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A CRITICAL ASSESSMENT OF METHODOLOGIES FOR OPERATIONS AND SAFETY EVALUATIONS OF FREEWAY TURBULENCE

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ABSTRACT

Turbulence in traffic is a commonly known phenomenon, but the exact characteristics of this phenomenon are not yet clear. It reflects individual changes in speed, headways, and lanes in the traffic stream. The currently used freeway design guidelines prescribe different measures for handling turbulence, such as sufficient ramp spacing, and spacing between road discontinuities. In situations where the available space between discontinuities is scarce, it might be necessary to make a trade-off between costs and safety/operation. For a valid trade off more insight is needed on the safety and operations effects when one deviates from the guidelines. A lot of research was done on the different causes of turbulence and their effect on safety and operation. This paper proposes a theoretical framework for turbulence phenomenon that facilitates the comparison of the available methodologies that can be used to evaluate a freeway design on the matter of turbulence and its impact on traffic operations and safety. The main finding of this review is that the currently available methodologies lack the ability to evaluate the impact of freeway turbulence on operations and safety simultaneously. Different recommendations to overcome limitations of current methodologies and further research possibilities to improve these methodologies are given.

Keywords: traffic safety; operations; turbulence; surrogate safety measures; freeway design

INTRODUCTION

Entering and exiting traffic from ramps and weaving areas will affect the traffic density on the freeway. Especially on the right lane. This change in density may cause freeway traffic to react, for example: changing lanes to a lane with a lower traffic density. Other reactions can be decelerating or accelerating in order to increase or decrease the headway with the vehicle in front (*1*). This phenomena is called ‘turbulence’ and it is mentioned several times in literature (*2-6*) and in guidelines (*1; 7; 8*).

The concept of turbulence is used consistently and this suggests a clear definition of turbulence. But neither the existing guidelines nor the literature define exactly what turbulence is. There is however a general agreement in literature on two main characteristics regarding turbulence: turbulence is a common phenomenon in a traffic stream (*1*), and will have a higher magnitude around freeway discontinuities, such as on-ramps (*4*), off-ramps, weaving areas, left side lane reductions, etc.. Also turbulence is stated to have a negative impact on traffic safety and traffic operations (*1-3; 6*).

According to design guidelines turbulence has to be taken into account for ramp spacing (*1; 7; 9*) and the spacing of discontinuities (*8; 10*). To do this guidelines prescribe certain lengths, but the scientific justification is lacking. The AASHTO for example uses a set of values for minimum ramps terminals spacing (*7*). The Dutch freeway guidelines (*10*) prescribe turbulence lengths for the spacing of discontinuities. In none of the guidelines the origin of the prescribed lengths is referenced.

In densely populated areas, such as the Netherlands, the space for new freeways is scarce. In some freeway design cases it was decided to deviate from the guidelines in order to be able to realize the desired interchange connections. In such cases it is tempting to accept a shorter length than prescribed. However, the implications for traffic safety and operations of deviating from the guidelines are not fully understood. A thorough understanding of turbulence, and its influence on traffic safety and traffic operations is critical in order to be able to make the right trade-off for the design choices in these situations.

The main aim of this paper is to review the currently available methodologies to assess the impact of turbulence in freeway traffic on traffic safety and traffic operations. The different methodologies are described and compared. Recommendations are given on how to use a wide range of different existing methods, and how to combine methods when assessing designs on operations and safety at the same time. The main focus of this review is turbulence in freeway traffic around on-ramps, off-ramps and weaving areas.

This review starts with a background on the turbulence phenomenon and its influence on traffic safety and traffic operations. The second part gives an overview of the available methods to quantify turbulence. The available methodologies for assessing the impact of turbulence on operations and safety are described and compared in the third and fourth part. This review ends with conclusions and gives recommendation for further research.

BACKGROUND

In freeway design the use of guidelines, manuals and standards in the design process is common. Documents such as the Highway Capacity Manual (HCM) and the ‘AASHTO Green Book’ in the USA, (*7*), the ‘Richtlinien für die Anlage von Autobahnen (RAA)’ (*9*) in Germany, the ‘Design Manual for Roads and Bridges (*8*)’ in Great Britain and ‘Nieuwe Ontwerprichtlijnen voor Autosnelwegen (NOA)’(new design guidelines for freeways) (*10*) in The Netherlands are prescribed in order to maintain consistency in road geometry and to provide safe freeways with sufficient level of service (*11*).

One of the important geometric elements in freeways is ramp spacing and the length of weaving areas. The basic principle in the design of these elements is that there should be sufficient spacing between succeeding ramps in order to cope with turbulence in the traffic stream.

Different approaches for dealing with turbulence are used in the different guidelines. For example: the AASHTO Green Book uses a set of minimum values for ramp spacing and the Dutch guidelines use a criteria called Turbulence length, which is the required length between succeeding discontinuities. The prescribed lengths differ per type of discontinuity and also per guideline. For example, table 1 shows the different prescribed distances between an on-ramp followed by an off-ramp (measured from nose to nose).

TABLE 1 Distance between On-Ramp and Off-Ramp Prescribed in Different Guidelines

Country	Distance	Design criteria
The Netherlands (*10*)	750 m	design speed
Germany (*9*)	1100 m*	minimum value for isolated intersection planning
USA (*7*)	600 m**	road category: freeway
	480 m***	road category: freeway
UK (*8*) , Vol.6, Sec. 2, Cpt 4.7	450 m****	3.75V, where V = design speed = 120 km/h

* 250 m acceleration lane + 600 m between acceleration and deceleration lane + 250 m deceleration lane

** system to service interchange (weaving)

*** service to service interchange (weaving)

**** may be increased to the minimum requirements for effective signing and motorway signaling

Despite the differences between the different approaches, the general concept behind ramp spacing and weaving areas in all the above guidelines is that the traffic stream will encounter a raised level of turbulence around freeway discontinuities. Turbulence will intensify when the available road length for lane changing becomes shorter. This should be taken into account by applying sufficient ramp spacing. This concept is supported by literature (*12; 13*).

In literature and guidelines turbulence is mentioned but no explicit definition for turbulence is given. These are some examples in which turbulence is mentioned:

- "Weaving segments require intense lane-changing maneuvers as drivers must access lanes appropriate to their desired exit leg. Therefore, traffic in a weaving segment is subject to lane-changing turbulence in excess of that normally present on basic freeway segments. This additional turbulence presents operational problems and design requirements" (*1*);
- "Ramp-freeway junctions create turbulence in the merging or diverging traffic stream. In general, the turbulence is the result of high lane-changing rates. The action of individual merging vehicles entering the traffic stream creates turbulence in the vicinity of the ramp. Approaching freeway vehicles move toward the left to avoid the turbulence. Thus, the ramp influence area experiences a higher rate of lane-changing than is normally present on ramp-free portions of freeway" (*1*);
- turbulence can be captured by four variables:" (1) variation in speeds in the left and interior lanes, (2) variation in speed in the right lane, (3) variation in flow in the left and interior lanes, and (4) variation in flow in the right lane" (*3*).
- "Turbulence is (among other things) defined by headway changes and a changed distribution of traffic over the different freeway lanes. Corresponding aspects of driving behavior are for example deceleration, evasive actions or (anticipating) lane changes" (*10*).

Since there is no explicit definition for turbulence available, a definition is still to be suggested. A non-turbulent traffic state can be considered as a state in which all vehicles on a road maintain the same relative distance and speed to others over a certain length of a road section and for a period of time. A turbulent traffic state can then be considered as the state in which speed, headway and the lateral position change over time, due to driver actions such as acceleration, deceleration and lane-change. Since acceleration, deceleration and lane-changes are common driver actions, turbulence can be considered as always present in the traffic stream (*1*). Therefore, a more specific definition of turbulence in the vicinity of discontinuities (such as ramps) is proposed in this paper as following:

- Turbulence:
  - individual changes in speed, headways, and lanes (i.e. lane-changes) in a certain road segment, regardless the cause of the change;
- Level of Turbulence:
  - the frequency and intensity of individual changes in speed, headways and lane-changes in a certain road segment, over a certain period of time;

Theoretical Structure for Turbulence

The *Level of Turbulence* is expected to increase before (upstream of) and to decrease after (downstream of) a ramp or a weaving area. This phenomena is described by Hovenga (*14)* who found that turbulence starts more or less about 500 meter upstream and ends more or less about 800 downstream from an on-ramp nose. Kondyli and Elefteriadou (*5)* found that turbulence due to merging maneuvers initiates 110 m upstream of the nose. According to the HCM (*1)* the merge influence area will occur about 460 m (1.500 ft.) upstream and 460 m downstream of the nose. To the best of our knowledge other literature that describes the start or the end of a raised level of turbulent traffic is not available.

Based on this concept a raised level of turbulence is for this study divided in three parts:
1) Upstream of (before) the ramp;
2) At the ramp;
3) Downstream of (after) the ramp.

At ramps and weaving areas drivers will execute their strategic route navigation decisions, which will lead to mandatory lane changes, in order to be able to enter or exit the freeway (*15*). These lane changes make other drivers react (*4*), which results in turbulent traffic (*1*). Figure 1 depicts the proposed structure for turbulence with consideration of the three parts.

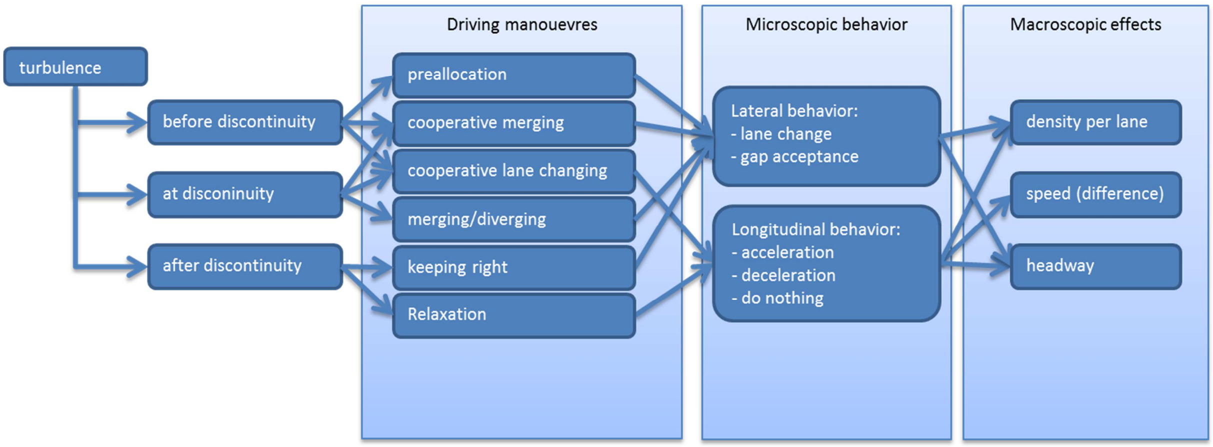

FIGURE 1 Theoretical structure for turbulence.

Lane changes upstream of a ramp are considered to be pre-allocating behavior, where the driver choses a lane in a tactical sense before the ramp, or cooperative behavior. Cooperative merging is behavior where an on-ramp a driver chooses to change lanes to the left to give way to the entering traffic (*5; 16*) or decelerate in order to enlarge the headway with the vehicle in front after a new vehicle has merged in (*17*). Or drivers might increase their headway to give way to entering traffic. This phenomena is called a cooperative lane change (*17; 18*) or courtesy yielding (*19*). Downstream of a ramp lane changes may occur due to the right side rule, which prescribes that drivers should change lanes to the right when possible. Downstream of a ramp drivers might decelerate to increase the headway to their leading vehicle. This phenomena is called relaxation (*18; 20*).

The different manoeuvers can be clustered in different types of microscopic behavior: lateral or longitudinal. The first considered lateral behavior is lane change, which can be classified as free, forced or cooperative (*17*). Lane changing and merging are closely related to gap acceptance and tactical lane choice. These can be considered as integrated behavior (*21*). Longitudinal behavior is classified as acceleration, deceleration, or do-nothing (*22*). Lateral and longitudinal behavior can be integrated in order to get a complete description of merging behavior (*23; 24*).

Microscopic behavior results in macroscopic effects. For example a lane changes will result in a changed density per lane and a changed headway distribution. Acceleration and deceleration might also result in a changed headway distribution, but result also in changing speed differences between different vehicles as illustrated in figure 1.

Impact of turbulence

The general hypothesis for the research on turbulence is that the level of turbulence is affected by certain conditions, such as road design, traffic characteristics (*1*), environmental aspects (such as weather and daylight), and drivers' population characteristics. These conditions affect driving behavior. The resulting manoeuvers drivers take affect traffic safety and operations (*1-3; 6*). This principle is shown graphically in figure 2.

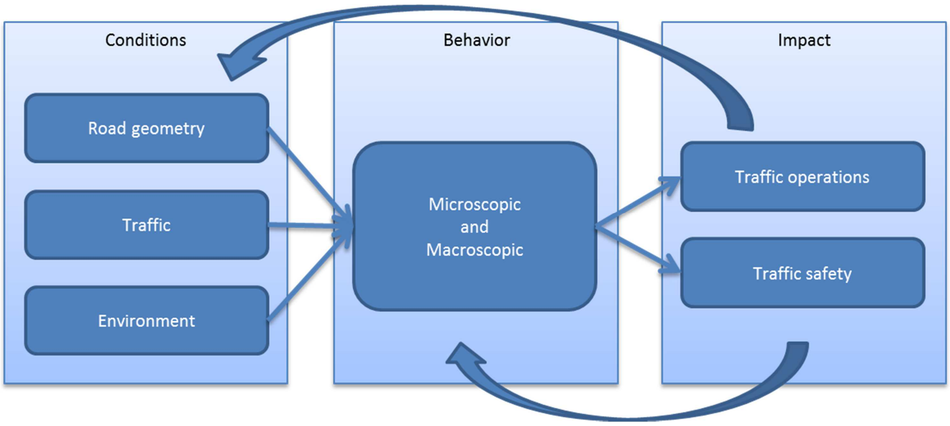

FIGURE 2 General concept of the effects of turbulence.

Figure 2 shows that certain conditions (road design, traffic and environment) affect (microscopic and macroscopic characteristics reflecting results of) driver behavior (such as the choice of driving speed, headway, gap acceptance) which in turn effects the freeway operations and safety. In reverse, some effects may influence driving behavior. For example, if the traffic stream becomes more turbulent, drivers may tend to drive more cautiously and lower their driving speeds. At the same time a low level of safety and operations might move the respective authorities to invest in improving the freeways' infrastructure by reconstructing some geometric design elements or adopt some new traffic management measures.

Problem definition

It is clear that turbulence is a complex phenomenon with different causes and impacts. To the best of our knowledge no literature is available which assesses all the causes of turbulence, the influence of road design and traffic conditions on turbulence and its impact on operations and safety. Therefore, it is argued that there is a lack of knowledge with respect to understanding the interaction of the causes and their impact on turbulence. This creates a twofold problem: (1) It is unknown if the current design guidelines lead to an optimal design; (2) It is unknown what the implication of deviating from the guidelines is and what impact this has on safety and operation.

Therefore, there is a need for a method to assess the (expected) level of turbulence for a design (only existing on paper), or an existing situation, and to evaluate the implications of design decisions on traffic safety and traffic operations. This method should take into account both the geometrical road design elements as well as the traffic and driver behavioral elements.

METHODOLOGIES TO COLLECT DATA RELATED TO TURBULENCE

This section is dedicated to the different methods to collect data that could be used to quantify turbulence in freeway traffic. We will consider loop detectors, video cameras, driving simulator and instrumented vehicles.

Loop detectors

Macroscopic traffic state variables such as density, speed and headway distributions can be measured using loop detectors (*25; 26*). Loop detector data represents vehicle passages and, depending on the type of loop detector, information such as speed and vehicle length. The data is usually aggregated to a fixed time period. Examples of chosen time periods are 30 seconds (*27-30*), 1 min (*14; 31*). The advantage of using loop detector data is its accessibility. Loop detector data from Dutch freeway for example can be accessed real time online. The disadvantage of using loop detector data is that detailed data of individual manoeuvers, such as lane change, acceleration and deceleration, cannot be collected.

Video cameras

Video footage can be used to generate trajectory data, which gives detailed time/space information of individual vehicles. From this data turbulence related driver maneuvers such as merging, overtaking and acceleration can be studied in a detailed way. Three examples of studies on Dutch freeways are given. Daamen, Loot and Hoogendoorn (*19)* studied merging behavior at two Dutch on-ramps and compared the empirical results to applied theories in existing microscopic simulation models. They found that that gap acceptance theories using a certain critical gap are not able to represent the observed behavior. Hoogendoorn, Hoogendoorn and Daamen (*32)* used the same data as (*19*) to propose a new approach to model and simulate car-following behavior. Marczak, Daamen and Buisson (*33)* combined the Dutch data with data from Grenoble (France) to study gap acceptance. They observed differences in the driver's behavior on the two locations: the merging drivers in Grenoble (France) tend to be more aggressive, i.e. accepting smaller gaps than in Bodegraven (Netherlands).

Cameras can be mounted on a high observation point such as a helicopter (*34*), a drone (*35*) or a building/structure (*36*).
The advantage of trajectory data is that it gives insight in the actual movements of vehicles. But it doesn't give any information about the underlying psychological driver behavior, it is relatively expensive to collect, and the data processing is time consuming. Thus, most studies that used trajectory data included limited number of sites.

Driving simulators

A driving simulator consists of a vehicle mock-up with a functional steering wheel, indicators, pedals and a shift stick. The simulator attempts to emulate a real driving environment. Behavioral aspects can be researched using data from a driving simulator. Two examples are given of freeway turbulence related studies. Winsum and Heino (*37)* studied time-headway during car-following and braking response. De Waard, Dijksterhuis and Brookhuis (*38)* studied the impact of proportion of HGVs, length of the acceleration lane and the speed of the driver ahead on the workload of elderly drivers, and the benefits of in-car support systems, when merging into freeway traffic.

The driving simulator has several advantages: the ability to test a wide variety of different existing and non-existing road design layouts, control of the intervening variables and it is a safe environment. One of the disadvantages of driving simulators is that its measurements are taken from a simulated environment and does not reflect drivers' behavior exactly as in reality, since drivers do not face a real risk of a collision which might bias the observed behavior (*39*). There is therefore a need to validate the results from the simulator with real life data. Furthermore, the other vehicles designed in a driving scenario although designed to behave "intelligently" do not represent real behavior of humans.

Instrumented vehicle and naturalistic driving

Driver behavior data from a real life traffic environment can be acquired by the use of an instrumented vehicle. An instrumented vehicle is equipped with sensors and radars that can record data relevant to the vehicle itself and also relative speeds and distances from other vehicles (*40*). All the behavioral aspects of the driver, such as driving speed, acceleration, deceleration, steering action, longitudinal and lateral position, can be measured comparable to the driver simulator. Such a vehicle was assembled and used by TRG Southampton (*41; 42*) for studying car following on UK motorways. Another study is conducted in Germany, where trajectory data from a radar equipped vehicle was used to calibrate car following models (*43*). A drawback of using an instrumented vehicle is the experimental and non-naturalistic setting in which the data is gathered. This might have an effect on the behavior of the participants and as a result bias the data.

As opposed to the experimental approach using an instrumented vehicle, naturalistic driving can be measured by drivers who operate daily using their own vehicles that have been equipped with specialized sensors, and recording equipment. Drivers operate their vehicle during normal driving routines while data is collected continuously. Olson et al. (*44)* and Blanco et al. (*45)* studied driver distraction in commercial motor vehicle operations and the impact of time-on-task on the risk of safety-critical events in the '100-car Naturalistic Driving Study'. Chong et al. (*46)* used data from naturalistic driving to propose a model to simulate driver behavior in terms of longitudinal and lateral actions in two driving situations, namely car-following situation and safety critical events. Another example is the Strategic Highway Research Program (SHRP2) Naturalistic Driving Study (NDS) project (*47*). The NDS database contains comprehensive video and vehicle sensor data collected from drivers and their vehicles over a three year period in six locations across the United States. The database contains data from 5.4 million trips taken by 3,147 volunteer drivers for between 4 and 24 months each nearly 50 million miles of driving (*48*). The advantage of naturalistic driving is that the resulting data is reliable and comes in large quantities. The disadvantage is that vehicles need to be equipped and operated. This requires a relatively big organizational effort. However, the rapid advancement in sensing and communication technologies is expected to facilitate these studies in the future.

METHODOLOGIES TO ASSESS TRAFFIC OPERATIONS

Turbulent traffic has a negative effect on road capacity (*1*). Numerous studies, for example (*26; 49-51*), have focused on explaining the mechanisms of driving in turbulent traffic and are based on traffic data such as loop detector data and individual vehicle trajectories. Traffic flow theories are derived from traffic data. These theories are used to describe traffic behavior in a mathematical sense by developing models. These models try to emulate the lateral and longitudinal behavior of drivers. A review of the lateral behavior models (lane change and gap acceptance) was made by (*52*), while a review on longitudinal behavior models was made by (*53*). Integrated models were also developed where lateral and longitudinal models are combined (*24*). These models can be used in microscopic simulation models, which simulate driving behavior for certain situations.

Following is a summary of the two most common methodologies for analyzing the impact of turbulence on traffic operations: (ex-post) data evaluation and (ex-ante) Microscopic simulation models.

Traffic data evaluation

The most direct way to study traffic operations is by studying traffic data. Several examples of studies are available in the literature. Coifman, Krishnamurthy and Wang (*54)* used trajectory data to study the impact of lane change manoeuvers on congestion. Laval and Leclercq (*55)* used trajectory data collected from a freeway to study driver behavior to explain the formation and propagation of stop-and-go waves in congested freeway traffic. They found that difference in driving behavior, ranging from aggressive to timid, seems a more appropriate cause for traffic oscillations than seeking lane change opportunities or acceleration and decel-

eration characteristics. This conclusion is also found in a follow-up study in which more trajectory data from multiple locations is used (*56*).
Zheng et al. (*57)* found that lane changing is a possible trigger for the deceleration waves in traffic at bottlenecks. They applied the Wavelet Transform method on Next Generation Simulation (NGSIM) empirical trajectory data. In a follow-up study in which the same method was used on a larger trajectory dataset, comparable conclusions were drawn (*58*).
Treiber, Hennecke and Helbing (*26)* used loop detector data from multiple German freeways to study congestion characteristics. Their data suggests that the congested states depend not only on the traffic situation but also on the specific infrastructure. Coifman, Krishnamurthy and Wang (*54)* used loop detector data to study traffic flow characteristics at bottle necks. In this study and a follow-up study (*51*) they found that the road capacity downstream of a bottleneck is reduced due to lane changing traffic.

Microscopic simulation models

The HCM suggests that traffic simulation can be used to assess the traffic operations performance of roads (*1*). A few examples of micro simulation software packages mentioned in literature are: CORSIM (*59*), VISSIM (*60*), PARAMICS (*61*), AIMSUN (*62*), ARTEMiS (*17*), TRITONE(*63*) and FOSIM (*64*). FOSIM is the prescribed microsimulation package for freeway assessments in The Netherlands.

The use of microscopic simulation software for evaluating a design is part of the regular freeway design process. Most of these applications do not result in scientific papers. However some examples of design evaluations, related to freeways, are found in the literature. Garber and Fontaine (*65)* used CORSIM to evaluate the performance of different interchange types under different magnitudes of traffic. Based on these results guidelines for intersections were developed. Wang, Hadiuzzaman and Qiu (*66)* used VISSIM for estimating the capacity of a weaving segment. They calibrated VISSIM with a capacity accuracy of about 90%, using 5 minute aggregated data recorded by videos and data from loop detectors. Martínez, Garcia and Moreno (*67)* used VISSIM to elaborate recommendations about the best freeway exit ramp layout. They calibrated VISSIM for speed distributions gained from video recordings. Sharma and Chatterjee (*68)* used VISSIM to compare two alternative interchange designs: diverging diamond and conventional diamond interchange to help in providing guidelines to the decision makers for selecting the best alternative.

In the above mentioned studies microscopic simulation programs have proven to be powerful methodologies for assessing and comparing different designs on the matter of operations. Especially macroscopic features are captured well. Current microscopic simulation programs however are not suitable for studying microscopic behavior and the effect of more detailed road geometry aspects, such as alignment, shoulders and super elevation. Most – if not all – microscopic models have problems in terms of their predictive validity. Research has shown that microscopic behavior, such as gap acceptance, is not simulated accurately (*19*). It is however possible to calibrate a program, but even after calibration the results may vary up to 10% from measured data (*66*).

METHODOLOGIES TO ASSESS TRAFFIC SAFETY

In recent years a lot of research was done to gain more understanding about the factors that affect traffic safety by combining traffic flow characteristics, road characteristics and crash statistics. This has resulted in multiple methodologies that can be used to assess traffic safety.

Crash prediction models

Crash prediction models are used to study the factors that affect the number of crashes occurring on a specific (stretch of) road over some specified time period (week, month, year, number of years). In general, the most basic crash data consist of crash location; date and time; crash severity; collision type; and basic information about the roadway, vehicles, and people involved. The HSM (*69)* Part C provides detailed steps for applying a predictive method for estimating expected average crash frequency of a network, facility, or individual site. The types of roads considered range from suburban arterials to rural multilane highways.

The use of crash statistics has a number of drawbacks: 1) only available for existing roads and existing situations (*61*); 2) crash data are not always sufficient due to small sample sizes leading to inconclusive results, and the lack of details to improve our understanding of crash failure mechanism and especially the driver crash avoidance behavior (*70; 71*); 3) accidents are rare events, making it troublesome to base traffic safety analyses at individual sites on accidents only (*71*); 4) not all crashes are reported and the level of underreporting depends on the accident's severity and types of road users involved (*71-73*) and 5) the lack of details to improve our understanding of crash failure mechanism and especially the driver crash avoidance behavior (*70*).

For the description of the relationship between different elements many different types of models were developed (*69*). A good overview on the available models, used data and their advantages and disadvantages is made by Lord and Mannering (*74)*. Different data issues are mentioned. For a detailed description of these data issues and the modelling methods which were developed the reader is referred to the overview by Lord and Mannering (*74)*.

All models are developed using crash statistics and traffic volumes, but the use of detailed traffic data and road geometry data depends on the focus of the research. There are some examples of studies that focus on estimating safety around freeway ramps and interchanges (*12; 13; 75*). The use of large datasets with many aspects makes it possible to examine the relationships between many different variables. For example Garber and Ehrhart (*76)* examined 44 variable combinations. To avoid circumstantial correlation only evidential differing variables can be chosen. This is a problem when more subtle variations, such as a slight reduction in ramp spacing, need to be investigated. The desired level of statistical validation requires sufficient data. When it comes to road geometric elements it is quite often difficult to get sufficient data on this (*13; 75*). Other models were developed to predict the crash likelihood based on real-time traffic flow variables measured from loop detectors. These studies used matched case-control methodology for the model development (*28; 77; 78*).

Surrogate safety measures

Because of the stated drawbacks of using crash statistics and the desire to take behavior of individual drivers into account, researchers studied the possibility to replace and complement the traditional crash statistics with a surrogate (*70; 71*). The surrogate was found in traffic safety indicators, which increase the possibility of: 1) evaluating traffic safety changes more efficiently and in a shorter time; 2) elaborating the relation between design elements and risk 3) more thoroughly understanding the relationships between behavior and risk and 4) a better understanding of the processes characterizing the normal traffic and critical situations including crashes and near crashes.

In order to do so, researchers tried to find measurable aspects in the traffic stream by which traffic safety can be quantified. The most frequently used measure is the Time To Collision

(TTC) value at an instant *t* is defined as: *"the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained"*(*15*). Minderhoud and Bovy (*15*) proposed two additional safety indicators based on the TTC: the TET (Time Exposed Time-to-collision) and the TIT (Time Integrated Time-to-collision). The duration of exposition to safety-critical time-to-collision values over specified time duration is used here as a safety indicator. The TET is a summation of all moments (over the considered time period) that a driver approaches a front vehicle with a TTC-value below a certain threshold value. The TIT is the integral of the time-to-collision profile. Although explicit thresholds are not mentioned, a general rule is applicable: the higher a TTC-value, the more safe the situation is (*15; 79*).

In the case where the leading vehicle is faster than the following vehicle, TTC index cannot be estimated in a finite number. This is a practical weak point of TTC index because the situation in which two subsequent vehicles following each other at a very close distance, can be considered as unsafe. Even if the leading vehicle drives at a slightly higher speed (*80*). To counter this weak point the Potential Index for Collision with Urgent Deceleration (PICUD) was proposed. This measures evaluates the possibility that two consecutive vehicles might collide, defined as the distance between the two vehicles considered when they completely stop (*80; 81*).

A further variation of the Time-to-Collision concept is Post-Encroachment Time (PET). This measure is used to measure situations in which two road-users that are not on a collision course, pass over a common spatial point or area with a temporal difference that is below a predetermined threshold (*73*). One study is found in which the PET is calculated for a freeway (*82*). The PET was calculated for lane changing traffic. This research concludes that the application of extreme value theory over PETs during lane change manoeuvers provides a promising approach for freeway safety evaluation.

Two other indicators related to braking were introduced: Individual Braking Time Risk (IBTR) and Platoon Braking Time Risk (PBTR) or J-value (*79*). IBTR stands for the likelihood of a rear-end crash if the leading vehicle stops. PBTR stands for the accumulated risk of collision for each vehicle inside a platoon.

Surrogate safety measures can be derived from trajectory data. For the validation of these measures crash statistics can be used. Also a method which does not require crash statistics is developed (*82; 83*). The most accurate way to derive surrogate safety measures is to use empirical trajectory data (*73; 84*). Also data from loop detectors can be used (*85*), but this kind of data gives less information than trajectory data. An alternative is to generate trajectories with micro simulation models (*63; 79*). This method however has a major drawback: the currently available micro simulation programs are not suitable for safety study purposes (*79*)

Assessment of recorded crashes on video

When video recordings of a crash are available a lot of useful information can be gained from these recordings (*86; 87*). Especially more insights in the conditions preceding the crash. Video footage of crashes can be used to generate individual vehicle trajectories on which microscopic analysis can be performed, such as deriving surrogate safety measures (*86; 88; 89*). The SHRP2 NDS study provided event files for approximately 700 crashes and 7,000 near-crashes. These files contain video footage, a trip summary and other data coded manually, such as driver distraction and cell phone use (*48*). But finding footage of specific locations will still take a lot of effort and will result in only a few number of crashes per facility.

COMPARISON

The different methods to collect data related to turbulence and the methods that assess the impact of turbulence on traffic operations and traffic safety, as detailed above are compared in Table 2. The table is organized based on the different aspects described in Figure 1 and 2, i.e. conditions and behavior.

Three different signs are used with the following interpretations: ‘+’ means that the specified method is suitable to take the considered functionality into account, ‘-‘ means that the specified method is **not** suitable to take the considered functionality into account and ‘+-‘ means that the specified method can take the considered functionality into account but with a lack of accuracy.

Loop detectors are very useful to acquire empirical macroscopic traffic data from which turbulence related aspects can be studied. However more detailed information, such as driving maneuvers and microscopic behavior cannot be measured directly. Video cameras can be used to derive empirical trajectory data which gives detailed information on driver maneuvers and macroscopic effects. Because of the level of detail of the collected information, the effects of the road geometry on turbulence can as well be studied. Trajectory data are not suitable for explaining the drivers’ decisions leading to maneuvers and turbulence. This can be studied using a driver simulator or an instrumented vehicle. The advantage of the driver simulator is the controlled environment in which also new designs can be studied. The advantage of an instrumented vehicle is that it can study actual road situation with actual traffic. Both the simulator and the instrumented vehicle consider only a single vehicle and its surrounding vehicles, while loop detectors and video cameras consider all vehicles. Therefore, data from loop detectors and video cameras are more suitable to be used for studying the macroscopic effects on turbulence, compared to data from a driver simulator or an instrumented vehicle.

When it comes to assessing the impact of turbulence on traffic operation, analyzing empirical traffic data is a good method for this purpose, especially when empirical trajectory data is available. For non-existing situations, such as new designs, microscopic simulation models can be used. These types of models however cannot model all aspects of the roads’ geometry and therefore cannot simulate microscopic behavior as realistically as desired.

Crash prediction models can be used as a method to assess the impact of turbulence on traffic safety. The drawback of this method is that large quantities of data are required to develop a model which can cope with a large set of variables. This is required when studying the effect of road and traffic characteristics on turbulence and its impact on traffic safety. Surrogate safety measures and video assessments give more traffic safety information on an individual vehicle level. Video recordings of crashes can give detailed insights on individual crashes that occurred in the past but give less insight on microscopic traffic conditions and preceding behavior and maneuvers. Surrogate safety measures can take the microscopic traffic conditions into account, but lack the capacity of explaining behavior. Also information regarding road geometry and environment cannot be directly extracted from these methods.

TABLE 2 Overview of Available Methodologies

		Methodologies to collect data related to turbulence				Methodologies to assess the impact of turbulence				
		Loop detectors	Video cameras (vehicle trajectories)	Driver simulator	Instrumented vehicle / naturalistic studies	Traffic operations		Traffic safety		
						Traffic data analysis	Simulation models	crash prediction models	Surrogate safety measures	Crash video assessment
New design		-	-	+	-	-	+	+	+	-
Existing situation		+	+	+-	+	+	+	+	+	+
Conditions to take into account	**Road Geometry**									
	Number of lanes	-	+	+	+	+	+	+	+-	+
	Shoulder width	-	+	+	+	+	-	+-	-	+
	Length of acc./dec. lane	-	+	+	+	+	+	+-	-	+
	Interchange spacing	-	+	+	+	+	+	+-	-	+
	Horizontal alignment	-	+	+	+	+	-	+-	-	+
	Vertical alignment	-	-	+-	+	+	-	+-	-	-
	Super elevation	-	-	-	+	+	-	+-	-	-
	Traffic									
	Average daily traffic	+	+	+-	+	+	+	+	+	+-
	Speed / speed differences	+	+	+-	+	+	+	+	+	+-
	Density per lane	+	+	+-	+	+	+	+	+	+-
	Environment									
	Weather conditions	-	+-	-	+	+	-	+-	-	+-
Behavior	Driving manoeuvers	-	+-	+	+	+	+-	-	+-	+-
	Microscopic behavior	-	+	+	+	+	+	+-	+	+-
	Macroscopic effects	+	+	-	-	+	+	+-	+	+-

CONCLUSIONS AND RECOMMENDATIONS

Turbulence covers different elements of microscopic traffic characteristics such as lane changing, variation in speeds and headways and is the result of a complex combination of different driving manoeuvers. Literature and freeway design guidelines agree that the level, or magnitude, of turbulence is influenced by road design, traffic volume and driver behavior, and that turbulence has an effect on traffic operations and safety. Although there seems to be an agreement on what turbulence is, there is no definition found which covers all causes and effects of turbulence. Since turbulence is a commonly present in the traffic stream, two definitions are proposed:

- Turbulence:
    - individual changes in speed, headways, and lanes (i.e. lane-changes) in a certain road segment, regardless the cause of the change;
- Level of Turbulence:

    the frequency and intensity of individual changes in speed, headways and lane-changes in a certain road segment, over a certain period of time.

The level of turbulence is expected to be higher around discontinuities (on freeways) compared to continuous road stretches. Although research and design guidelines agree on the concept of turbulence, a gap can be observed between guidelines and research: where guidelines frequently rely on unreferenced assumptions and rules of thumb, research tries to assess the impacts of different elements of turbulence on traffic safety and traffic operations and the influence of design characteristics on these impacts. Furthermore, the results of research do not seem to fully find their way into the freeway design guidelines. One of the reasons for this may be that the currently available methodologies are not able to combine the effects of road design on turbulence with its impact on both traffic safety and traffic operations.

Several methods to assess traffic operations and traffic safety exist today, such as the use of microscopic simulation programs, surrogate safety measures, crash prediction models and driver simulators. However, each of the methods has its own strengths and weaknesses. Considering these strengths and weaknesses, combining different methods might be a potential solution for this problem, that is worth researching in the future. The overview in Table 2 suggests that combining microscopic simulation software with surrogate safety measure methodologies is the most promising way forward. By doing that, road characteristics, traffic characteristics and microscopic behavior can be taken into account to evaluate the safety and capacity of a certain freeway segment. There are however a few challenges that need to be overcome.

The first challenge is that the currently available microscopic simulation programs are not designed for traffic safety studies (*79*). These programs also do not simulate merging behavior as accurately as desired. This makes them unsuitable for generating trajectory data from which surrogate safety measures can be derived (*79; 90*). Also surrogate safety measures seem to be in a theoretical stage, where valid threshold values need still to be set.

For the improvement of the existing microscopic simulation models a more realistic, mathematical description of merging behavior is needed. Despite the huge improvements in microscopic simulation models' appearance and visualization, the advancement in its traffic behavior performance is at a much slower pace. For example, the most recent car following model in VISSIM dates from 1999 and AIMSUN uses a car-following model based on the model developed by Gipps (1981).

The most important improvements should be the merging behavior in itself by using gap selection instead of gap acceptance theory. Other types of behavior such as pre allocation, courtesy yielding and relaxation phenomena should also be integrated more realistically. But also unsafe situations should be possible to occur in models in order to be able to generate realistic trajectories to derive surrogate safety measures. It is also important to develop mathematical models that take into account, for example, different driving styles and behaviors of drivers and account for drivers' heterogeneity. Also existing or maybe new models should be calibrated and validated by the use of empirical trajectory data. The behavioral aspects can be studied by using driver simulator, instrumented vehicle or a naturalistic driver study.

A second challenge is that good quality empirical trajectory data is scarce. The available trajectory data focusses mainly on the merging area (*19; 33; 36*) and not so much on the areas upstream and downstream of the discontinuity. Therefore new data is needed.

A third challenge is that not all the design elements can be taken into account by available microscopic simulation models. Elements such as shoulder width, horizontal alignment, vertical alignment and super elevation, can either not be modelled at all, using the existing simulation programs, or do not affect the simulated driving behavior realistically. The impacts of the different design elements on driving behavior related to turbulence need to be studied more in order to be able to show if and how design elements have an impact on driving behavior. Suitable methodologies for this research are the use of a driver simulator, instrumented vehicle and/or a naturalistic driver study. It is recommended to include these methodologies in further research on turbulence and the effects on safety and operation.

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