THE RELATIONSHIP BETWEEN TRAFFIC SAFETY AND MACROSCOPIC FUNDAMENTAL DIAGRAM (MFD)

Raed Alsalhi¹, Vinayak Dixit²

¹,²School of Civil and Environmental Engineering, University of New South Wales, Australia

E-mail: r.alsalhi@student.unsw.edu.au, v.dixit@unsw.edu.au

Abstract

The Macroscopic Fundamental Diagram (MFD) remains a common tool of choice for evaluating and controlling urban traffic networks. In particular, the MFD provides a consistent and reliable method to develop algorithms that improve traffic conditions. Similar to congestion, safety is an important externality of traffic. However, there is a limited understanding and theoretical underpinnings for the relationship between MFD and safety. Based on previous studies, generally, traffic flow and speed have been found to significantly influence traffic safety. The theory and relationship with MFD will provide insight into analysing the correlation of crashes and traffic flow, and this will lead to develop dynamic control measures to improve safety. This is achieved via the assessment of influence areas making use of conflict analysis technique. The results obtained from this analysis are identified via the observation of the simulated traffic patterns, at first, and then a test performed using Surrogate Safety Assessment Model (SSAM) conflict analysis software. The results show that the change of speed and density has more effect on safety than change flow. Therefore, this model supports us understand the real-time correlation between traffic characteristics and safety from a macroscopic viewpoint.

1. Introduction

In modern times, the need for reducing the rate of accidents on the freeways as well as arterial roads has increased tremendously. This, as a result, has motivated research which has mostly focused on the proactive traffic management tactics for preventing accidents or crashes. These studies seemingly come to the same conclusion: that the development of applications aimed at improving road safety, such as proactive control and management, rely on understanding the association between traffic flow and crash probability. This relationship has been well documented in studies conducted in the past. These studies have mostly used and analysed historical data in order to show this relationship (Oh et al., 2005). In a study conducted by (Abdel-Aty et al., 2007), it was determined that accident data analysis represents the commonly used method through which the safety performance of vehicles is assessed. In review study (Theofilatos and Yannis, 2014), the researchers mentioned that the most exciting historical studies tended to use too aggregate traffic data.

What this implies is that more short-term traffic impacts, which potentially give rise to crashes, cannot be accounted for or captured. The researchers in the past studies extracted the real time traffic variables for every time slice prior to the occurrence of the accident. Again, they measured the essence of every variable with the aim of assessing the safety of the traffic, at least in the short-term. Studies that focus on the severity and frequency of traffic accidents through the use of real time data have been conducted but there are few examples. While this is the case, a slightly more macroscopic way could be adopted successfully. However, this would necessitate the integration of time series of the traffic parameters. It would also require a more dynamic examination of the impacts of the parameters on safety (Theofilatos and Yannis, 2014). MFD, which denotes Macroscopic Fundamental Diagram, is used to define the relationship between the characteristics or the attributions of the traffic flow at a macroscopic level. Three variables are used. These include mean speed, density, as well as volume. Despite the progress, a clear understanding
regarding the manner in which different characteristics of the traffic flow is linked with the safety for freeways and Arterial road.

In this study, the aim is to integrate an entirely new method called the "Macroscopic Safety Diagram" (MSD), which can elicit understanding, and at the same time relate the conditions of traffic and crashes on freeways and arterial roads. The findings of the present study are essential as they will assist in filling the gaps from previous studies on traffic flow and safety. In addition to this, the outcomes of the study will assist the transport practitioners to have a better understanding on the relationship between safety and the diverse parameters of the traffic flow. In the following section, a concise background about road safety as well as MSD will be provided. Following this, the proposed methodology will be set out. The results will then be presented and a conclusion reached.

2. Background

2.1. Safety

There have been a range of studies that have been conducted with the aim of identifying the connection between the occurrences of accidents on freeways on one hand and the traffic flow on the other hand. For example (Ceder and Livneh, 1982, Martin, 2002, Dixit et al., 2011, Dixit, 2013) The majority of these studies have accounted and analysed both macroscopic characteristics of the traffic flow and crash frequencies for specified periods, ranging from several hours to a set of years. The studies have shown that there indeed exists a link between the rate of accidents and traffic flow. Accidents tend to take place when the traffic is on the move. In the light of this, it is natural to investigate the attributions of traffic in order to achieve a clear understanding of the effects that accidents normally bring about (Martin, 2002). Mostly, the characteristics of traffic can be classified as congestion, speed, flow and density. All these attributes, according to (Martin, 2002), usually affects road safety.

2.1.1. Speed

This has been documented by researchers such as (Elvik et al., 2004) as an essential factor that affects crashes with regard to occurrence and severity. A set of studies aiming to investigate the link between the number of accidents and speed have been completed. Most of them have suggested that increased speed leads to a higher rate of crashes. (Nilsson, 2004) comprehensively investigated the effect of change in speed on safety. The researcher incorporated the use of before-after studies conducted in Sweden using the Power Model. The researcher established that changes in the rate of accidents can rightly be associated with changes in speed. The researcher also found that there is a positive relationship between speed change and accidents. While this is the case, the researcher clarified that the magnitude often depends on the forms of accidents, whether injury or fatal. In another study by (Elvik et al., 2004), an extensive evaluation on the impacts of speed and accidents was conducted. The researchers also used the Power Model. It was identified that a causal relationship between the changes in speed and the rate of crashes exists. As such, the rate of crashes goes down if the speed is low and increases if speed increases.

In his study, (Wang et al., 2013b) evidenced that speed often has mixed impacts on safety. However, other studies have reported dissimilar findings, stating that speed tends to reduce safety or speed increases safety. On top of this, it has been argued that by itself, speed might not pose as a safety issue. However, variation in speed could do. These differences imply that there is a need for more research in order to clarify on the correlation between speed and safety.
2.1.2. Density

There has been significantly little literature on the link between the density of traffic and accidents. The common reason for this is the dearth of appropriate data. Of the ones conducted, only a few have used variables in order to represent density. Good examples include (Shefer, 1994) and (Ivan et al., 2000) who used the Volume over Capacity (V/C) ratio. In another study by (Zhou and Sisiopiku, 1997), the rate of accidents per hour and the V/C ratio on the interstate highway in the US was examined. It was established that the relationship between these two variables usually follows a U-shaped pattern. It was also established that accidents that involved fatalities and injuries decreased while the V/C ratio increased. Other studies have established that the relationship between density and safety and other forms of accidents is mixed (Wang et al., 2013b). This clearly indicates that there is tremendously limited research in the area and that further investigations are necessitated.

2.1.3. Flow

A set of studies have focused on investigating the interrelation between the flow and accidents. Among these include seminal works by (Belmont and Forbes, 1953, Ceder and Livneh, 1982, Gwynn, 1967). In the study by (Belmont and Forbes, 1953), a theory whose aim was to relate the volume of traffic and the occurrence of accidents was modelled. It was revealed that the rate of crashes tends to increase in a linear manner with the traffic flow per hour especially on two-lane road sections during the day. (Ceder and Livneh, 1982), also in (Hall and Pendleton, 1989), sought to determine the way in which the rates of crashes often vary with the flow of traffic. It was established that the link between relationship of the flow of traffic and the rate of accidents follows a U-shape. Other researchers such as (Golob et al., 2004, Lee et al., 2002, Oh et al., 2001) have used a variety number of measures of the conditions of traffic. Each of the researchers derived the conditions and the data from the loop detector with the aim of determining the characteristics of traffic, which often leads to incidences of accidents. The studies revealed that there is usually a statistical interrelationship between the traffic characteristics which are time varying and the accident outcomes. Overall, it can be determined that the aggregate level of accidents often increases as the flow of traffic increases. With respect to the rate of accidents, there is seemingly a U-shaped relationship with the rate of traffic flow per hour (Wang et al., 2013b).

2.1.4. Congestion

There have also been a few studies focusing on the consequences of traffic congestion, with reference to quantitative and empirical evidence. In addition to this, studies on the effects of congestion on the severity of crash given that an accident takes place are particularly few (Wang et al., 2013a). One of the few studies which have been conducted in this area is the one by (Quddus et al., 2009). It was revealed that there is little impact of congestion on the severity of accidents. In another study by (Shefer, 1994), it was proposed that there exists an inverse relationship between accidents and congestion. The researcher used the V/C. It was mentioned by (Wang et al., 2013a) that traffic congestion usually has mixed effects on safety. Historical studies, in line with the conventional wisdom, revealed that the relationship between the congestion of traffic and accidents is U-shaped. These studies have made this conclusion due to the fact that speed would be lower in congested traffic situations. While this is the case, the most recent studies have revealed that congestion is likely to increase the rate of accidents on roads. This is especially due to the notion that a diverse range of measurements for road congestions are used in different modern studies.

2.2. Macroscopic Fundamental Diagram (MFD)

The MFD represents a very essential tool that can be used in the evaluation of the performance of traffic within an urban location, though at a macroscopic scale. It is also vital in the evaluation of the characteristics of the urban network capacity. The diagram usually represents not only a reliable connection between the density and the average flow within a
defined system of road networks but also a consistent one. It is held in a theoretical model such as the traffic flow theory that the density, speed and flow parameters associated with traffic are interconnected based on the fundamental diagram. In the past few decades, the MFD has been a major focus among researchers. MFD was first used in studies including (Godfrey, 1969, Herman and Prigogine, 1979). However, later studies such as that by (Geroliminis and Boyaci, 2012, Geroliminis and Sun, 2011, Geroliminis and Daganzo, 2008, Daganzo, 2007, Gayah et al., 2014) have popularized the term. However, among these studies, the one by (Geroliminis and Daganzo, 2008) is the most notable. This research showed that urban neighbourhoods exhibit MFD that relates the number of vehicles to the space mean flow. The diagram, according to (He et al., 2014, Mahmassani et al., 2013) are extremely powerful tools which can be used in monitoring the road network’s efficiency. The diagram has also been mentioned in the works by (Zheng and Geroliminis, 2013, Knoop and Hoogendoorn, 2013, Doig et al., 2013) as providing not only a simple but also an aggregate vision of the dynamics of the road network.

3. Methodology

In this particular study, a power model of the link between road safety and speed was utilized. The model defined that a specified form of a change in the mean speed of traffic is connected with a relative change in the level of crashes by the means of a power function (See equation1). The essence of the power model was supported by (Cameron and Elvik, 2008, Elvik, 2009, Nilsson, 2004). The researcher stated that the speed usually has a major impact on the level of accidents along with the injury severity. The researcher also defined that the relationship between road safety and speed takes both statistical and a causal form. The power model is defined as so due to the fact that it tends to define the connection between casualty accidents and speed.

\[
\left( \frac{\text{CrashesAfter}}{\text{CrashesBefore}} \right) = \left( \frac{\text{SpeedAfter}}{\text{SpeedBefore}} \right)^{\text{Exponent}}
\]  

(1)

Just like the case of speed and crashes power model, the new method proposed in the present study was developed in order to correlate crashes with diverse characteristics of traffic for the two types of roads under consideration. Following this, experiments have been carried out using simulation data. All the equations that define the new model were then tested for both road types. MFD and crash analysis were established for both roads. The equations, which seek to determine the relationship between the conditions and collisions of traffic, are represented below;

\[
\frac{C_2}{C_1} = \left( \frac{V_2}{V_1} \right)^E
\]  

(2)

\[
\frac{C_2/V_2}{C_1/V_1} = \left( \frac{V_2}{V_1} \right)^E
\]  

(3)

\[
\frac{C_2/Q_2}{C_1/Q_1} = \left( \frac{V_2}{V_1} \right)^E
\]  

(4)

\[
\frac{C_2/K_2}{C_1/K_1} = \left( \frac{V_2}{V_1} \right)^E
\]  

(5)

\[
\frac{C_2/(Q_2 * K_2)}{C_1/(Q_1 * K_1)} = \left( \frac{V_2}{V_1} \right)^E
\]  

(6)
THE RELATIONSHIP BETWEEN TRAFFIC SAFETY AND MACROSCOPIC FUNDAMENTAL DIAGRAM (MFD)

\[ \left( \frac{C_2}{Q_2 * V_2} \right) = \left( \frac{V_2}{V_1} \right)^E \]  
(7)

\[ \left( \frac{C_2}{C_1} \right) = \left( \frac{K_2}{K_1} \right)^E \]  
(8)

\[ \left( \frac{C_2/K_2}{C_1/K_1} \right) = \left( \frac{K_2}{K_1} \right)^E \]  
(9)

\[ \left( \frac{C_2/Q_2}{C_1/Q_1} \right) = \left( \frac{K_2}{K_1} \right)^E \]  
(10)

\[ \left( \frac{C_2/V_2}{C_1/V_1} \right) = \left( \frac{K_2}{K_1} \right)^E \]  
(11)

\[ \left( \frac{C_2/(Q_2 * V_2)}{C_1/(Q_1 * V_1)} \right) = \left( \frac{K_2}{K_1} \right)^E \]  
(12)

\[ \left( \frac{C_2/(Q_2 * K_2)}{C_1/(Q_1 * K_1)} \right) = \left( \frac{K_2}{K_1} \right)^E \]  
(13)

\[ \left( \frac{C_2}{C_1} \right) = \left( \frac{Q_2}{Q_1} \right)^E \]  
(14)

\[ \left( \frac{C_2/Q_2}{C_1/Q_1} \right) = \left( \frac{Q_2}{Q_1} \right)^E \]  
(15)

\[ \left( \frac{C_2/K_2}{C_1/K_1} \right) = \left( \frac{Q_2}{Q_1} \right)^E \]  
(16)

\[ \left( \frac{C_2/V_2}{C_1/V_1} \right) = \left( \frac{Q_2}{Q_1} \right)^E \]  
(17)

\[ \left( \frac{C_2/(Q_2 * V_2)}{C_1/(Q_1 * V_1)} \right) = \left( \frac{Q_2}{Q_1} \right)^E \]  
(18)

\[ \left( \frac{C_2/(Q_2 * K_2)}{C_1/(Q_1 * K_1)} \right) = \left( \frac{Q_2}{Q_1} \right)^E \]  
(19)

Where \( C \) crashes or accidents, \( V \) is speed, \( Q \) is flow, \( K \) is density and \( E \) is exponent.

4. Test results and analysis

4.1 Network simulation and safety analysis

This study plays an important role in understanding the relationship between macroscopic fundamental diagrams (MFDs) and traffic safety. In this study, traffic safety was analysed dynamically on a macroscopic scale. The results were divided into three main sections, each
of which represented a different traffic parameter (speed, density, and flow) and its relationship with accidents. We used simulation data for an arterial network. The experiment was run five times with different random seeds by using the microscopic simulation program VISSIM. The data were then collected for five-minute slides in order to generate MFDs for all study areas. (See figure 1.) The MFDs were generated by using generalized flow and density, as in the average network flow and density equation 20 and equation 21, respectively. The generalized formula for these equations was proposed by (Edie, 1963). The MFDs were classified into three regimes based on traffic density: the free-flow state was located at density values between (2–16), the saturation flow state was located between (16–28), and the congested flow state was located between (28–55).

\[ Q = \frac{\sum d_i}{L \times T} \]  

(20)

\[ K = \frac{\sum t_i}{L \times T} \]  

(21)

Where \( \sum d_i \) total distance travelled by all vehicles, \( \sum t_i \) is total time of all vehicles, \( T \) is time, and \( L \) is area.

Similarly to MFD, the trajectory file that was generated by the simulation software was analysed by using surrogate safety assessment model (SSAM) conflict analysis software to create an accident report. In the accident report, accidents were classified according to time to collision (TTC) into four critical values: TTC\( = 0 \), TTC\( \leq 0.5 \), TTC\( \leq 1 \) and TTC\( \leq 1.5 \). The accidents were then grouped into five-minute intervals.

Figure 2 displays the correlation between MFDs and accidents for different TTC thresholds. It is clear from the figure that the accidents started to increase with the increase of traffic density until reaching the optimal flow state, and then the accidents decreased with the increase of congestion levels for all TTC values except TTC\( = 0 \); in this case, the number of accidents continuously increased. Figure 3 displays the connection between MFD and accidents/density, which is measured by accidents/hr. It is clear that the number of accidents

![Figure 1: MFD for the arterial network (five-minute intervals).](image)

\[ y = -0.4501x^2 + 22.739x + 71.551 \]

\[ R^2 = 0.9028 \]
per hour was higher during the free-flow state, with a lot of scattering until it reached the saturation state, at which point it started to decrease with the increase in congestion. The accidents per hour for TTC=0, on the other hand, started low and continued to increase with the increase of traffic density.

Figure 2: Accidents for all TTC values

Figure 3: Accidents/density for all TTC values

Figure 4 shows the relationship between MFD and accidents/flow, which is measured by accidents/km. It is clear that the accidents per km increased almost linearly with increasing density, with a great deal of scattering. Figure 5 represents the correlation between MFD and
(accidents/(flow*density)), which is measured by accidents/km*hr. The number of accidents clearly began slightly higher in the free-flow condition, with a lot of scattering, and then it dropped and continued in a straight line with the increase of density. The accidents for TTC=0, meanwhile, started low but continually increased with the increase of traffic density.

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**Figure 4: Accidents/flow for all TTC values**

**Figure 5: Accidents/(flow x density) for all TTC values**

In figure 6, the relationship between MFD and accidents/speed, which is measured by (accidents*hr.)/km was tested. The figure clearly shows that the accidents/hr./km increased almost linearly with increasing density, with only a little scattering. Figure 7 represents the...
The relationship between MFD and accidents per productivity (accidents/(flow*speed)), which is measured by accidents/hr. /km^2. It is clear from figure 7 that the accidents were quite low at first, until the traffic density reached the optimal flow state, and then accidents started to increase alongside the increases in the congestion level.

Figure 6: Accidents/speed for all TTC values

Figure 7: Accidents/(flow x speed) for all TTC values
4.2 Speed and safety

In this section, the relationship between speed and accidents was investigated. The computation of the value of the exponent \((E)\) and the coefficient of determination \((R^2)\) was completed for equations (2, 3, 4, 5, 6, and 7). In figure 8, we can see the linear regressions for the six equations, where figures (a, b, c, d, e, and f) represent equations (2, 3, 4, 5, 6, and 7), respectively, with \(TTC=0\).

![Figure 8: linear regressions for equations (2, 3, 4, 5, 6, and 7).](image)

From table 1, we can see that the exponent \((E)\) value decreases with the increase in the \(TTC\) value for all equations. We can also note that the \(TTC\) value increases, resulting in increased \(R^2\) values in some equations, and decreased values in others. We can also see that the value of \(R^2\) was very important in equation 7, as well as in equations (3, 4, 6), while in equations (2 and 5), the \(R^2\) values were less important.

<table>
<thead>
<tr>
<th>(\frac{V_t}{V_i})</th>
<th>(E)</th>
<th>(R^2)</th>
<th>(E)</th>
<th>(R^2)</th>
<th>(E)</th>
<th>(R^2)</th>
<th>(E)</th>
<th>(R^2)</th>
</tr>
</thead>
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Table 1: Exponent values \((E)\) and coefficient of determination \((R^2)\) values for equations (2, 3, 4, 5, 6, and 7).
4.3 Density and safety

In this section, the relationship between density and accidents was investigated. The computation of the value of the exponent (E) and the coefficient of determination (R²) was completed for equations (8, 9, 10, 11, 12, and 13). From figure 9, we can see the linear regressions for the six equations, where figures (a, b, c, d, e, and f) represent equations (8, 9, 10, 11, 12, and 13), respectively, with TTC=0.

Figure 9: linear regression for equations (8, 9, 10, 11, 12, and 13).

Table 2 shows that the increase in TTC value resulted in an increase in exponent (E) value for all equations. It also shows that in some equations, the TTC value increases, resulting in increased R² values, while in others it decreases. In addition, when looking at R² values, we can see that equations (8 and 11) are very important, as are equations (9, 10, and 12), while equation (13) is not important.

<table>
<thead>
<tr>
<th>TTC</th>
<th>( \frac{C_2}{C_1} )</th>
<th>( \frac{C_2}{K_2} )</th>
<th>( \frac{C_2}{Q_2} )</th>
<th>( \frac{C_1}{V_1} )</th>
<th>( \frac{C_1}{Q_1} )</th>
<th>( \frac{C_1}{K_1} )</th>
<th>( \frac{C_1}{V_1} )</th>
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<td>0.5493</td>
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Table 2: Exponent values (E) and coefficient of determination (R²) values for equations (8, 9, 10, 11, 12, and 13).
4.4 Flow and safety

In this section, the relationship between flow and accidents was investigated. The computation of the value of the exponent ($E$) and the coefficient of determination ($R^2$) was completed for equations (14, 15, 16, 17, 18, and 19). Figure 10 shows the linear regressions for the five equations, where figures (a, b, c, d, e, and f) represent equations (14, 15, 16, 17, 18, and 19), respectively, with TTC=0.

![Figure 10: linear regression for equations (14, 15, 16, 17, 18, and 19).](image)

Table 3 shows that increases in the TTC values also increase the ($R^2$) and exponent ($E$) value in some equations, while in others they decrease. Looking at the value of $R^2$, we see that it is not important in all equations.

<table>
<thead>
<tr>
<th>$\frac{Q_{2}}{Q_{1}}$</th>
<th>$\frac{C_2}{C_1}$</th>
<th>$\frac{C_2/Q_2}{C_1/Q_1}$</th>
<th>$\frac{C_2}{K_2}$</th>
<th>$\frac{C_1}{K_1}$</th>
<th>$\frac{C_2/V_2}{C_1/V_1}$</th>
<th>$\frac{C_2/(Q_2 \times V_2)}{C_1/(Q_1 \times V_1)}$</th>
<th>$\frac{C_2}{(Q_2 \times K_2)}$</th>
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<td>$E$</td>
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Table 3: Exponent value ($E$) and coefficient of determination ($R^2$) for equations (14, 15, 16, 17, 18, and 19).
5. Concluding remarks

In this paper, we have proposed a methodology to understand the relationship between traffic safety and traffic parameters. We developed a new method called a "macroscopic safety diagram (MSD)" for evaluating traffic safety at the macroscopic scale. The proposed method contains eighteen equations linking accidents and traffic parameters (speed, density, and flow). We applied the method to simulated data for an arterial network. We found that while some equations had a strong relationship, others had no relationship. Future work will be using this new method to develop algorithms to control traffic conditions in order to reduce accidents. Before that can happen, however, more real data must be tested.
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