The relationship between traffic volume and road safety on the secondary road network

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A literature review

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Summary

On motorways, congestion is a well-known traffic problem. On the secondary road network, the same problem arises when traffic volume increases and the driven speed decreases. At certain times of day, roads get congested and the number of interactions between road users increases. In general, higher traffic volumes and congestion affect road safety. But how and to what extent does this happen?

This study aims to gain more insight into the relationship between traffic volume and road safety and is limited to road sections and intersections on 80 km/h roads in the Netherlands. The two most common types of intersections - roundabouts and signalised intersections - are discussed in the present study. A literature review is carried out to investigate the relationship between traffic volume and road safety on secondary rural roads (mainly 80 km/h distributor roads).

From the literature review carried out in this study, the conclusion is drawn that the relationship between traffic volume and road safety has not been studied widely. Although crash prediction models include traffic volumes, studies on these models focus on how infrastructural characteristics of road sections or intersections influence road safety, rather than on how traffic volumes affect road safety. Therefore, only a limited number of studies on crash prediction models could be reviewed in this study. Insight into the effect of traffic volumes on different types of crashes is limited, as is the relationship between traffic volume, overtaking behaviour and road safety. Since related studies have not been conducted in the Netherlands, this relationship is explored using research carried out abroad. It is unknown if the relationships described there can directly be translated to the Dutch situation. This study designates different topics which could be studied in future research.

Contents

1. Introduction

Congestion is a well-known traffic problem, in particular on motorways. On the secondary road network, the same problem arises when traffic volume increases. Roads with a speed limit of 80 km/h are part of this secondary road network. In the Netherlands, these roads are generally single carriageway two-lane roads and are outside the built-up area. These roads have different types of intersections, namely signalised or priority intersections and roundabouts. From the perspective of the Sustainable Safety vision, roundabouts are the preferred control since they reduce conflicts and conflicting speeds. Traffic signals, although essential from a capacity point of view, are not a preferable alternative from a safety perspective since they result in high speeds and red light violations, and lead to relatively high crash rates (SWOV, 2009). The 80 km/h roads are labelled as a relatively unsafe road category (Inspectie Verkeer en Waterstaat, 2008). In 2008, 36% of the registered fatalities occurred on these roads (source: BRON). For Dutch traffic, the relationship between traffic volumes and crashes, and traffic volumes and crash severity is not completely understood. This report focuses on the effects of traffic volume on road safety on roads of the secondary road network. In a literature search relevant studies will be sourced and analysed.

Chapter 2 of this report presents some background to the topic of this study. Some basic traffic flow relationships are discussed and the research aim, questions and method are described. *Chapter 3* presents the literature review on the relationship between traffic volume and road safety on 80 km/h roads. *Chapter 4* presents the conclusion and issues for further research.

2. Problem statement

2.1. Background

The road network in the Netherlands cannot keep up with the growing volume of traffic. At certain times of day, traffic volumes increase, the driven speed decreases and roads get congested. Furthermore, the number of interactions between road users increases. In general, higher traffic volumes and congestion affect road safety. But how and to what extent this happens, has not been widely investigated. This study is limited to the relationship of congestion and road safety on 80 km/h roads. An exploration of the relationship between congestion and road safety on motorways is described in a study by Marchesini (2010).

Before studying this problem, the basic correlations) of three important traffic flow characteristics will be discussed:
1. flow (*q*): ‘the number of vehicles passing a specific point or short section in a give period of time in a single lane’;
2. density (*k*): ‘the number of vehicles occupying a section of roadway in a single lane’;
3. speed (*u*): ‘the average rate of motion’ (May, 1990).

Figure 1 shows the basic traffic flow correlations in three diagrams. These correlations are rather theoretical. The actual field conditions need to be described while distinguishing more sophisticated correlations. However, for the purpose of this study, a description of the theoretical correlations suffices. When there are hardly any vehicles and therefore density approaches zero, speed will approach free-flow speed (u_f), meaning that a driver’s speed is not influenced by that of other drivers. Simultaneously, flow will approach zero as well. Speed will decrease to an optimum speed (u_o) when density increases to the optimum value (k_o). As there are more vehicles on the roadway, there is more interaction of vehicles. At the same time, traffic flow will increase to the maximum flow called capacity (q_m). A further increase of density to the maximum value or jam density (k_j) will result in a further reduction of speed until speed approaches zero. Flow will also decrease and approach zero (May, 1990; Transportation Research Board, 2000). In such a case, vehicles are queuing in a traffic jam.

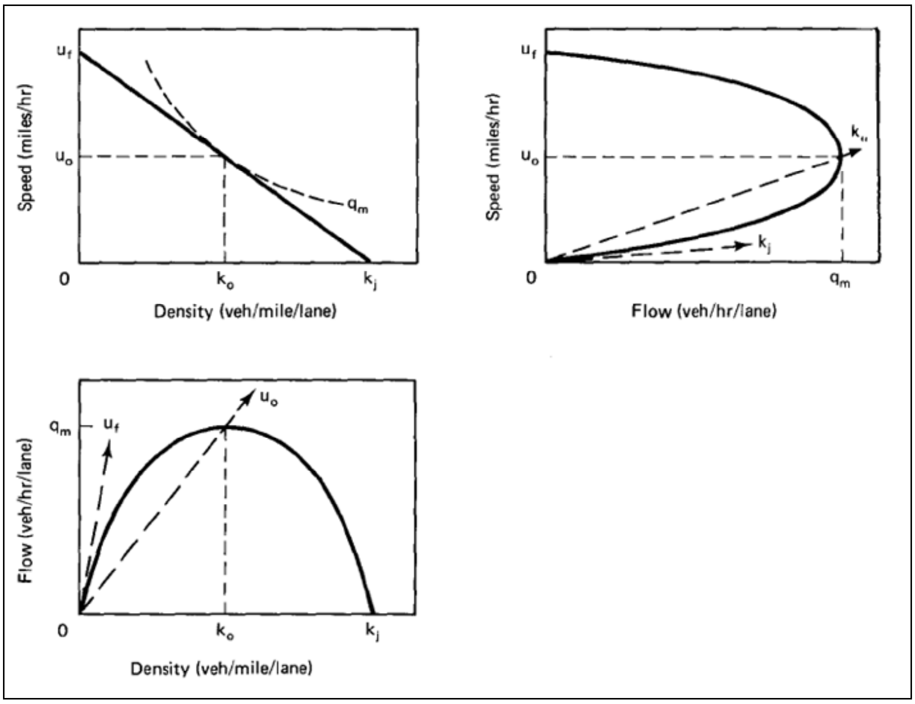

Figure 1. *Traffic flow diagrams (Source: May, 1990).*

The flow-speed and the density-flow diagrams are used to characterise the operational conditions of the traffic flow. These conditions are called the 'level of service' (LOS), which is a qualitative measure. The level of service is based on measures such as speed and freedom to manoeuvre. In the Highway Capacity Manual, six levels have been defined, from A describing the best operating conditions to F describing the worst (Transportation Research Board, 2000). *Table 1* shows the six levels of service defined by the American Association of State Highway and Transportation Officials AASHTO (2001). In the Netherlands, the level of service is not used to describe the operational conditions of traffic flow.

Level of service
A - Free flow
B - Reasonably free flow
C - Stable flow
D - Approaching unstable flow
E - Unstable flow
F - Forced or breakdown flow

Table 1. *The six levels of service (Source: American Association of State Highway and Transportation Officials AASHTO, 2001).*

How is road safety affected by an increase in the volume of traffic and of the number of interactions between vehicles? When studying the relationship between road safety and traffic volume on the secondary road network, it is necessary to make a distinction between road sections and intersections as these have different characteristics. In the Highway Capacity Manual (2000), this distinction is also made, namely between uninterrupted and interrupted traffic applications. An example of an uninterrupted traffic application is a motorway-type facility such as a road section. A signalized intersection is an example of an interrupted traffic application. Uninterrupted flow facilities do not have external fixed elements which might disrupt traffic flow, such as traffic signals. At interrupted flow facilities, there are controlled access points such as traffic signals and uncontrolled access points such as stop signs which may interrupt the traffic flow. These access points cause the traffic to stop periodically or slow down significantly, irrespective of the volume of traffic. The traffic process of road sections and intersections is described in the next paragraphs. On the basis of those traffic processes, expectations about how traffic volume affects road safety are formulated and presented in the next paragraphs.

Intersections
In the Netherlands as in the rest of the world, there are different types of intersections between two 80 km/h roads. The two most common types are roundabouts and signalised intersections. From a road safety point of view, a roundabout is safer than a traditional 3- or 4-arm intersection as there are fewer conflict locations (SWOV, 2009). In order to pass the roundabout, driven speeds are low, which results in a low crash severity. It is expected that when the volume of traffic increases, the roundabout and the intersecting arms will become congested resulting in more rear-end crashes. When the speed difference between the queue and the approaching vehicles increases, crash severity will also increase.

Traffic signals affect the operations at intersections by designating times to movements (traffic flows), allowing drivers to enter and pass the intersection (Transportation Research Board, 2000). When there is not much traffic at intersections, speeds are high. It is expected that in cases of red light running, speeds will also be high. It is expected that high speeds will result in high crash severity of side impacts. When traffic volume increases, the intersecting arms will become congested, resulting in more rear-end crashes at the tail of the queue, with lower crash severity when traffic is approaching this queue. In this case, the expectation is that there will be fewer side impacts. However, when the speed difference between the queue and the approaching vehicles increases, crash severity will increase as well. It is expected that red light running is more likely to happen when there is not much traffic, as a result of a relatively empty intersection which does not require drivers to stop for other traffic.

Road sections
Road sections are uninterrupted flow facilities where ‘traffic flow conditions result from the interactions among vehicles in the traffic flow, and between vehicles and the geometric and environmental characteristics of the roadway’ (Transportation Research Board, 2000). When there is not much traffic, speed will be high, as there is low interaction between vehicles. If allowed, vehicles can overtake each other. It is known that crash severity is higher when speeds are high. It is expected that when there is not much traffic, more single vehicle crashes will occur. As density and flow increase, speed decreases which results in lower crash severity of single vehicle crashes. This situation is also expected to result in a change of crash type, as speed of vehicles is now limited by the vehicle in front. Since it becomes more difficult to overtake other vehicles, the number of single vehicle

crashes will decrease, but the amount of head-on crashes will increase. It is also expected that an increase in density and flow will result in an increase of the number of risky overtaking manoeuvres and in a higher crash severity of head-on crashes. When the road is oversaturated (high density, low speed), overtaking manoeuvres are no longer possible, resulting in a decreasing number of head-on crashes. However, there will be more rear-end crashes. But since speeds are low, crash severity is expected to be low.

Although not included in this study, characteristics of the road and the roadside are also important factors which play a role in the relationship between road safety and traffic volumes, such as the presence of area access roads and the presence of agricultural vehicles. On some Dutch 80 km/h distributor roads, agricultural vehicles are allowed. As the volume of traffic increases, the number of overtaking manoeuvres decreases, but the number of *risky* overtaking manoeuvres increases. It is expected that this will affect road safety in a negative way. The presence of rural access roads (80 km/h roads) combined with an increase in traffic volume is also expected to affect road safety negatively. It is not hard for vehicles to enter and to leave the main roads when traffic volume is low. However, as the volume of traffic increases, it becomes more difficult to enter or leave the main road, in particular for left-turn manoeuvres. An increasing volume of traffic is expected to result in an increasing amount of side impacts with a high crash severity and also in an increasing amount of rear-end crashes with low crash severity, in particular for vehicles which are planning to make a turning manoeuvre. On some 80 km/h roads, turning lanes for left-turn manoeuvres are provided. As traffic volume approaches the capacity level and speeds decrease, it is expected that it will become difficult to enter the main traffic flow resulting in fewer side impacts.

Road network
When considering the combined road sections and intersections in the road network, a growing volume of traffic affects road safety negatively as vehicles take shortcuts to avoid the congested roads. Vehicles take short cuts on the secondary road network (80 km/h roads) when the motorway becomes congested. Similar to this, shortcuts on the 60 km/h roads will be taken when the secondary road network becomes congested. This is not a desirable situation since the shortcuts are usually over roads that are not designed for large volumes of motorised traffic and generally also have bicyclists and pedestrians using them. The issue of shortcuts is not part of the present study.

2.2. Research aim

This study aims to gain more insight into the relationship between traffic volume and road safety by means of a literature review.

The study is limited to the road sections and intersections on 80 km/h roads in the Netherlands. Two different types of intersections will be discussed in the present study, namely roundabouts and signalised intersections as these are the most common types. Literature from other countries and literature about comparable roads is used, since there is not enough literature on the Dutch situation alone. The study focuses on motorised traffic only.

2.3. Research questions

This study will focus on three research questions, which are:

- How and to what extent does traffic volume affect road safety of road sections of 80 km/h roads?
- How and to what extent does traffic volume affect road safety of signalised intersections on 80 km/h roads?
- How and to what extent does traffic volume affect road safety of roundabouts on 80 km/h roads?

When studying the effects on road safety, the various crash types and crash severity levels will be considered.

2.4. Research method

A literature review is carried out to investigate the relationship between traffic volume and road safety on secondary rural roads (mainly 80 km/h distributor roads). To search for literature, the following databases were used: SWOV Library and the websites of ScienceDirect and Scopus. Combinations of the following keywords were used:

- Road: arterial, distributor road, rural, roundabout, signalised, intersection;
- Road safety: crash/accident, (road) safety, rear-end, multiple vehicle, single vehicle, head-on, side impact, fatal, injury, overtaking (behaviour);
- Traffic: flow, volume, density, speed, queue.

3. Literature review

3.1. Studies on crash prediction models and traffic volumes

Crash prediction models are mathematical models that express the safety performance of road types or intersection types or a road network, based on traffic and road characteristics. According to Reurings et al. (2006) the following equation of a crash prediction model is the basic form of almost all models developed:

$$E(\lambda) = \alpha Q^{\beta} e^{\sum \gamma_i x_i}, \quad (1)$$

where $E(\lambda)$ is the estimated number of crashes, Q is traffic volume, x_i is a risk factor ($i = 1, 2, 3, \ldots, n$), γ_i is the corresponding coefficient and β is the effect of traffic volume on crashes. The aim of crash prediction models is to provide insight into the safety level of types of roads and intersections. Researchers are developing crash prediction models in order to estimate the road safety performance of certain road types or intersection types. These models can also be used to monitor the safety performance of a road network and give road authorities the opportunity to enhance it in case it is necessary (Duivenvoorden, 2009).

As can be seen in Equation 1, traffic volume is a variable in crash prediction models. In general, the annual average daily traffic (AADT) is used to represent traffic volume. To develop such models, a considerable amount of data is required, in particular data related to the length of and annual average daily traffic (AADT) on these roads (Eenink et al., 2008). A crash prediction model can also be represented by a graph, see Figure 2. On the x-axis, the AADT is plotted, and on the y-axis the number of road crashes per kilometre. On the x-axis the annual traffic volume (AADT) of different intersections is displayed, which means that it does not represent an increasing traffic volume of a single intersection.

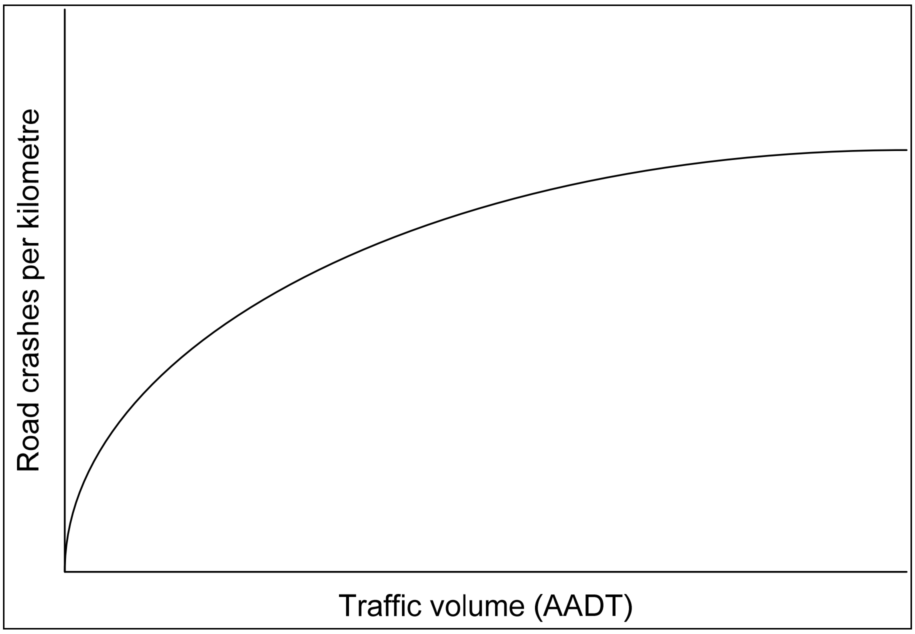

Figure 2. *Graph of crash prediction model (adapted from Reurings & Janssen (2007))*.

Another comment concerns the variable AADT itself. The AADT is the average number of vehicles in one year, which means that variations in traffic volume are averaged out. This problem is acknowledged by Reurings et al. (2006). These variations in traffic volume occur depending on both the hour of the day and the day of the week. Differences in traffic volume over the months, for example during holidays and as a consequence of seasonal conditions (rain, snow), are not considered either.

Studies on crash prediction models do not always focus on how traffic volumes affect road safety. They usually do focus on the influence of infrastructural characteristics on road safety. The present study, however, focuses on the former. Therefore, only studies on crash prediction models discussing the effects of traffic volume on road safety are taken into account in this literature review.

3.2. Road sections

In the European project RiPCORD-iSEREST, crash prediction models were developed (Eenink et al., 2008). The study shows that the number of crashes increases with an increasing traffic volume. This increase is not a proportional one, however. This means that the crash rate, which is here defined as ‘the number of crashes per motor vehicle kilometre’, decreases with increasing traffic volume. It is however unknown whether this is due to the higher traffic volumes or to a safer design of roads with higher traffic volumes.

Chang & Xiang (2003) carried out a literature study on the relationship between congestion levels and crashes and they also analysed a crash dataset containing almost 10,000 crashes that occurred at five major arterials and five primary motorways. Which crash types are investigated is not well defined by the authors. They state that a large body of research

focuses either on congestion or on road safety, instead of investigating the correlation between these two issues, such as how peak and off-peak traffic volumes affect crash rate or crash severity. On the basis of a literature review, the authors conclude that the relationship between congestion and crash rate and between congestion and crash severity is complex and has not been studied widely. The authors also conclude that the relationship between traffic volume and crash rate seems is seems to result in a U-shaped graph and that, in general, an increase in traffic volume seems to result in an increase in crash frequency.
In this study of Chang & Xiang, three relationships are investigated, namely the relationship between (1) crash frequency and congestion level, (2) crash rate (which is defined as 'the ratio between the number of crashes and associated volumes') and congestion level and (3) crash severity and congestion level. The authors do not clearly define the term 'congestion level'. They use the volume per lane as the surrogate variable for congestion. In the study, peak (7:00-9:00 and 16:00-18:00) and off-peak periods at five arterials are investigated. They find that for the relationshop between crash frequency and congestion level, there is an increase in crash frequency on arterials with increases in traffic volume. If the number of intersections per unit length (intersection density) on arterials increases, the crash frequency seems to increase as well. They also find that for the relationship between crash rate and congestion level on arterials, the crash rate declines if the traffic volume increases. In general, the crash rate increases as intersection density increases. The analysis of the relationship between crash severity and congestion level on arterials leads to the conclusion that crashes with a lower severity level are more likely to occur at arterials, whereas at intersections crashes with a higher severity level are more likely to occur when compared to road sections.

Hall & Pendleton (1990) examined the relationship between hourly crash rates and the ratio of traffic volume to capacity (V/C ratio) on rural highways. In their literature review, they state that previous studies, with some notable exceptions, found that the rate of traffic crashes on roadway sections increases with increasing traffic volume. However, data which are needed in order to support this relationship were highly scattered. According to the authors, the assumption of a relationship between traffic crash rates and traffic volume is valid but the exact nature of the relationship is unknown. Their own study is based on 44 study sites with a total length of approximately 680 kilometres. Contrary to most of the previous studies reviewed by them, Hall and Pendleton find that the highest crash rates occur during hours with the lowest traffic volumes. According to the authors, these low traffic volumes occur at night, and at night crash rates are known to be higher. The analysis of crash types shows that multiple vehicle crashes rather than single vehicle crashes increase as congestion increases beyond a threshold value. The threshold value is not further specified in the study.

Hiselius (2004) investigated the relationship between crash frequency and hourly traffic flow on rural roads. According to the author, there is a variation in results of earlier studies which investigated the relationship between crash frequency and traffic flow. Some conclude that crash rate decreases when traffic flow increases and some conclude that crash rate does not significantly increase. In the study of Hiselius, an increasing traffic flow consisting of both cars and trucks is shown to lead to a decrease in crash rate. However, the crash rate is constant or even increases when only cars

are analysed and trucks are left out of the analysis. There thus appears to be a difference in results when determining crash rates of cars and trucks together (heterogeneous traffic flow) or crash rates of cars only (homogeneous traffic flow). This difference seems to be present for daylight crashes, single and multiple vehicle crashes. The study does not provide detailed information on these results. In the study, the traffic flow frequencies for each road section are calculated by using the traffic flow data from stationary counters. For a homogeneous traffic flow an interval level of 25 vehicles per hour is used and for a heterogeneous traffic flow an interval level of 25 cars per hour together with an interval of five trucks per hour is used. The study does not provide more detailed information on this choice of interval levels.
Hiselius also investigates how an increasing number of trucks affect the number of crashes. It was expected that the number of crashes would increase as a result of an increasing number of possibly dangerous overtaking manoeuvres. However, contrary to expectations, the number of crashes declined. According to the author, this can be explained by trucks causing the average speed to decline, since the speed limit for trucks is lower than for cars.

The studies described above address the relationship between road safety and traffic volumes. In general, as traffic volumes increase, the number of crashes seems to increase, but the crash rate (the number of crashes per motor vehicle kilometre) seems to decrease. Studies addressing intersections will be discussed below.

3.3. Intersections

Crash prediction models have also been developed for intersections. Kulmala (1995) developed crash prediction models for three- and four-arm intersections. It is unclear if signalised intersections are part of this study. The study shows that increasing minor road traffic volumes lead to higher crash rates (number of crashes per million vehicle kilometres). When the volume of traffic on the minor road is high, crashes with a left-turning vehicle are in general more frequent while single vehicle crashes are less frequent. The report does not provide a clear definition of what a high volume of traffic on the minor road is. It appears that the volume of traffic on the minor road is more important at four-arm than at three-arm intersections.
The presence of heavy vehicles also plays a role according to Kulmala. For road sections and three-arm intersections it appears that a high percentage of heavy vehicles is associated with an increased risk of an injury crash. The crash rate for rear-end crashes at three-arm intersections increases when the percentage of heavy vehicles increases. According to the author, rear-end crashes with vehicles that are planning to make a left-turn are more frequent at intersections with a high percentage of heavy vehicles. The author also states that, when a heavy vehicle is involved as the vehicle colliding with the rear of another vehicle, this crash will have more severe consequences than other rear-end crashes.
As traffic volume increases, the percentage of crossing and rear-end crashes increases while the number of single vehicle crashes decreases. According to the author, many multiple vehicle crashes ‘have originated as potential single vehicle’ crashes where the vehicles concerned crashed into another vehicle instead of running off the road or crashing into an obstacle. In these situations, the presence of other vehicles seems to be naturally

correlated with traffic volume. It also appears that with increasing volumes, the risk of rear-end crashes increases as a result of the traffic driving in platoons with short headways.
In conclusion, it appears that the number of crashes and their victims is proportional to the total number of vehicles entering the intersection and that the risk of crashes increases with an increasing traffic volume on the minor road.

In the next paragraphs, roundabouts and signalised intersections will be discussed. Also red light running occurring at signalised intersections will be addressed.

3.3.1. *Signalised intersections*

Kim, Washington & Oh (2006) developed crash prediction models for different types of crashes at rural intersections. In the study, nonlinear relationships between AADT and different crash types are found, meaning that an increase in AADT will lead to an improvement in safety. According to the authors, this outcome corresponds to previous studies which developed nonlinear crash prediction models with respect to AADT. The authors find that roadway geometric and traffic volume variables affect the safety of two-lane intersections. It appears that an increase in AADT at the site will result in an increase in exposure to risk at the site. This is not described in further details, as this study focuses on geometric variables, such as the median width of the major road, presence of turning lanes and presence of lighting for the major road.

Red light running
A phenomenon common to signalised intersections is ‘red light running’, meaning that a vehicle deliberately or accidentally enters the intersection after the onset of red. Thus, the vehicle may crash into another vehicle which has entered the intersection legally (McGee & Eccles, 2003). According to McGee & Eccles (2003), there are two types of crashes, namely a vehicle crashing into another vehicle which is coming from the cross street, or a vehicle which is making a left-turn crashes into a vehicle coming from the opposite direction. Huang, Chin & Heng (2006) define similar types of crashes which can be related to red light running, namely right angle crashes and rear-end crashes. The former occurs if a vehicle crashes into a red light runner approaching from a conflicting stream and the latter occurs if the leading vehicle decides to stop for the red light and the follower anticipates the leader to go. Hakkert & Gitelman (2004) define two crash categories: (1) crashes with vehicles from conflicting traffic flows, such as right angle crashes and crashes of opposing vehicles with left turning vehicles, and (2) crashes of vehicles driving in the same direction, such as rear-end crashes.

Green (2003) identifies three categories of red light runners, namely:
1. ‘drivers who deliberately run red lights to avoid delays;’
2. ‘drivers who through sun glare, faulty signals or overhanging signs or vegetation do not see the red light. This circumstance is more likely to occur if there are no other vehicles travelling in the same direction as the offending vehicles, hence there are no triggers for the driver to realise he must stop at the intersection;’
3. ‘drivers who through some form of distraction do not see the red light.’

Lawson (1991) mentions a study of Baguley (1988) in which three types of red light running drivers are identified, namely:

1. ‘those who could have entered the intersection before the onset of the red light, but were delayed either by their own indecision or by slower traffic in front;’
2. ‘those in a ‘dilemma zone’ who could neither stop safely nor cross the stop-line before the onset or red;’
3. ‘those who could have stopped safely but chose to run the red deliberately.’

These types of drivers are more or less similar to the ones that Green identifies. From these two studies describing different types of drivers who run a red light, it appears that traffic volume is not taken into account except when considering the second type identified by Green (2003). A driver of this type is not triggered to stop as no other traffic driving in the same direction is present.

In order to investigate the phenomenon of red light running, Green (2003) carried out site observations at 15 intersections. At each intersection, video images are collected for a period of usually eight hours between 6:00 and 20:00. Data on traffic volume are also collected, although the data collection is performed in 10-minute intervals. Fourteen of the intersections observed are cross roads and one is a 3-arm intersection. The number of instances of red light running per 1,000 vehicles is determined. The speed limit of the majority of the selected roads is 60 km/h, and for a few cases 80 km/h. Analysis of the site observations suggests a higher rate of red light running at large intersections. Large intersections are those which are both physically large and large in terms of traffic volume. The study does not provide a definition of a large intersection.

Lawson (1991) carried out a study in Great Britain that investigated the occurrence of red light running by using cameras. The author suggests that the majority of red light running cases occur ‘during high levels of traffic flows and on roads where there is most traffic.’ According to Lawson, congestion affects red light running, as analysis of the results suggests that red light running occurs during peak morning and afternoon/evening periods. Finally, it appears that red light crashes were over-represented in evening periods, and especially in weekends, compared to other crashes at signalised intersections. In the study, the absolute number of crashes during a five-year period is analysed.

Bonneson & Son (2003) developed a model to predict if red-light running is expected to be a problem at certain signalised intersections and to indicate if these therefore need to be treated. The model shows that approaches with higher speeds appear to have a higher frequency of red light running. This also applies to platoons of vehicles approaching the intersection at the end of the yellow phase.

Camera enforcement is a countermeasure against red light running. On the basis of existing information, McGee & Eccles (2003) have studied how red light running camera enforcement affects crashes and crash severity. The authors state that the existing literature shows that red light running camera enforcement reduces the frequency of red light running violations, but that it is unknown how it affects crash experience (number and type of crashes). According to the authors, the results indicate that the overall safety of intersections is positively affected by red light camera enforcement. However, the information found is not conclusive. The number of right angle crashes generally declines but, in some situations, the number of rear-end crashes marginally increases. The increase in the number of rear-end crashes appears to be a result of a following vehicle crashing into a leading vehicle which stops when seeing the yellow signal. The authors explain that the following vehicle, which is not anticipating the need to stop, is keeping a too short headway. According to McGee & Eccles, right angle crashes are more severe than rear-end crashes and they state that 'even a zero change in the total number of crashes may prove to be safer, if there is a smaller proportion of right angle to rear-end crashes with the use of cameras.' McGee & Eccles also find that the majority of the studies reviewed have 'some experimental design or analysis flaw' (e.g. there is no proper control group and the sample sizes are small).

3.3.2. *Roundabouts*

Only one study was found which addresses the relationship between road safety and traffic volume at roundabouts. Saccomanno et al. (2008) performed a microscopic simulation study to compare traffic conflict patterns at roundabouts and signalised intersections. Three volume levels are investigated: low (1,500 vehicles per hour), medium (2,000 vehicles per hour) and high (2,500 vehicles per hour). From the results it appears that, with an increasing volume, the percentage of vehicles in conflict increases for both roundabouts and signalised intersections. When analysing rear-end conflicts, signalized intersections have a significantly higher proportion of vehicles being in conflict than roundabouts have. According to the authors, roundabouts 'result in a reduced exposure to rear-end traffic compared with signalised traffic control at intersections.' An explanation for this is, however, not provided by the authors.

3.4. **Discussion**

The previous sections describe different studies on the relationship between traffic volume and road safety. Since related studies have not been conducted in the Netherlands, this relationship was explored using studies from foreign countries. It is unknown if the described relationships can be directly translated to the Dutch situation.

Although many studies state that the subject matter of the study is the relation between road characteristics (e.g. median treatment, number of lanes), traffic volume and crash rate/severity/frequency, the studies do in fact not focus on the relation between traffic volume and road safety. Especially studies in which crash prediction models are developed do not explicitly investigate how traffic volume affects road safety. This does not mean that data on traffic volume are not collected or used. In fact, traffic volume is the requisite variable in order to be able to develop crash prediction models. In other studies, traffic volume is not used as an explanatory variable, but the effect of traffic volume is cancelled out by normalising crash rates for traffic volume. In general, these studies appear to be less interested in the effect of traffic volume on road safety. Instead, they focus on other characteristics and their relationship with road safety. An explanation for this omission may be that it is not possible for engineers or road authorities to adjust the traffic volume, as it is a given of the traffic system. Other characteristics of the road can be changed, such as the road width and presence of a median, and may therefore be more interesting to study. However, the subject matter of the present study is the relationship between traffic volume and road safety and it aims to gain a better understanding of factors influencing road safety on roads and intersections. Since the primary road network is burdened with increasing congestion, there is a possibility that the secondary road network will consequently experience increasing traffic volumes. It is therefore important to understand the relationship between traffic volume and road safety on this network as well. Unfortunately, not many studies addressing this relationship have been found.

4. Conclusion and further research

The aim of this study has been to investigate the relationship between traffic volume and road safety on 80 km/h rural roads belonging to the secondary road network. Three research questions have been examined:

- How and to what extent does traffic volume affect road safety of road sections on 80 km/h roads?
- How and to what extent does traffic volume affect road safety of signalised intersections on 80 km/h roads?
- How and to what extent does traffic volume affect road safety of roundabouts on 80 km/h roads?

By means of a literature review, relevant studies have been sourced and analysed in order to provide answers to the three research questions. The answers to the research questions will be discussed below.

How and to what extent does traffic volume affect road safety of road sections on 80 km/h roads?
In general, as traffic volumes increase, the number of crashes seems to increase but the crash rate seems to decrease. However, since this relationship has not been studied extensively, this conclusion is seen as a preliminary conclusion and not as a hard fact. One study found that, with an increase in traffic volumes, the number of multiple vehicle crashes seems to increase in contrast to single vehicle crashes. No studies have been found which mention how overtaking behaviour affects road safety when traffic volume increases.

How and to what extent does traffic volume affect road safety of signalised intersections on 80 km/h roads?
One study concludes that as traffic volumes increase the percentage of crossing and rear-end crashes seems to increase as well. In contrast, the percentage of single vehicle crashes appears to decrease. According to this study, the number of crashes and victims is proportional to the number of vehicles entering the intersection, and the risk of crashes increases when the traffic volume on the minor road increases.
Some of the studies on signalised intersections focus on the red light running problem which is typical at these intersections. One study concludes that red light running is affected by traffic volume, as most of the red light running cases occur during peak periods. A possible explanation, given by Bonneson & Son (2003), is that platoons of vehicles are approaching the intersection at the end of the yellow phase and some following drivers do not anticipate that leading drivers will stop, resulting in a relatively high incidence of rear-end crashes. The studies do not focus on the severity of crashes. Since this topic has not been studied widely, no clear results on the relationship between traffic volume and road safety are available.

How and to what extent does traffic volume affect road safety of roundabouts of 80 km/h roads?
Only one study has been found in which roundabouts are compared to signalised intersections on the basis of the number of rear-end conflicts at

three volume levels. More studies are needed to draw conclusions on how traffic volume affects road safety of roundabouts.

From this literature review the conclusion is drawn that the relationship between traffic volume and road safety has not been studied widely. Although crash prediction models include traffic volumes, studies on these models focus on how infrastructural characteristics of road sections or intersections influence road safety, rather than on how traffic volumes affect road safety. Therefore, only a limited number of studies on crash prediction models have been presented in this study.

Insight into the effect of traffic volumes on different types of crashes is limited, as is the relation between traffic volume, overtaking behaviour and road safety. Likewise, the foreign studies give no indication as to how the results should be translated to the Dutch situation. In this study, only the traffic volumes of motor vehicles are investigated. At the intersections on 80 km/h Dutch roads, there are generally cyclists present, and often special provisions exist to accommodate them. Another feature is the presence of agricultural traffic on some parts of the road network. This traffic is tolerated on parts of the rural secondary road network as no other alternatives exist to accommodate this traffic. This situation is not unique to the Netherlands. Two studies focus on how trucks affect road safety on road sections and intersections. However, in these studies different results are found. From this present study no conclusion can be drawn as to how Dutch features affect the relationship between traffic volume and road safety. These topics could be studied in future research.

There are several options to study the relationship between traffic volume and road safety on the Dutch secondary road network in further research. One possible research method is using a microsimulation model, such as Paramics, to study a specific road network. By varying the volume of traffic on the selected road network, the effects on the number and types of conflicts can be analysed. It is, however, not possible to analyse crashes as they cannot be introduced into in the model.
Another possible research method is an observation study during which driving behaviour on a certain road section or intersection ‘in the real world’ is analysed. The data can be collected by using video cameras or observers. An observation study is a time consuming and expensive method for collecting data. As a result of this, it is not possible to observe a large number of locations. In order to collect data on traffic volumes, it is possible to sample volume (e.g. 10 minutes) and to convert these to hourly traffic volumes. It is however preferable to use data collected during longer time intervals, data such as the annual average daily traffic (AADT). It is normal to observe locations during a peak and an off-peak period and to extrapolate the data to a 24-hour-period. Generally, these data are collected by detection loops in the road surface. However, detector loops have only been implemented in a small part of the secondary road network.
A third method is analysing crash data and traffic volume data. For information on the crashes occurring on the secondary road network, the database of registered crashes (BRON) in the Netherlands can be analysed. Additionally, police reports could be analysed as they contain more detailed background information. Traffic volumes at the time of a crash are more difficult to obtain. Since detector loops are not applied on the entire

secondary road network, it may be impossible to obtain traffic volumes for all crashes under investigation.
It depends on the research aim and questions of the future research which method should be applied. A crash analysis can be performed to gain more insight into the relationship between the time of crash and traffic volumes (if available). Police reports can be used for background information. A micro simulation study can be conducted to study the relationship between conflicts and traffic volume, and an observation study can be carried out on overtaking behaviour at road links.

Interesting topics for further research on the relationship between traffic volumes and road safety:

- for road sections, three different topics can be distinguished, namely overtaking behaviour, speed and crash risk. From the present study no conclusion can be drawn as to how an increase in traffic volume will affect overtaking behaviour or speed. Also the relationship between traffic volumes and crash risk is unknown. Overtaking behaviour and speed can be analysed in an observation study. An analysis of crash data and traffic volume data can be performed in order to investigate the relationship between traffic volumes and crash risk.
- For intersections, topics for further research are roundabouts and signalised intersections. From the present study no conclusion can be drawn as to how an increase in traffic volume affects road safety at roundabouts and signalised intersections. Both topics may be investigated by an analysis of crash data and traffic volume data.

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