and improving the safety of cyclists and mopeds at the T-Intersection.

- **Future applications of Jerk Analysis**: Apart from quantifying safety-critical situations, jerk analysis has many more applications in the future. It can have some significant contributions with tuning the simulation model and vehicle speed control models. So, performing a bicycle simulator study with various types of lane marking nudge would also be a cheaper option compared to the field, such as done in this research simulator. So, it is also recommended to test a wide variety of lane marking, with a different orientation, gap, length of the nudge stretchy and then choose the best kind of lane marking nudge to check for the obsolete or at least relative validity with the field test. This would be a more economical option and probably would not give unexpected results as obtained from the filed study as performed in this research.

- **Errors and Uncertainty with the variables calculated**: Almost all the fields of research involving empirical analysis involve a certain degree of error and uncertainty associated with the measurement (Von Martins (2000); Hund, Massart, and Verbeke (2001)). Especially the error and the uncertainty may propagate more with the third and higher-order variables obtained from the measured variables in the filed study as in this research. So, it is highly recommended in the future to incorporate the errors and uncertainty analysis, especially when the jerk analysis is being applied. Since jerk is a third-order differential, it might have an error associated with it, even though the positional and temporal data might be highly accurate. Since in this research it is a comparative study with the use percentages changes for the interpretation of the results, it is reasonable to assume error if any would be present in both the scenarios and the changes in the behaviour or the safety is due to the presence of the lane marking nudge. However, if the Jerk analysis is used for other applications like the simulation models and vehicle speed control models, it is advisable to perform the error and uncertainty analysis.

  So, in future applications of jerk, for improved accuracy detection of all the safety-critical driver behaviour, it is recommended to filter out the noise to such an extent that the fluctuations of the derivatives are minimised. In order to calculate jerks based on acceleration data as done in this research, it is highly recommended to reduce the noise as much as possible, apart from the method of moving averages used to calculate the performance indicators applied in this research.

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A Global Framework Plan of Action for Road Safety

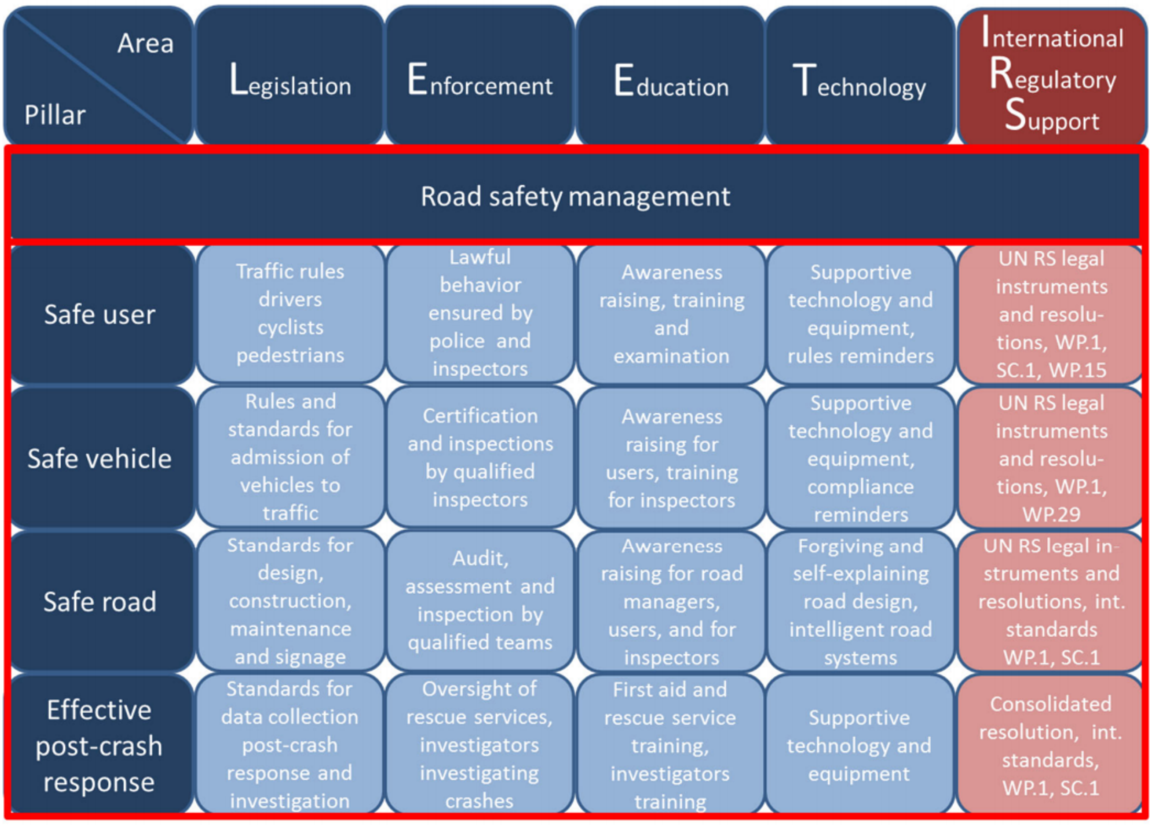

Figure 41. Global Framework Plan of Action for Road Safety (UNRSTF, 2018)

B Results for all the cases

All the tables stat ring from table 23 shows the mean speeds, accelerations and the percentage changes for only the through cyclists, with the clear distinction of each specific case in the first three columns grouped together with the header representing the time of day and the cross-sectional band position in which the speeds and accelerations were calculated followed by the percentage changes of the indicator. It has to be noted that in the column of percentage change with mean accelerations 'CD' represents the change in the directionality, which means that there is a change in sign of the mean acceleration either from accelerating to decelerating or vice-versa with and without the nudge scenario. These tables are generated to to have a structured presentation of the results (before statistical testing) and generic understanding with all the various cases (categorised in the figure 23) per road user per movement type.
Based on the calculations elaborated in section 4.6.2,the final results of the critical deceleration counts and the jerk counts (per 1000 road users) for through cyclists, through mopeds, turning cyclists and turning mopeds are presented in tables 26, 28 and 34 respectively, for both nudge and no-nudge scenarios separately. Finally, table 39, shows the Pearson's correlation coefficient to capture the relationship between the critical braking instances and critical jerk counts for all the different combination groups.

Table 23

Mean Speeds and Acceleration of Upstream Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
			Nudge	No-Nudge		Nudge	No-Nudge	
Upstream Cyclists	Sun	Before	14.992	13.843	8.300	0.078	-0.043	CD
		Start	15.896	15.527	2.377	0.118	0.135	-12.621
	Mon MP	Before	17.050	15.874	7.406	-0.418	-0.520	-19.550
		Start	16.869	16.738	0.781	0.130	0.098	32.931
	Mon EP	Before	16.669	15.289	9.024	-0.640	-0.372	71.757
		Start	16.337	15.698	4.066	0.128	0.148	-13.209

Table 24

Critical Jerk counts & Deceleration counts of Upstream Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Relative Critical Jerk Count/ 1000 road users		Relative Critical Dec Count/ 1000 road users	
			Nudge	No-Nudge	Nudge	No-Nudge
Upstream Cyclists	Sun	Before	11.418	15.810	11.048	11.788
		Start	17.128	11.160	4.249	4.080
	Mon MP	Before	13.101	12.036	14.789	17.603
		Start	19.651	12.036	1.056	10.269
	Mon EP	Before	11.227	13.956	14.937	15.422
		Start	21.051	11.165	9.505	3.629

Table 25

Mean Speeds and Acceleration of Through Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
			Nudge	No-Nudge		Nudge	No-Nudge	
Through Cyclists	Sun	Middle	15.086	14.805	1.897	0.172	0.094	84.002
		End	14.825	14.605	1.504	-0.024	0.013	CD
		After	14.778	14.234	3.820	-0.065	-0.091	-28.193
	Mon MP	Middle	15.897	16.025	-0.802	-0.065	0.024	CD
		End	15.244	15.328	-0.548	-0.073	-0.198	-63.389
		After	15.291	15.181	0.726	0.013	-0.008	CD
	Mon EP	Middle	15.145	14.823	2.168	-0.052	0.126	CD
		End	14.346	14.573	-1.558	-0.149	-0.019	680.001
		After	14.897	14.714	1.238	0.060	-0.017	CD

Table 26

Critical Jerk counts & Deceleration counts of Through Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Relative Critical Jerk Count/ 1000 road users		Relative Critical Dec Count/ 1000 road users	
			Nudge	No-Nudge	Nudge	No-Nudge
Through Cyclists	Sun	Middle	13.681	11.647	16.180	18.656
		End	11.401	19.966	9.561	8.111
		After	11.401	21.630	3.677	2.433
	Mon MP	Middle	30.444	11.547	29.458	15.761
		End	12.178	18.474	14.729	18.013
		After	12.178	53.114	1.473	6.755
	Mon EP	Middle	11.260	13.146	36.876	22.139
		End	19.055	11.951	22.628	8.156
		After	11.260	16.731	9.219	6.991

Table 27

Mean Speeds and Acceleration of Turning Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
			Nudge	No-Nudge		Nudge	No-Nudge	
Turning Cyclists	Sun	Middle	12.805	10.436	22.700	-0.193	0.407	CD
		End	12.006	10.333	16.198	-0.258	0.200	CD
		After	11.897	11.626	2.334	-0.349	0.240	CD
	Mon MP	Middle	13.463	11.230	19.882	0.103	0.501	-79.343
		End	13.164	10.946	20.258	-0.085	0.131	CD
		After	12.997	12.279	5.842	-0.563	0.263	CD
	Mon EP	Middle	13.268	10.730	23.649	-0.219	0.331	CD
		End	11.920	10.928	9.084	-0.421	0.179	CD
		After	11.812	11.569	2.107	-0.143	0.220	CD

Table 28

Critical Jerk counts & Deceleration counts of Turning Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Relative Critical Jerk Count/ 1000 road users		Relative Critical Dec Count/ 1000 road users	
			Nudge	No-Nudge	Nudge	No-Nudge
Turning Cyclists	Sun	Middle	50.953	11.146	35.216	4.347
		End	48.527	11.146	9.391	4.347
		After	50.953	11.146	9.391	2.173
	Mon MP	Middle	148.085	15.385	9.882	0.000
		End	204.255	15.385	4.941	15.000
		After	163.404	15.385	9.882	0.000
	Mon EP	Middle	56.452	16.182	21.849	7.889
		End	101.614	16.182	16.387	0.000
		After	50.807	16.182	0.000	0.000

Table 29

Mean Speeds and Acceleration of Upstream Mopeds

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
			Nudge	No-Nudge		Nudge	No-Nudge	
Upstream Mopeds	Sun	Before	23.634	21.924	7.802	-0.507	-0.346	46.745
		Start	23.133	22.989	0.625	-0.299	-0.403	-25.834
	Mon MP	Before	22.701	21.779	4.234	-0.908	-0.274	231.431
		Start	21.501	21.170	1.567	-0.086	-0.396	-78.186
	Mon EP	Before	23.843	21.207	12.431	-0.412	-0.558	-26.207
		Start	21.267	21.131	0.641	-0.532	-0.167	219.224

Table 30

Critical Jerk counts & Deceleration counts of Upstream Mopeds

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
			Nudge	No-Nudge		Nudge	No-Nudge	
Upstream Mopeds	Sun	Before	23.634	21.924	7.802	-0.507	-0.346	46.745
		Start	23.133	22.989	0.625	-0.299	-0.403	-25.834
	Mon MP	Before	22.701	21.779	4.234	-0.908	-0.274	231.431
		Start	21.501	21.170	1.567	-0.086	-0.396	-78.186
	Mon EP	Before	23.843	21.207	12.431	-0.412	-0.558	-26.207
		Start	21.267	21.131	0.641	-0.532	-0.167	219.224

Table 31

Mean Speeds and Acceleration of Through Motor-Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
			Nudge	No-Nudge		Nudge	No-Nudge	
Through Mopeds	Sun	Middle	21.123	22.453	-5.923	0.146	0.169	-13.624
		End	13.638	13.461	1.317	-0.055	0.161	CD
		After	21.085	21.780	-3.190	-0.296	-0.315	-6.209
	Mon MP	Middle	19.222	20.880	-7.942	-0.330	-0.187	76.748
		End	15.052	15.708	-4.172	-0.030	-0.049	-38.919
		After	19.337	20.594	-6.106	0.123	0.083	49.601
	Mon EP	Middle	19.122	18.968	0.810	-0.369	-0.004	NA
		End	13.891	15.666	-11.328	-0.044	0.172	CD
		After	19.564	19.132	2.260	0.033	-0.093	CD

Table 32

Critical Jerk counts & Deceleration counts of Through Motor-Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
			Nudge	No-Nudge		Nudge	No-Nudge	
Through Mopeds	Sun	Middle	21.123	22.453	-5.923	0.146	0.169	-13.624
		End	13.638	13.461	1.317	-0.055	0.161	CD
		After	21.085	21.780	-3.190	-0.296	-0.315	-6.209
	Mon MP	Middle	19.222	20.880	-7.942	-0.330	-0.187	76.748
		End	15.052	15.708	-4.172	-0.030	-0.049	-38.919
		After	19.337	20.594	-6.106	0.123	0.083	49.601
	Mon EP	Middle	19.122	18.968	0.810	-0.369	-0.004	NA
		End	13.891	15.666	-11.328	-0.044	0.172	CD
		After	19.564	19.132	2.260	0.033	-0.093	CD

Table 33

Mean Speeds and Acceleration of Turning Motor-Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
			Nudge	No-Nudge		Nudge	No-Nudge	
Turning Mopeds	Sun	Middle	15.370	16.092	-4.485	-0.784	-0.730	7.393
		End	11.800	10.731	9.956	-0.673	-0.644	4.609
		After	13.645	13.947	-2.170	0.041	0.078	-46.877
	Mon MP	Middle	14.925	14.610	2.150	-1.772	-0.321	451.658
		End	12.391	12.635	-1.937	-0.621	-0.978	-36.451
		After	12.297	12.115	1.501	-0.006	0.480	CD
	Mon EP	Middle	14.713	14.882	-1.132	-0.622	-0.606	2.644
		End	12.094	11.287	7.155	-0.484	-0.643	-24.667
		After	12.960	12.967	-0.053	0.339	-0.093	CD

Table 34

Critical Jerk counts & Deceleration counts of Turning Motor-Cyclists

User/Time of Day/Cross-Sectional Band Position w.r.t. Nudge			Relative Critical Jerk Count/ 1000 road users		Relative Critical Dec Count/ 1000 road users	
			Nudge	No-Nudge	Nudge	No-Nudge
Turning Mopeds	Sun	Middle	14.782	28.935	85.816	70.530
		End	14.782	28.935	64.362	56.424
		After	22.172	14.468	28.605	21.159
	Mon MP	Middle	160.486	0.000	116.464	29.583
		End	0.000	121.367	0.000	29.583
		After	80.243	0.000	38.821	0.000
	Mon EP	Middle	0.000	87.384	76.281	85.200
		End	59.126	0.000	38.140	21.300
		After	78.835	0.000	0.000	42.600

Table 35

Mean Speeds and Acceleration of Control Group Cyclists

Cyclists		Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
		Nudge	No-Nudge		Nudge	No-Nudge	
Control Group	Sunday	14.268	15.205	-6.164	0.041	-0.103	CD
	Mon MP	16.160	15.380	5.074	0.025	-0.122	CD
	Mon EP	15.139	15.450	-2.018	0.288	0.180	59.332

Table 36

Critical Jerk counts & Deceleration counts of Control Group Cyclists

Cyclists		Relative Critical Jerk Count/ 1000 road users		Relative Critical Dec Count/ 1000 road users	
		Nudge	No-Nudge	Nudge	No-Nudge
Control Group	Sunday	0.153	0.112	0.104	0.137
	Mon MP	0.119	0.217	0.135	0.211
	Mon EP	0.119	0.188	0.190	0.193

Table 37

Mean Speeds and Acceleration of Control Group Mopeds

Mopeds		Mean Speed (kmph)		% Change in Mean Speed of Nudge w.r.t to No-Nudge	Mean Acceleration (m/s^2)		% Change in Mean Acc of Nudge w.r.t to No-Nudge
		Nudge	No-Nudge		Nudge	No-Nudge	
Control Group	Sunday	18.606	19.733	-5.712	0.190	-0.041	CD
	Mon MP	18.991	16.391	15.857	-0.006	0.267	CD
	Mon EP	18.756	17.696	5.988	0.304	0.191	59.506

Table 38

Critical Jerk counts & Deceleration counts of Control Group Mopeds

Mopeds		Relative Critical Jerk Count/ 1000 road users		Relative Critical Dec Count/ 1000 road users	
		Nudge	No-Nudge	Nudge	No-Nudge
Control Group	Sunday	0.185	0.130	0.202	0.329
	Mon MP	0.126	0.229	0.204	0.224
	Mon EP	0.115	0.218	0.484	0.320

Table 39
Pearson's Correlation Coefficients

Group/Category	Pearson's Correlation Coefficient	t-statistic	p-value
All Road Users	0.268	3.085	0.003
Cyclists	0.313	2.478	0.018
Motor-Cyclists	0.310	2.581	0.014
Sunday Road Users	0.138	0.892	0.377
Monday Morning Peak Road Users	0.452	3.189	0.003
Monday Evening Peak Road Users	0.233	1.483	0.151
Sunday Cyclists	0.585	3.224	0.005
Monday Morning Peak Cyclists	0.106	0.436	0.655
Monday Evening Peak Cyclists	0.157	0.651	0.517
Sunday Motor-Cyclists	0.114	0.508	0.606
Monday Morning Peak Motor-Cyclists	0.429	2.144	0.047
Monday Evening Peak Motor-Cyclists	0.212	0.909	0.375

C Intervention Functions- Behaviour Change Wheel

Table 40

Definitions of Intervention Function from the Behaviour Change Wheel (Michie et al., 2011)

S.No	Interventions	Definition	Examples
1.	Education	Increasing knowledge or understanding	Providing information to promote healthy eating
2.	Persuasion	Using communication to induce positive or negative feelings or stimulate action	Using imagery to motivate increases in physical activity
3.	Incentivisation	Creating expectation of reward	Using prize draws to induce attempts to stop smoking
4.	Coercion	Creating expectation of punishment or cost	Raising the financial cost to reduce excessive alcohol consumption
5.	Training	Imparting skills	Advanced driver training to increase safe driving
6.	Restriction	Using rules to reduce the opportunity to engage in the target behaviour (or to increase the target behaviour by reducing the opportunity to engage in competing behaviours)	Prohibiting sales of solvents to people under 18 to reduce the use for intoxication
7.	Environmental restructuring	Changing the physical or social context	Providing on-screen prompts for GPs to ask about smoking behaviour
8.	Modelling	Providing an example for people to aspire to or imitate	Using TV drama scenes involving safe-sex practices to increase condom use
9.	Enablement	Increasing means/reducing barriers to increase capability or opportunity	Behavioural support for smoking cessation, medication for cognitive deficits, surgery to reduce obesity, prostheses to promote physical activity

D MINDSPACE Framework

Table 41

Nine Key Effects of MINDSPACE Applied to Road Safety Behaviour Context (Source: Dolan et al. (2010) and Dolan et al. (2012))

S.No	What is the Theory?	How can it work in practice in a road safety context?
1.	Messenger: We are heavily influenced by who communicates information	Information about risks associated with certain types of behaviours is more likely to be acted on if communicated by a person or organisation seen to have authority and to be 'independent'; by an individual who has similar characteristics to us; or by someone for whom we have positive feelings. Example: Peer-to-peer education and youth-initiated monitoring of safety belt use among teens.
2.	Incentives: Our responses to incentives are shaped by mental shortcuts	Making 'good' road safety behaviour a matter for financial reward might discourage it. For example, penalties on illegal parking might be seen by some as a probabilistic price as a signal of market price that might substitute a social norm.
3.	Norms: We are strongly influenced by what others do	Providing people or organisations with information about their peers can exert a strong influence on them to modify their behaviour accordingly. Examples - inform residents of the proportion of people who perform desirable behaviours (e.g. use seatbelts, do not drink and drive).
4.	Defaults: We 'go with the flow' of pre-set options	Locating pedestrians' near-side signals or push buttons on the same side as the pedestrian, oriented to focus the pedestrian's attention in the direction of approaching traffic, making it a default direction for observing traffic.
5.	Salience: Our attention is drawn to what is novel and seems relevant to us	High-pitch sound alert when driving over the speed limit; 'look right/left/both ways' signs reminding passengers to look at the direction of coming traffic.
6.	Priming: Our acts are often influenced by unconscious cues	Physical features of the road infrastructure may subconsciously trigger certain behaviours, e.g. more responsible driving (example – speed reduction marking).
7.	Affect: Our emotional associations can powerfully shape our actions	For example, road safety campaigns have sought to reinforce the emotional consequences of traffic accidents for those affected. Example - campaigns to increase awareness and empathy towards other road users (such as moped).
8.	Commitments: We seek to be consistent with our public promises, and reciprocate acts	Individuals and organisations who make a public commitment to change their road safety behaviour in some way (e.g. signing safety pledge cards) are more likely to sustain their change in behaviour, particularly if they have the support of others trying to do the same.
9.	Ego: We act in ways that make us feel better about ourselves	An educational program aimed at increasing road safety behaviour, providing incentives to generate motivation through competition.