KTH Architecture and
the Built Environment

A Methodology for Operations-Based Safety Appraisal of Two-Lane Rural Highways: Application in Uganda

Godfrey Mwesige

Doctoral Thesis in Transport Science
Stockholm, Sweden 2015

Supervisors:
Professor Haris N. Koutsopoulos: Division of Transport Planning, Economics and Engineering, KTH
Associate Professor Umaru Bagampadde: Department of Civil and Environmental Engineering, Makerere University
Assistant Professor Haneen Farah: Department of Transport and Planning, Delft University of Technology
Associate Professor Nissan Albania: Division of Transport Planning, Economics and Engineering, KTH

Mwesige, G. (2015). A methodology for operations-based safety appraisal of two-lane rural highways: Application in Uganda. Department of Transport Science, KTH, Stockholm.

ABSTRACT

The majority of the road infrastructure in developing countries consists of two-lane highways with one lane in each travel direction. Operational efficiency of these highways is derived from intermittent passing zones where fast vehicles are permitted by design to pass slow vehicles using the opposite traffic lane. Passing zones contribute to reduction of travel delay and queuing of fast vehicles behind slow vehicles. This however increases crash risks between passing and opposite vehicles especially at high traffic volumes due to reduction of passing opportunities. Reduction of passing-related crash risks is therefore a primary concern of policy makers, planners, and highway design engineers. Despite the wide application of passing zones on two-lane highways, there is limited knowledge on the underlying causal mechanisms that exacerbate crash risks, and the essential tools to assess safety of the passing zones.

This thesis presents a methodology to appraise safety of two-lane rural highways based on observed operation of passing zones. The proposed methodology takes into account the impact of traffic and geometric factors on the rate passing maneuvers end inside passing zones and in the no-passing zones, adequacy of the design passing sight distance, and time-to-collision at the end of passing maneuvers. The thesis is comprised of five papers addressing capacity and safety aspects of passing zones on two-lane rural highways. *Paper I* presents a review of the literature on capacity and safety of passing zones. *Paper II* discusses adequacy of the design passing sight distance based on the sight distance required to complete a passing maneuver using observed data. *Paper III* discusses formulation, estimation, and application of a model to predict the passing rate using geometric and traffic factors, and applications. *Paper IV* discusses risk appraisal of the passing process based on the probability to complete passing maneuvers with time-to-collision less than 3.0 seconds taking into account the accepted gap in the opposite direction and the passing duration. *Paper V* discusses formulation and estimation of models to predict the probability and the rate at which passing maneuvers end in a no-passing zone, and applications.

Results show that passing zones of lengths between 1.30 and 2.50 km are good for both operational efficiency and safety. Passing zones of lengths between 0.50 and 1.30 km exhibit increasing crash risks resulting from delayed passing maneuvers that end in the no-passing zone where the sight distance is limited to evade potential collisions. Safety of these passing zones could be enhanced with additional signage to indicate the farthest point along a passing zone that maneuvers can be initiated so as not to end in a no-passing zone. Passing zones less than 0.50 km compel drivers to commence passing maneuvers close to the beginning of the passing zone, and should be avoided during design for safety reasons.

The results further show that the passing rate depends on the length of the passing zone, absolute vertical grade, traffic volume in two travel directions, directional split, 85th percentile speed of free flow vehicles, and percent of heavy vehicles in the subject direction. The peak-passing rate also known as the passing capacity occurs at 200, 220, and 240 vph in the subject direction for 50/50, 55/45, and 60/40 directional splits, respectively. The rate at which passing maneuvers end in a no-passing zone increases with traffic volume and unequal distribution of traffic in two directions, absolute vertical grade, and percent of heavy vehicles in the subject direction. The thesis further discusses practical applications of the study findings in highway planning and design to enhance safety and improve operational efficiency of two-lane rural highways.

Key words: *passing zones, passing rate*, *collision risk, accepted gap, time-to-collision, passing sight distance*, *two-lane rural highways, Uganda*

ACKNOWLEDGEMENTS

This research was funded by the Swedish Government through the Swedish International Development Agency through SIDA/SAREC research grant to Makerere University, and KTH Royal Institute of Technology Stockholm. I am grateful to the Swedish Government for enabling me to study a subject of my choice, which has enabled me to contribute to the understanding of the effects of geometric design decisions on operation and safety of two-lane highways in Uganda. I thank the Government of Uganda and Makerere University for all the support throughout the study.

I also thank my supervisors Haris Koutsopoulos, Umaru Bagampadde, Haneen Farah, and Nissan Albania for constructive discussions and guidance. There is a huge difference between knowing what you want to study and doing it in a scholarly way. Thank you Haris, Haneen, and Umaru for guiding me along the scholarly path. I would also like to thank Karl-Lennart Bang for the constructive discussion and comments received during the final pre-doctoral seminar.

I am also grateful to the Uganda National Roads Authority and Uganda Police Force for giving me permission to collect traffic and geometric data used in this study without any hindrance or interference.

I would also like to thank KTH, Department of Transport Science, and Division of Transport, Planning, Economics and Engineering for providing a conducive study environment and the awesome KAFFE. Special people in the division I met, Lennart, Susanna, Mahmood, Erik, Jana, Oskar, Kalle, Ary, Athina, Jiali, Hans, and Anders.

I would also like to thank the Directorate of Research and Graduate Training, and Human Resources Director of Makerere University for facilitating travel, and research activities in Uganda.

I would also like in a special way to thank Bjorn Erik Alfredsson for always reserving me a place to stay in Stockholm, despite experiencing unreliable travel schedules for reasons beyond my control. Bjorn you have been a wonderful person to me, thank you.

Last but not the least; I would like to thank my family for supporting me. My mum, Astella Nyiradende who has always encouraged me to study despite not going to school herself. My wife, Jacqueline Namazzi for all the love and support for our children Ethan, Patricia, Jayden, Justin, and Austin while away in Sweden.

Godfrey Mwesige
Stockholm, 2015

LIST OF PAPERS

This thesis includes five papers written as part of the doctoral study in the period from 2011 to 2015. The author is the main contributor to all the papers from planning, model development, data collection, processing and analysis, and paper writing.

I Mwesige, G., Farah, H., Bagampadde, U. & Koutsopoulos, N. H. (2014). Capacity and safety of passing zones on two-lane rural highways: A review of theory and practice, *Journal of Traffic and Logistics Engineering, Vol. 2, No. 2, June 2014*.

II Mwesige, G., Bagampadde, U., Farah, H., & Nissan, A. (2015). Operational Characteristics of Passing zones on two-lane rural highways in Uganda. Submitted for publication in *Transportation Research Part F: Traffic psychology and behavior*.

III Mwesige, G., Farah, H., Bagampadde, U. & Koutsopoulos, N. H. (2014). A model for predicting the passing rate at passing zones on two-lane rural highways and applications; *In the compendium of papers of Transportation Research Board 93rd Annual Meeting, No. 14-0611*. Revised paper was submitted for publication in the *Journal of Transportation Engineering*, American Society of Civil Engineers.

IV Mwesige, G., Farah, H., & Koutsopoulos, N. H. (2015). Risk Appraisal of Passing Zones on Two-Lane Rural Highways and Policy Applications. Submitted for publication in *Accident Analysis and Prevention.*

V Mwesige, G., Farah, H., Bagampadde, U., & Koutsopoulos, N. H. (2015). Effect of Passing Zone Length on Operation and Safety of Two-Lane Rural Highways in Uganda. Submitted for publication in *IATSS Research.*

Conference Participation

1. Transportation Research Board 93rd Annual Meeting January 12-16, 2014, Washington, D.C., Session 644: Designing for high-speed operations
2. 2014 3rd International Conference on Traffic and Transportation Engineering, Lisbon, Portugal. April 17-18, 2014.
3. International Research and Innovations Dissemination Conference organized by Makerere University and Embassy of Sweden, April 20-21, 2015, Kampala, Uganda.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
A_G	Absolute vertical grade (percent)
AIC	Akaike Information Criteria
EAG	Effective accepted gap in the opposite direction
LOS	Level of service
MOWHC	Ministry of Works, Housing, and Communications
MOWT	Ministry of Works and Transport
MUTCD	Manual on Uniform Traffic Control Devices
NPZ	No-passing zone
PC	Passenger cars (saloon, four wheel drives, and pick-ups)
PHV	Percent heavy vehicles
Pr	Passing rate, passes per hour
PRT	Perception reaction time
PSD	Passing sight distance
PZ	Passing zone
TRB	Transportation Research Board
TTC	Time-to-collision
UBOS	Uganda Bureau of Statistics
UNRA	Uganda National Roads Authority
UPF	Uganda Police Force
V_{85}	85^{th} percentile speed of passenger cars under free flow conditions
vph	Vehicles per hour

1.0 INTRODUCTION

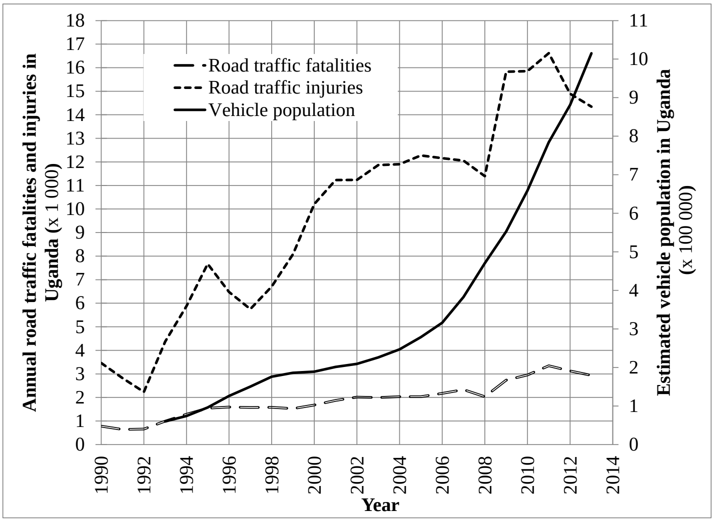
1.1 Background

Two-lane highways have one lane in each travel direction separated by centerline paint markings (Federal Highway Administration [FHWA], 2009; Ministry of Works Housing and Communications [MOWHC], 2004c). *Highway* is a technical term for *road* often applied in planning, design, and operational analyses related to roads (American Association of State Highway and Transportation Officials [AASHTO], 2001, 2011; Ministry of Works and Transport [MOWT], 2010). For consistency with technical applications, the term highway is used throughout this thesis. Highways in Uganda traverse diverse land-use types: built-up (urban or semi-urban), and non-built-up (*rural*). The Highway Code of Uganda distinguishes built-up and non-built-up areas based on the posted speed limits. That is, 50 km/h for built-up areas, and 80 or 100 km/h for non-built-up areas (MOWHC, 2004b). The present study focuses on highway sections traversing non-built-up areas referred to in this thesis as '*rural highways'* with posted speed limit of 80 km/h.

Two-lane highways in Uganda play a fundamental role in transportation of passengers and freight within the country, and between neighboring countries in East Africa. The National Roads network, which is primarily two-lane highways is 21000 km long with 4000 km (19%) paved and 17000 km (81%) un-paved (Uganda National Roads Authority [UNRA], 2015). The length of paved highways increased from 2800 km in 2008 to 4000 km in 2015 as a result of accelerated investment in highway development by the Government of Uganda (UNRA, 2015). The objective was to reduce vehicle-operating costs, travel time, and traffic crashes.

Fatalities and injuries arising out of traffic crashes however, continued to increase to 2937 in 2013 up from 2035 in 2008 despite growth in the length of highways with good pavement surface (Uganda Bureau of Statistics [UBOS], 2014). The traffic fatalities and injuries have been on the rise since 1990 as shown by the aggregate annual traffic crash data summarized in Fig. 1-1 (Ministry of Finance Planning and Economic Development, 1998; UBOS, 2002, 2006, 2008, 2010, 2014). The traffic fatalities for example increased from 778 in 1990 to 2937 in 2013. Similarly, traffic injuries increased from 3460 in 1990 to 14346 in 2013. Most of the fatalities (44% involving drivers and passengers) in 2013 were reported to occur on two-lane rural highway sections, attributed to over-speeding and careless/dangerous driving (UBOS, 2014).

The above traffic fatalities and injuries are unacceptably high for the low vehicle population, which was 60 000 in 1993 and 1.01 million in 2013 (Fig.1-1). Although, the vehicle population has exponentially increased since 1993, it is still very low in comparison with Uganda's population of 34.9 million people in 2013 (2908 vehicles per 100 000 people) (UBOS, 2014). The vehicle population is expected to continue to increase exponentially with sustained economic growth, which may result in more traffic crashes unless measures are put in place to mitigate factors that increase the risk of traffic crashes.



(Source: Statistical Abstracts 1998, 2002, 2006, 2008, 2010, 2014)

Fig. 1-1: Annual recorded road traffic fatalities and injuries in Uganda from 1990 to 2013

In comparison with Sweden, one of the countries with the lowest traffic crash fatalities despite having a high vehicle population shows a bigger traffic fatality problem in Uganda in terms of absolute fatalities and rates. For instance, by the end of 2006, Sweden recorded 445 traffic fatalities with a vehicle population of 5.04 million vehicles[1]. The corresponding recorded annual traffic fatalities in Uganda were 2171 with 0.32 million vehicles. That is, traffic fatalities in Sweden reduced to 260 in 2013 despite the vehicle population increasing to 5.60 million. Fig.1-2 summarizes the trends of annual traffic fatalities and fatalities per 100000 vehicles of Sweden and Uganda in the eight-year period between 2006 and 2013. Note from the figure that the fatality rates per 100 000 vehicles are very low for Sweden (5-9) compared to Uganda (289-687) in the eight-year period.

The fatality rates in Uganda show a downward trend not because the annual fatalities have been decreasing but rather the vehicle population is increasing faster than the traffic fatalities. This is the major application drawback of traffic crash rates in policy and planning for safety improvements. The low Swedish traffic fatalities and rates stem from the '*Swedish Vision Zero*' policy passed by parliament in 1997 to improve safety on the nation's highways (Fahlquist, 2006). Under vision zero, the

[1] *Source of Swedish vehicle and traffic fatality data: http://www.trafa.se/en/Statistics/Road-traffic/ accessed on June 2, 2015)*

responsibility of highway safety was placed on designers to identify and remove potential traffic conflicts on all Swedish highways. As a result, the Swedish Roads Administration in 1998 commenced a program to specifically convert 13-meter existing two-lane highways to 2+1 highway system separated by a steel median barrier to mitigate passing-related conflicts (Bergh et al., 2003). It was projected that the measure would contribute to a reduction of fatal and serious injury crashes by 50%. The 2+1 highway system has since been adopted in Germany and Finland with significant success in reduction of fatalities and severe injuries as well as improving operational efficiency (Transportation Research Board [TRB], 2003). Elimination of traffic conflicts and other policy measures from a holistic perspective have contributed to reduction of road traffic crashes and fatalities in Sweden. The Swedish experience has shown that it is possible to reduce traffic fatalities and injuries through appropriate design interventions geared at reducing traffic conflicts.

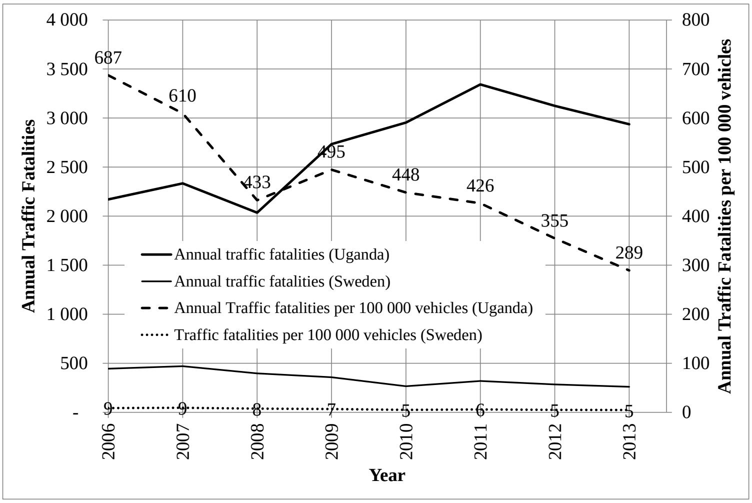


Fig. 1-2: Comparison of the annual traffic fatalities and fatality rates between Sweden and Uganda from 2006 to 2013

In an effort to reduce traffic fatalities and injuries, the Government of Uganda introduced mandatory road safety audits of highway development projects after publication of the *Road Safety Audit Manual* in 2004 (MOWHC, 2004a). Road safety audits are now mandatory for all highway development projects undertaken by UNRA. Despite this effort and enforcement strategies, traffic fatalities and injuries on completed highways have continued to rise especially on rural sections. This is partly because the road safety audits and expert reviews currently in use are largely qualitative and rely on expertise of the audit team, which is often lacking. The situation has been compounded by lack of quality traffic crash data collection, storage, and retrieval system in Uganda to carry out detailed blackspot analyses

(Mwesige et al., 2011). This therefore calls for evidence-based approaches to planning and design of Uganda's high-speed two-lane highways.

The traffic crash problem especially of two-lane rural highways is not unique to Uganda but rather global, resulting in higher fatal crashes and fatalities compared to other highway types (Agent et al., 2001; Gårder, 2006; Persaud et al., 2004; Shariat-Mohaymany et al., 2011; Turner & Tate, 2009; Tziotis et al., 2010). For instance, Jurewicz et al., (2015) reported that 60% and 70% of fatal traffic crashes in Australia and New Zealand, respectively occurred on rural sections of two-lane highways. Inappropriate passing (accepting shorter gaps or sight distance limitations) using the opposite traffic lane has been cited as one of the major cause of frequently observed head-on crashes on two-lane rural highways (Bergh et al., 2003; Clarke et al., 1998; Farah, Bekhor, & Polus, 2009; Gårder, 2006; Harwood et al., 2008; Tziotis et al., 2010). Other reported causes of head-on crashes include; drifting of subject vehicle in the opposite traffic lane or the shoulder, over-correcting and entering the path of the opposite vehicle, misjudging the needed gap in the opposite direction to complete passing maneuvers safely, and cutting across lanes when negotiating curves (Tziotis et al., 2010).

The above causes, to a great extent, relate to passing using the opposite traffic lane, which is both a design and operational characteristic of two-lane rural highways (AASHTO, 2001, 2011; MOWT, 2010; TRB, 2010). Passing using the opposite lane improves operational efficiency of these highways by reducing the time fast vehicles spend behind slow vehicles (TRB, 2010). This however, increases the risk of head-on collisions between the passing and opposite vehicles if the sight distance or the gap in the opposite traffic is not sufficient to complete passing maneuvers safely. Research on the passing process and the operation of passing zones could yield analytical tools to appraise risks of passing-related traffic crashes on two-lane rural highways.

1.2 Statement of the Problem

The unique operational characteristic of two-lane rural highways in which fast vehicles are permitted by design to pass slow vehicles using the opposite traffic lane has been reported to contribute to the occurrence of head-on crashes (Bar-Gera & Shinar, 2005; Harwood et al., 2008; Hegeman, 2004; Tziotis et al., 2010). Despite the high number of road traffic crashes on Uganda's two-lane rural highways, there is limited research on passing behavior and operational characteristics of passing zones. As such, the impact of the passing process on occurrence of road traffic crashes is largely incomprehensible. This has made it difficult for policy makers, planners, and highway design engineers to determine the factors that exacerbate traffic crash risk, and accordingly to propose measures to enhance safety of the passing process.

Studies of the passing process on two-lane rural highways have been conducted in several developed countries namely: Israel (Bar-Gera & Shinar, 2005; Farah & Toledo, 2010; Farah et al., 2008; Polus et al., 2000), Spain (Llorca & Garcia, 2011; Moreno et al., 2013), The Netherlands (Hegeman, 2008), The United States (Carlson et al., 2006; Harwood et al., 2008), Iran (Shariat-Mohaymany et al., 2011), South Africa (Van As & Van Niekerk, 2004), and Greece (Vlahogianni & Golias, 2012; Vlahogianni, 2013). The outcomes often formed the basis for the revision of design guidelines, investment decisions, and enforcement to enhance safety of two-lane rural highways. Transferability of research findings between countries is however, limited by differences in driver behavior, infrastructure quality, and traffic characteristics.

Past studies have specifically addressed: adequacy of passing sight distance [PSD] required to complete a passing maneuver comparing design and marking thresholds (Carlson et al., 2006; Harwood et al., 2008; Llorca & Garcia, 2011); the duration a passing vehicle spends in the opposite traffic lane (Farah, 2013; Llorca & Garcia, 2011; Vlahogianni, 2013); the accepted gaps in the opposite direction (Farah et al., 2009; Llorca, et al., 2012; Toledo & Farah, 2011); and time-to-collision at the end of the passing maneuver (El Khoury & Hobeika, 2007; Farah, Bekhor, & Polus, 2009; Hegeman, 2008; Jenkins & Rilett, 2005; Polus et al., 2000; Shariat-Mohaymany et al., 2011). Despite the above research efforts, there are still knowledge gaps in general especially on the causal factors that lead to passing-related traffic crashes.

For instance, adequacy of the design PSD is often assessed considering the sight distance required to complete individual passing maneuvers rather than the likelihood of completion of several passing maneuvers to satisfy the passing demand (AASHTO, 2001, 2011). That is, there is no consideration of the number of passing maneuvers that can be successfully completed inside passing zones equal in lengths to the design threshold. This is specifically important because from operational perspective, the passing process should be able to disperse platoons behind slow vehicles on arrival at a passing zone (TRB, 2010). Presence of opposite vehicles close to the beginning of a passing zone may for instance cause delays to initiate passing maneuvers, requiring longer passing zones than the design thresholds. Therefore, there is need to assess the effect of the passing zone length on the number of passing maneuvers ending outside the passing zone (in the no-passing zone). This is specifically important for safety reasons because no-passing zones are often located on crests or horizontal curves, where sight distance between the passing and the opposite vehicles is limited to evade potential collisions.

Further research is also required to determine the impact of geometric and traffic factors of passing zones on the rate passing maneuvers end inside the passing zone as a direct measure of passing capacity. This is important from policy and planning perspectives to determine when passing capacity is reached on two-lane rural highways so that passing using the opposite lane is prohibited for safety reasons. A recent study by Moreno et al. (2013) developed a model for the rate of passing maneuvers at a passing zone with length of passing zone, directional split and traffic flow in two directions as the explanatory variables. The study did not explore the impact of other traffic and geometric variables such as absolute vertical grade, percent of heavy vehicles and speeds of vehicles on the rate passing maneuvers end inside the passing zone and in the no-passing zone.

Safety of the passing process has been evaluated using a safety surrogate measure known as the *time-to-collision* estimated from the remaining time when the passing vehicle goes back to its lane, and arrival of the opposite vehicle (Polus et al., 2000). The time-to-collision concept originated from traffic conflict techniques that have long been applied to safety appraisal of intersections (Campbell & King, 1970; Hauer, 1982; Hyden, 1987; Laureshyn et al., 2010; Minderhoud & Bovy, 2001; Williams, 1981). The time-to-collision as a surrogate safety measure of the passing process has been determined independent of the other traffic variables such as the accepted gap in the opposite direction and the passing duration (Hegeman et al., 2005; Polus et al., 2000; Shariat-Mohaymany et al., 2011). Past studies have shown that the size and proportion of sufficient accepted gaps in the opposite direction decreases with directional traffic volume (Farah et al., 2009; Polus & Cohen, 2009; Rozenshtein et al., 2013; TRB, 2010). This affects the magnitude of the time-to-collision at the end of a passing maneuver, with safety consequences at higher directional traffic volumes. Further research is therefore required to explore the relationship between the time-to-collision, the passing duration, and the accepted gap in the opposite direction with applications to safety appraisal of two-lane rural highways.

1.3 Study Objectives

The main objective of this study is to assess, using empirical data, the impact of geometric and traffic factors on the passing behavior of drivers and consequently on the operation and safety of passing zones.

More specifically, the research aims at the following:

1) Assessing adequacy of design passing sight distances based on observed passing behavior at passing zones in Uganda.
2) Developing a model to predict the passing rate at passing zones based on geometric and traffic factors.
3) Assessing the risk associated with completion of passing maneuvers with shorter than safe time-to-collision accounting for the passing duration and the accepted gap in the opposite direction.
4) Assessing the effect of the length of passing zone on the operation and safety of two-lane rural highways based on the probability and the rate passing maneuvers end in the no-passing zone.

1.4 Significance of the Study

The study contributes to the United Nations Decade of Action on Road Safety requiring member countries to reduce road traffic crashes through road safety management, safer roads and mobility, safer vehicles, safer road users, and post-crash response (World Health Organization, 2011). This study in particular falls under the second pillar on safer roads and mobility, and explores ways to reduce road traffic conflicts that result in crashes through planning, design, and operation of two-lane highways. Secondly, the study contributes to the Government of Uganda's mission 'to develop and maintain a safe national roads network that fosters the economic development of Uganda' (UNRA, 2015). The study also contributes to the understanding of safety impacts of the passing process on two-lane rural highways. Specifically, the relationship between capacity of passing zones and safety at higher directional traffic volumes is explored with applications to policy, planning, and highway geometric design.

1.6 Approvals

Approvals were sought and obtained from UNRA and Uganda Police Force [UPF] to collect speed, passing maneuver and other traffic data along the highway sections namely: Jinja-Iganga; Iganga-Bugiri; Kampala-Masaka; and Masaka-Mbarara. In addition, as-built drawings showing alignment features on the highway sections were obtained from UNRA's Directorate of Planning. Field data collection of speeds and passing maneuvers adhered to safety standards and the laws of the Republic of Uganda.

1.7 Delimitations

The findings and discussion of this study is limited to observed passing behavior on two-lane rural highways in Uganda. Model formulation and estimation techniques proposed are transferable but not absolute parameter estimates because they were determined based on passing behavior in Uganda. The study was carried out at macroscopic level using aggregate data rather than individual driver behavior or vehicle trajectories. The data used in the analyses was collected by static video recording using tripod-mounted camcorders on clear non-rainy days between 13:00 and 18:00 hours East African standard time between March and May in 2012 and 2013. All passing zones had absolute vertical grade in the range -4% to $+4\%$ for a flat terrain (MOWT, 2010). This excluded passing zones that could be located in rolling and mountainous terrain. The lane and shoulder widths were 3.50 and 2.00 meters, respectively. The effect of lane and shoulder width on the passing behavior was not investigated in this study. The highway sections had similar surfacing type of 50 mm asphalt concrete in good condition thus controlling for the effect of frictional resistance on passing behavior. The data was collected on non-rainy days to control for the impact of the reduction of surface frictional resistance on passing behavior. The directional traffic volume was in the range 44-254 vph on sections of the northern highway corridor of East African Region.

1.8 Outline of the Thesis

The rest of the thesis is organized as follows. Chapter 2 presents a discussion on traditional approaches to safety appraisal of two-lane rural highways, which include traffic crash-based methods and the operations-based methods. In this chapter, the study conceptual framework, research questions, and hypotheses are also presented. Chapter 3 presents the methods and tools used in the study including site selection considerations, data collection tools, field layout of data collection, and data processing. Finally, Chapter 4 presents summaries of appended papers, study contributions, a summary, and proposals for future research.

2.0 APPROACHES TO SAFETY APPRAISAL OF TWO-LANE HIGHWAYS

This chapter presents a discussion of the approaches to safety appraisal of two-lane rural highways. The chapter presents a discussion of the traffic crash-based and operations-based methods. These are followed by discussions of the study conceptual framework, research questions and hypotheses.

2.1 Traffic Crash-Based Methods

Safety appraisal of two-lane highways has traditionally used traffic crash data analyses to identify blackspots on highways and to propose improvements. Decision support to policy makers, planners, and highway design engineers has conventionally been based on recommendations obtained from: before-and-after studies (Benekohal & Hashmi, 1992; Labi, 2006; McLean et al., 2010; Persaud et al., 2004; Srinivasan et al., 2010); safety reviews (Montella, 2005); and the aggregate traffic crash prediction models using geometric, traffic and environmental factors as explanatory variables (Anderson & Krammes, 2000; Labi, 2006, 2011; Lord et al., 2005; Miaou & Lum, 1993; Miaou, 1994; Mitra & Washington, 2007; Srinivasan et al., 2010). These methods are widely used in practice albeit with limitations.

Before-and-after studies for instance are reported to suffer the regression-to-the-mean [RTM] effect (Elvik et al., 2009; Hauer, 1971; 2001), and failure to account for local changes in traffic flow conditions at study sites (Hirst et al., 2004; Labi, 2006). The RTM effects lead to overestimation of treatment effects on crash reduction. Hirst et al., (2004) and Labi (2006) observed that in order to account for RTM effect there is need to consider changes in traffic crashes that would occur if the treatment were not in place, as well as changes in traffic flow conditions, which is rather difficult in practice. To correct for the RTM effect in before-and-after studies, the Empirical Bayes [EB] method is often used to account for changes in traffic volumes and other factors (Elvik et al., 2009; Hirst et al., 2004; Persaud et al., 2004). On the other hand, traffic crash prediction models are reportedly limited by lack of adequate traffic crash data as well as failure to account for spatial variability effects (Lin, 1990; Anderson & Krammes, 2000; Aarts & Schagen, 2006).

Traffic crash-based methods have also been criticized for being reactive rather than proactive, unstable, unreliable; and do not adequately explain the underlying cause-effect relationships between traffic crashes and other factors related to highway geometry, traffic and the environment (Bonneson & Ivan, 2013; Songchitruksa & Tarko, 2006; Tarko et al., 2009). Bonneson & Ivan (2013) have argued that spatial aggregation of traffic crash data increases bias of estimated coefficients leading to inaccurate safety inferences and conclusions. The authors proposed structural modelling (*mechanism-based*) approach in future safety research using theoretical relationship between traffic and geometric factors than relying on statistical correlations as is the case with traffic crash prediction modelling. Laureshyn et al.,

(2010) held the view that safety measures based on traffic crash data are not sufficient to assess operational efficiency of a traffic system. Songchitruksa & Tarko (2006) for example proposed use of '*the extreme value theory'* where traffic events are analyzed in a continuum from the safest to the most dangerous (that result in traffic crashes) for vehicles whose paths cross at a common conflict point. The authors argued that crashes are minor events that do not adequately represent the entire operational continuum of a traffic system. They proposed organizing traffic encounters into a hierarchy based on an operational severity measure from safest to the most dangerous encounters (resulting in crashes). Songchitruksa & Tarko (2006) and Laureshyn et al., (2010) used the time-to-collision as a safety surrogate measure with application to traffic conflicts at intersections.

More recently, the *Highway Safety Manual* was published as a single reference source for planners and highway design engineers to appraise safety of two-lane rural highways (AASHTO, 2010). The manual contains models and procedures derived from a combination of historical traffic crash data, traffic crash prediction models, before-and-after studies, and expert judgement. The manual states amongst its practical limitations; lack of consideration of differences of driver populations, changes in climatic conditions, hourly traffic volume variations during the day, and safety issues arising out of the interaction between adjacent features. Nevertheless, the prescribed procedures provide promising tools for safety appraisal of two-lane highways notwithstanding general limitations of traffic crash-based methods.

2.2 Operations-Based Methods

Recent advances in road traffic safety research have adopted proactive methods such as road safety audits [RSA] to assess safety of specific highway elements and to propose interventions (Kanellaidis, 1999; Spring, 2005). Road safety audits rely heavily on the expertise of the audit team to assess safety of existing highways and development projects using a combination of design reviews and targeted site investigations. The RSA procedure are now used in Uganda after publication of the *Road Safety Audit Manual* in 2004 (MOWHC, 2004a). The drawback of RSA is its reliance on the expertise of the audit team and absence of quantitative methods to check or validate recommendations.

The second operations-based method is the 'geometric design consistency', which uses operating speed models of passenger cars under free flow conditions at horizontal curves (Collins & Krammes, 1996; Gibreel, Easa, & El-Dimeery, 2001; Hassan et al., 2000; Hassan, 2004; Kanellaidis et al., 1990; Krammes et al., 1995; Lamm et al., 1990; Marchionna et al., 2011; Turner & Tate, 2009; Zuriaga et al., 2011). The method requires development of models to predict the 85^{th} percentile speed of passenger cars under free flow conditions for horizontal curves or tangents using independent variables derived from their respective geometric attributes. The models are then used to check for operating speed consistency between two successive alignment elements against a defined safety criterion.

Lamm et al. (1988) proposed safety criterion based on three thresholds for evaluating geometric design consistency by comparing 85th percentile speed difference (ΔV_{85}) between two successive horizontal curves or tangent and horizontal curve as follows: good design: ($\Delta V_{85} \leq 10$ km/h); fair design: ($10 \leq \Delta V_{85} \leq 20$ km/h); and poor design: ($\Delta V_{85} \geq 20$ km/h). These thresholds were implemented in the Interactive Highway Safety Design Model [IHSDM] as an additional tool for highway designers to appraise geometric consistency of alignments (FHWA, 1999). The objective of geometric design consistency approach is to provide a highway alignment during design that guarantees a consistent speeding environment. This indirectly contributes to reduction of loss-of-control traffic crashes resulting from excessive speeds especially in horizontal curves (Anderson & Krammes, 2000; Krammes, 2000).

The third operations-based method is the operational analysis of the passing process traditionally accomplished using methods and tools contained in the *Highway Capacity Manual* [HCM 2010] namely the average travel speed, and percent-time-spent-following [PTSF] (TRB, 2000, 2010). The PTSF is widely applied in operational analyses of two-lane highways as a surrogate measure of passing demand estimated from the proportion of vehicles travelling with headways less than 3.0 seconds. The PTSF however does not take into account the interaction effects that occur on two-lane highways and supply of passing opportunities such as the sight distance and gaps in the opposite traffic stream at passing zones. Design and marking of passing zones focusses on the sight distance required to complete a single passing maneuver but not the likelihood of completing several passing maneuvers to satisfy the demand to pass, which is often the objective of placing passing zones on two-lane highways (AASHTO, 2001, 2011; FHWA, 2009; MOWT, 2010; MOWHC, 2004c). The disjoint between design and marking of passing zones, and the need to satisfy the passing demand creates a knowledge gap, making it difficult to comprehend the impact of limited passing opportunities on safety of two-lane rural highways. The joint effect of increasing passing demand and reduction of passing opportunities could for instance yield insights into the factors that exacerbate passing-related crash risks (head-on, rear-end, and sideswipe in the opposite direction), and contribute to safety appraisal of two-lane rural highways.

2.3 Conceptual Framework

The focus of this study is to appraise safety of two-lane rural highways by jointly considering passing demand and opportunities using observed operation of passing zones and passing behavior. The study extends operations-based methods for safety appraisal of two-lane rural highways to consider mechanisms and factors that could help explain and quantify passing-related crash risks. Fig. 2-1 is a conceptual framework showing categorization of passing-related crash types and the potential causal factors. The causes of passing-related crashes are broadly grouped into ‘*systematic*’ and ‘*random*’ in view of the theoretical likelihoods of occurrence on two-lane rural highways during normal operation. Systematic causes arise because by design and operation, passing using the opposite lane increases collision risk attributed to: (*a*) insufficient passing gaps in the opposite direction especially at high traffic volumes (Gårder, 2006; TRB, 2010); and (*b*) inadequate sight distance to complete passing maneuvers safely (Tziotis et al., 2010). The expectation is that two-lane rural highways with insufficient passing opportunities experience high passing-related crash risks in form of accepting shorter than safe gaps to complete passing maneuvers, and reduction of the rate of completion of passing maneuvers in comparison with the demand to pass.

In contrast, random causes, which include vehicle mechanical condition, weather and visibility and driver behavior (fatigue, alcohol and other drugs use) should result in crashes less frequently unless the vehicle population is characterized by regular breakdowns or the driver population is largely impaired. Random causal factors have been reported to result into unintentional crossing of the centerline to the opposite traffic lane lead to head-on crashes (Clarke et al., 1998; Gårder, 2006; Tziotis et al., 2010). Findings by Gårder (2006) on these random causes in head-on crashes in Maine supports the theory that they less frequently result in crashes. For instance, driver fatigue was reported to be responsible for one in forty; and alcohol or drugs one in twelve of all head-on crashes.

This study is focused on estimation of crash risks resulting from the systematic causes resulting from normal operation of two-lane rural highways. Specifically, passing capacity and its impact on safety of two-lane rural highways is examined considering design and operational aspects of passing zones. This is because the passing capacity is known to decrease with increase in passing demand due to reduction of passing opportunities especially at high opposite traffic volumes (TRB, 2010). In this study, the passing capacity is estimated considering the rate at which passing maneuvers end inside a passing zone using geometric and traffic factors controlling environmental, driver and vehicle factors as illustrated in Fig. 2-1. The impact of passing capacity on safety is assessed considering adequacy of passing sight distance to complete passing maneuvers, risk appraisal based on time-to-collision at the end of passing maneuvers, and the probability and rate at which passing maneuvers end outside the passing zone (in the no-passing zone).

2.4 Research Questions and Hypotheses

The following are the five study research questions and hypotheses:

Q1: How is the capacity and safety of passing zones on two-lane rural highways defined and estimated?

This research question is explored in Paper I based on previous studies, design and marking standards of passing zones on two-lane rural highways. It provides the foundation onto which other research questions (*Q2-Q5*) were derived as shown in the conceptual framework in Fig. 2-1.

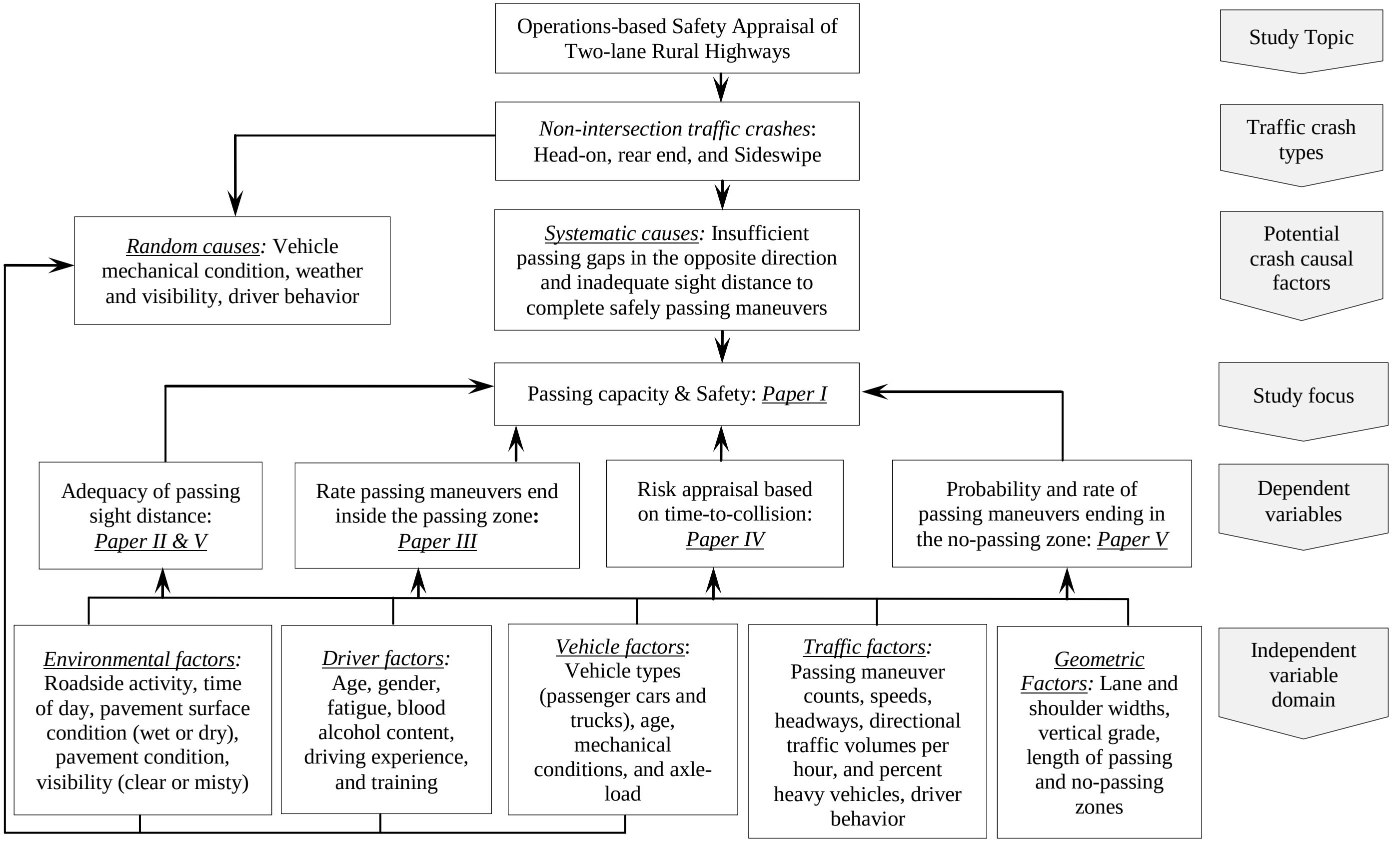


Fig. 2-1: Study Conceptual Framework

Q2: What is the required PSD threshold to complete passing maneuvers safely based on observed passing behavior in Uganda? How does the PSD threshold compare with those used to design and marking of passing zones in Uganda?

The second research question is explored in Paper II. The adequacy of PSD thresholds to complete safely passing maneuvers based on observed passing behavior on two-lane rural highways in Uganda in explored. In addition, performance of passing zones is compared with design and marking thresholds used in Uganda.

Q3: How does the rate at which passing maneuvers end inside the passing zone vary with geometric and traffic factors?

The third research question is explored in Paper III by presenting the rational and formulation of the model to predict the rate at which passing maneuvers end inside the passing zone for a set of geometric and traffic factors, also referred to as the passing rate. The null hypothesis was tested that the passing rate: (*a*) increases at a decreasing rate with traffic volume in two directions, percent of heavy vehicles, and length of passing zone; and (*b*) increases with the directional split, the 85th percentile speed of passenger cars under free flow conditions, the absolute percent vertical grade, and the length of upstream no-passing zone.

Q4: What is the relationship between time-to-collision at the end of passing maneuvers, the passing duration, and accepted gap in the opposite direction? How can this relationship be used to explain crash risk at high opposite traffic volumes?

The estimated passing rate model in *Q3* is not sufficient to explain why passing rates decrease at high opposite direction traffic volumes, and to quantify passing-related risks, which is necessary for safety appraisal. From a theoretical point of view, the passing rate decreases at high opposite traffic volumes because of the reduction in size and proportion of gaps to complete passing maneuvers safely. To explain this behavior, it is important to explore the relationship between the time-to-collision at the end of a passing maneuver, the passing duration, and the accepted gaps in the opposite direction. This research question is explored in Paper IV. The null hypothesis tested is that the probability of completing individual passing maneuvers with time-to-collision less than safe threshold increases: (*a*) as the size of accepted gaps in the opposite direction gets smaller; and (*b*) as the duration taken to complete the passing maneuver gets longer.

Q5: How does the rate at which passing maneuvers ending in the no-passing zone change with the length of the passing zone and the directional traffic volumes? What factors increase the probability of individual passing maneuvers ending in the no-passing zone?

The fifth research question addresses an important issue of what happens to the operation of passing zones at high opposite traffic volumes. Theoretically, it is expected that commencement of individual passing maneuvers increasingly become delayed as suitable gaps appear later inside the passing zone. This increases the risk and rate of passing maneuvers ending in the no passing zone where there is limited sight distance to evade potential collisions. This research question is explored in Paper V, and comprises of two parts: (*i*) estimation of the probability of passing maneuvers ending in the no-passing zone for a given length of passing zone; and (*ii*) the rate at which passing maneuvers end in the no-passing zone based on geometric and traffic factors. Two hypotheses investigated are: (*a*) the probability of passing maneuvers ending in the no-passing zone decreases as the length of the passing zone increases, and increases with the delay to initiate the maneuver from the beginning of the zone; (*b*) the rate at which passing maneuvers end in a no-passing zone increases with the increase of the traffic volume, and unequal distribution of traffic in the two travel directions, absolute vertical grade, and percent heavy vehicles.

3.0 METHODS AND TOOLS

This chapter describes the methods and tools used in the study for data collection and processing. It is comprised of five sections namely; site selection considerations, data collection tools, layout of tools during field data collection, and data processing.

3.1 Site Selection Considerations

Study sites were selected with the objective of controlling for external (environmental, terrain, driver, and vehicle) factors that could influence vehicle speeds and passing behavior. Rural sections of two-lane highways were selected to control for the impact of roadside activity and access density on vehicle speeds. A study by Cruzado & Donnell (2010) for instance reported that vehicle speeds reduced by 0.60 km/h for every increase in access points to a highway section. Moreover, presence of access points within the passing zone would, from a theoretical point of view, influence the passing behavior. Thus, selected sites did not have any access points and were in rural areas with a posted speed limit of 80 km/h.

The sites were also selected in flat terrain to have consistent vehicle speed characteristics and sight distances than in rolling and mountainous terrain. Fitzpatrick et al. (2000) have shown that the vertical grade leads to significant reduction of vehicle operating speeds. This study concentrated on two-lane rural highway sections located in a flat terrain with vertical grades between -4% and 4% (MOWT, 2010). All study sites were located on a tangent with clear centerline delineators to mark the beginning and end of a passing zone.

All sites were located on undivided National Road Class Ib (MOWT, 2010) with lane and shoulder widths of 3.50 and 2.00 meters, respectively. The sites were located on the highway that forms the continental Northern Corridor serving the Great Lakes region of East Africa shown in Fig. 3-1. The highway carries local and through traffic from Mombasa in Kenya through Kampala Capital City of Uganda to Rwanda, Burundi, and the Democratic Republic of Congo. The highway was also chosen because it carries high hourly traffic volumes than other highways in Uganda. Study sites were selected from the eastern (07), central (04), and southwestern (08) regions of Uganda as shown in Fig. 3-1. The purpose was to increase data variability and to control for local effects that would affect driver behavior in relation to speeds and passing behavior.

To control for the impact of frictional resistance on vehicle speeds and passing behavior, all study sections had 50 mm asphalt concrete pavement surface in good condition. Frictional resistance has been reported to impact the ability of vehicles to stop in emergencies, and differences exist between dry and wet pavements (Labi, 2006). The selected highway sections had recently been rehabilitated with no pavement distresses such as ruts and potholes that would influence operating speeds. For instance, no sites were selected between Kampala Capital City and Jinja Town because of pavement distresses.

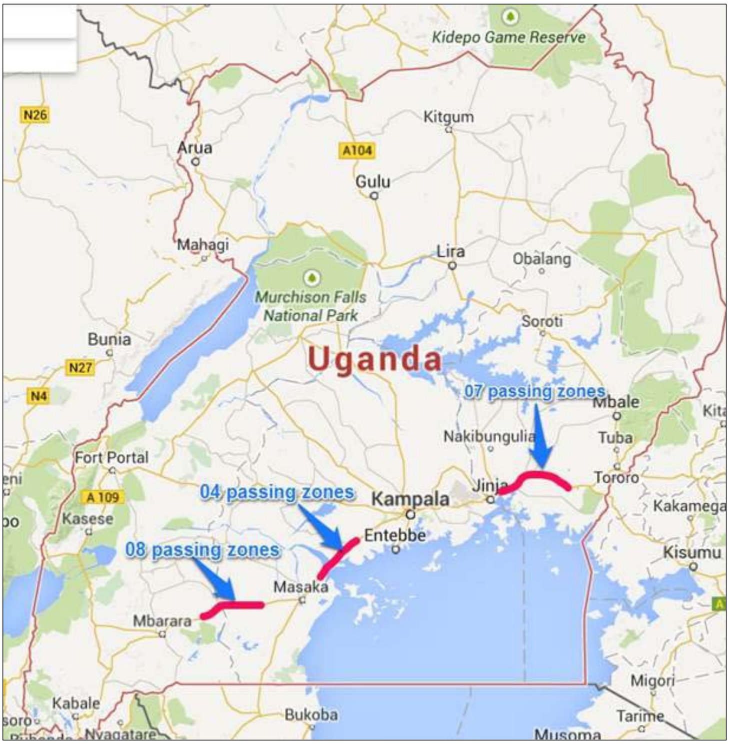


Fig. 3-1: Map of Uganda showing location of study passing zones *(Adopted from Google Maps, 2014)*

3.2 Data Collection Tools

Three categories of data were required for the study, namely: observed passing maneuvers, highway geometric characteristics, traffic volumes, and speeds. Each of the three data types required a different tool for collection in the field. These tools are presented in the subsequent sub-sections.

3.2.1 Observed Passing Maneuver Attributes

Observed passing maneuver attributes include: (*a*) the number passing maneuvers per hour; and (*b*) individual passing maneuver characteristics (such as the passing duration, accepted gaps in the opposite direction, speeds of all vehicles involved, and types of passing and passed vehicles). These variables were measured at the beginning of the passing zone and at abreast position, when the passing and passed vehicles appeared parallel to each other during the passing maneuver. According to the study objectives, it was necessary to classify passing maneuver counts by where they began and ended with respect to the passing zone. This classification meant that the selected data collection tools should be capable of observing both ends of a passing zone in addition to collecting individual passing maneuver attributes.

Past studies used different methods to collect passing maneuver data namely; helicopter hovering over a highway section (Polus et al., 2000); instrumented vehicle (Carlson et al., 2006; Hegeman, 2008; Llorca et al., 2014); tower-mounted cameras (Harwood et al., 2008; Llorca & Garcia, 2011); roadside cameras (Hegeman, 2008; Polus et al., 2000); and driving simulator (Bar-Gera & Shinar, 2005; El Khoury & Hobeika, 2007, 2012; Farah, Bekhor, & Polus, 2009; Vlahogianni & Golias, 2012; Vlahogianni, 2013). The merits and limitations of each of the methods are discussed in the subsequent sections.

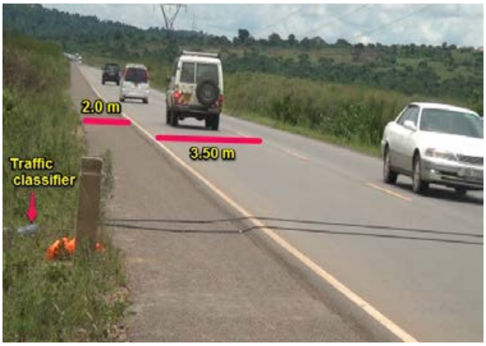
Polus et al. (2000) used a helicopter hovering above the highway section, and roadside cameras to study the passing process on two-lane rural highways in Israel. The authors used data from the helicopter to develop trajectories of individual passing maneuvers, and the roadside camera data to compute speeds of the vehicles involved in the passing maneuver. Data collection using a helicopter is expensive, in addition to requiring supplementary data from roadside cameras to estimate speeds of vehicles involved in the passing maneuver.

An instrumented vehicle, which is a car fitted with cameras in the front and rear can record passing maneuver characteristics such as the speed of the passing vehicle, the following distance before the maneuver, speeds of the passing vehicle before the maneuver and at abreast position, and the passing duration. The instrumented vehicle acts as the slow vehicle by setting the driving speeds to a relatively low speeds to enable passing of fast vehicles (Carlson et al., 2006; Hegeman, 2008; Llorca et al., 2014). The major drawback of this method is the inability to collect data of other vehicles, such as the opposite vehicle, and passing maneuver counts. The method also reduces variability of speeds of the passed vehicle since the researcher sets speeds at which the instrumented vehicle is driven.

Studies by Harwood et al. (2008) in the United States, and Llorca & Garcia (2011) in Spain used tower-mounted cameras to collect passing maneuver data. The Spanish study used six cameras mounted on a single tower with adjustable zone placed in the midway of the passing zone. Using this method, the authors could process passing vehicle trajectories up to 600 meters from the position of the cameras due to resolution loss. The tower was positioned by the roadside away from direct sight of drivers to minimize effect on driver behavior. Harwood et al. (2008) used one camera on the tower placed at one end of the passing zone. The authors similarly cited loss of image resolution at long distances from the camera position, and inaccuracies in distance measurements at curved alignment sections.

Other studies have used a driving simulator to study characteristics of the passing process at a microscopic level to determine the impact of vehicle and driver factors on passing behavior. The driving simulator has been for instance used to study factors that govern the driver’s desire to pass (Bar-Gera & Shinar, 2005; Vlahogianni & Golias, 2012); driver gap acceptance characteristics (Farah et al., 2009; Farah & Toledo, 2010); and risk proneness of drivers in passing maneuvers based on faulty decision making, average driving speed, and acceleration noise (Farah et al., 2008). The driving simulator is applicable for studies that seek to determine individual driver behavior characteristics, and the impact on the passing process. The purpose of this research was to collect empirical data on both the passing behavior and operation of passing zones on two-lane rural highways for which a driving simulator was not applicable.

In light of the limitations of the methods used in past studies to collect passing maneuver data, this study opted to use ordinary high definition tripod-mounted camcorders placed along the passing zone. The reasons for the choice of this tool were lower acquisition costs, portability, and deployment flexibility to collect both individual passing maneuver data and to observe the operation of the passing zone. For instance, to observe the operation of passing zones, it was necessary to place camcorders at both ends of the passing zone. In the case of tower-mounted camera, two towers would be required, which is costly.



a) Placement of tripod-mounted camcorder

b) Measuring wheel

c) Traffic classifiers and pneumatic tubes placed across the highway pavement

Fig. 3-2: Tools used in the study to collect geometric, passing maneuver and other traffic data

Tripod-mounted camcorders were placed by the roadside and parallel to the centerline of the highway to collect passing maneuver data. The set-up and positioning of the camcorder are as shown in Fig. 3-2a. Despite the above-mentioned advantages, data collection using roadside cameras has the limitation of falls due to wind, and suction from long vehicles if positioned close to the shoulder. To overcome this limitation, surcharge weights where attached to the tripods to enhance stability of the camcorders (see Fig.3-2a).

3.2.2 Geometric Attributes

The geometric data required for the study included: lane and shoulder widths, absolute vertical grade, length of passing and upstream no-passing zones at individual passing zones. The lane and shoulder widths, lengths of passing and no-passing zones were measured using a digital measuring wheel shown in Fig. 3-2b. The measuring wheel is portable, accurate, and easy to use since one person is sufficient to collect the required data. The vertical grades of the respective passing zones were extracted from as-built drawings obtained from UNRA for the respective highway sections.

3.2.3 Traffic Volume and Speeds

Traffic volume and speed data of the other vehicles in the traffic stream, which were not involved in the passing maneuvers, were collected using pneumatic tube sensors connected to traffic classifiers. The Apollo II traffic classifiers were used to collect directional traffic characteristics namely; timestamps of each vehicle, headways, axle length, vehicle type, and speeds of individual vehicles (Diamond Traffic Products, 2006). The choice to use Apollo II classifiers was based on robustness and reliability (the classifier had solar panel to charge battery while recording in rural areas), accuracy and acquisition cost. The procedure for tube installation involved a series of steps that included; laying two parallel tubes at right angles to travelled direction at a spacing of 1.22 meters, plugging and anchoring one end of the tubes with nails and clamps, and connecting the other ends of the tubes to traffic classifiers as shown in Fig. 3-2c.

3.3 Field Layout of Data Collection

Tripod-mounted camcorders were placed by the roadside at the edge of the shoulder or the side drain and not visible to the passing vehicles from a distance in order not to influence driver and passing behavior. Three camcorders were positioned by the roadside at the beginning, midway, and end of the passing zone (see Fig. 3-3). Two additional cameras were placed in between the three camera positions to capture passing maneuvers that were initiated and completed in the intermediate sections at long passing zones. In addition, pneumatic tube sensors were laid at the beginning, midway and at end of each passing zone as shown in Fig. 3-3. The traffic classifiers were configured to collect directional traffic data including; time stamps, number of axles, vehicle type, and the speed of each vehicle.

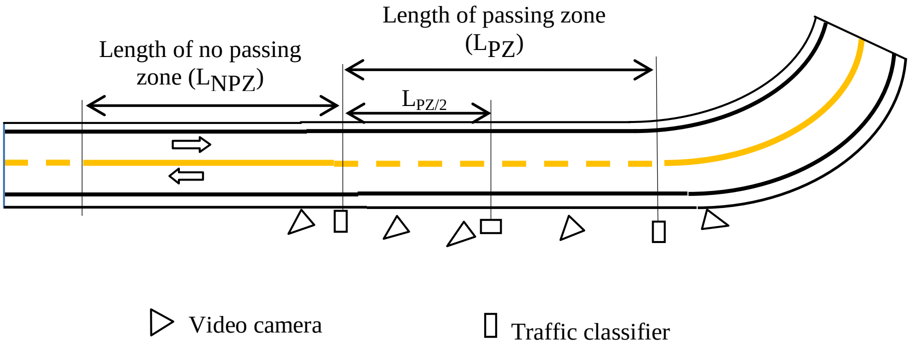


Fig. 3-3: Field layout and equipment used for speed and passing data collection

Traffic and passing maneuver data were collected for a period of five hours on a single day from 13:00 to 18:00 East African Standard Time at individual passing zones. During this time, it is possible to capture clear videos and minimize shadow effects from sunrays. This period also provided drivers with clear visibility of the passing zone to initiate and complete passing maneuvers. To control for weather effects on surface friction as discussed in Polus et al. (2000), and Harwood et al. (2008), data collection was carried out on dry non-rainy days. The data collection assistants were deployed to protect the equipment at a distance not to interfere with the data collection process. The data was collected in the period between March and May in 2012 and 2013.

3.4 Data Processing

Videos were transferred from camcorders and saved on three external hard disks each with a capacity of one terabyte. The videos where stored by name of passing zone and the camcorder number to ease retrieval during data processing. Passing maneuver data was extracted from the videos using an open source video analysis software, Kinovea (Charmant, 2011) to manually read time stamps of vehicles against pre-determined reference points on the highway and the vehicle. The software breaks down the video into a series of frames making it possible to mark reference points and to read time stamps in microseconds. The type of vehicles involved in the passing maneuver, time stamps when the maneuver commenced or ended and the number of passed vehicles was recorded in Excel spreadsheets. The data processing method is however time consuming. Each hour of video takes on average 4-8 hours to process depending on the traffic volumes, frequency of observed passing maneuvers and the type of data required.

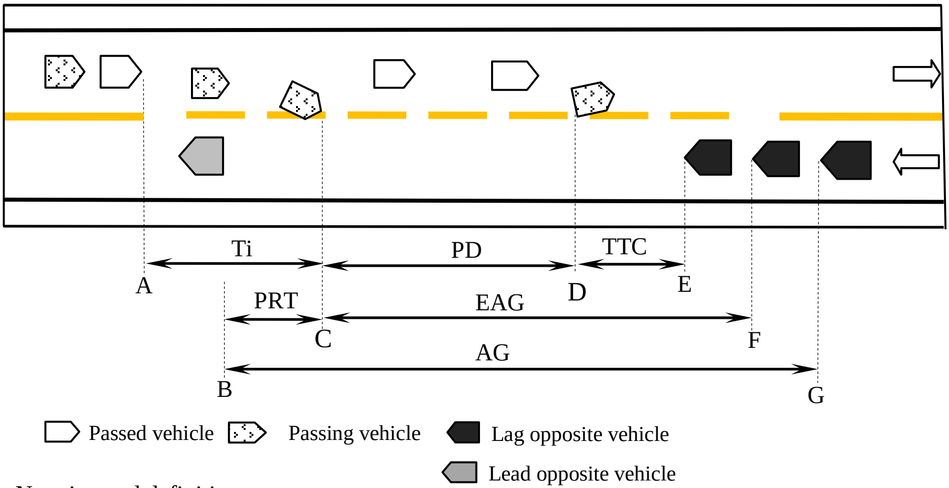
Traffic volume and speeds of vehicles at the beginning, midway, and end of the passing zone were transferred from Apollo II classifiers to hard disks using centurion software (Diamond Traffic Products, 2006). The data was uniquely stored for each passing zone and position in Excel files for further applications. Table 3-1 provides a summary of geometric and traffic variables of nineteen passing zones used in the study. The length of passing zones was in the range of 290 and 2985 meters, thus including passing zones shorter and longer than the design passing sight distance of 730 meters (MOWT, 2010). The range of average percent of heavy vehicles was between 20% and 56%, which is not surprising given the fact that the passing zones were located on a major export-import route in Uganda. The range of two-directional traffic volumes was 112 and 426 vph.

Table 3-1: Geometric and traffic attributes of passing zones used in the study

Section Name	**Length of passing zone (meters)**	**Absolute vertical grade (%)**	**Traffic volume in two directions (vph)**		**Average percent of heavy vehicles**
			Minimum	Maximum	
Bulanga	960	4,20	344	370	36
Busesa	1270	2,97	169	216	45
Idudi	355	3,12	191	217	56
Namasoga	355	2,37	366	426	26
Igenge	290	1,97	291	313	28
Busobi	675	2,72	211	214	45
Kaguta	610	1,56	115	125	33
Ruyonza	457	2,61	121	136	33
Kyapa	397	0,08	132	134	29
Kityaza	890	0,02	114	127	34
Rushororo	902	3.00	163	174	20
Kibega1	1330	2.00	127	133	24
Kiruhura	704	1,54	132	135	29
Munaana	1500	0,67	112	119	30
Kyabadaaza	664	0.00	258	343	33
Kuyaya	1625	0.00	278	368	25
Mbizinya	1122	1,40	330	402	21
Nyondo	2985	0.00	262	298	28
Nakalama	730	2,40	179	234	35

Fig. 3-4 illustrates other variables used in the study that were determined from video data: passing duration; time-to-collision at the end of a passing maneuver, perception reaction time; and accepted and effective accepted passing gaps in the opposite direction.

The passing duration (PD) was determined as the time from when the front right tire of the passing vehicle crossed the centerline to initiate a maneuver and the rear-right tire crossed the centerline after the maneuver to return to its lane (in Uganda drivers use the left lane). The duration was determined for single passing maneuvers involving a passenger car and another; a passenger car and a short truck (2-3 axles) of length less than 10 meters; and a passenger car and a long truck (4-7 axles) of length between 10-23 meters. In all these passing maneuvers, the passing vehicle was always a passenger car.



<u>Notation and definitions</u>

A: Beginning of the passing zone

B: Lead opposite vehicle position when the passing vehicle initiates a maneuver

C: Position when the passing vehicle initiates a maneuver (front right tire crosses the centerline)

D: Position the passing vehicle completes the maneuver (rear right tire crosses the centerline)

E: Position of lag opposite vehicle when passing vehicle returns to its lane

F: Position of lag opposite vehicle when passing vehicle initiates a maneuver

G: Position of lag opposite vehicle when passing and lead opposite vehicles are parallel to each other

PD: Passing duration (duration passing vehicle occupies opposite traffic lane).

TTC: Time-to-collision (the duration the passing vehicle returns to its lane and arrival of opposite vehicle)

PRT: Duration from when the lead opposite vehicle and passing vehicle appear side-by-side up to initiation of the maneuver

AG: Accepted gap measured as the time gap between two successive opposite traffic vehicles

EAG: Effective accepted gap in the opposite direction

Ti: The time from the beginning of the passing zone up to initiation of a passing maneuver

Fig. 3-4: Definition and measurement of passing maneuver variables

The TTC was measured as the time between a passing vehicle and an opposite vehicle at the moment when the passing vehicle completes the passing maneuver and returns to its lane. This is consistent with that used in previous studies (Farah, 2013; Jenkins & Rilett, 2004; Polus et al., 2000). Hegeman (2008) defined the TTC as the duration between the end of the maneuver, and meeting of the passing and opposite vehicles. This definition excludes the duration the opposite vehicle takes between meeting the passing vehicle and arrival at the position the passing vehicle returned to its lane at the end of the maneuver.

The perception reaction time (PRT), measured as the duration a passing vehicle takes to move from the position when it is parallel with the lead opposite vehicle to the point of initiation of the maneuver. This definition was similarly used in a study conducted in the Netherlands (Hegeman, 2008). The AASHTO (2001) design guide uses the time of initial maneuver consisting of the perception reaction time and time up to encroachment on the opposite lane. The design guide acknowledges there is no clear distinction between the two time components if the passing vehicle was in a following state before initiating a maneuver. This variable was measured for the passing vehicle in the constrained state behind a slow vehicle prior to passing the lead opposite vehicle. That is, the passing vehicle is close enough to the passed vehicle when the lead opposite and passing vehicle appear side-by-side. Six-seconds headway threshold between passing and passed vehicles at the beginning of the passing zone was used to indicate free flow conditions (Al-Kaisy & Karjala, 2010).

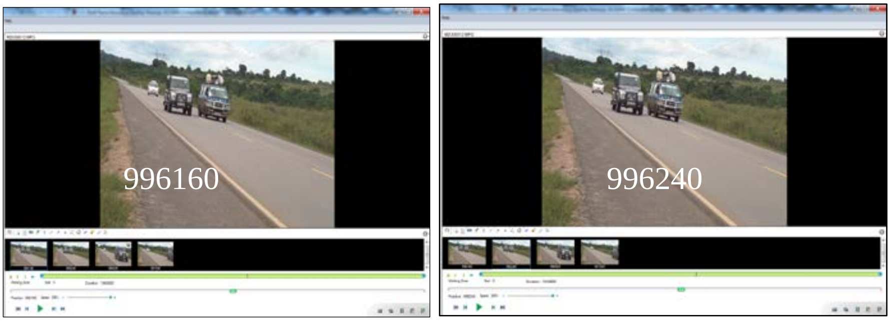
The accepted gap (AG), measured as the time gap between two successive vehicles in the opposite direction in which a maneuver was successfully completed. It was measured at the point the lead opposite vehicle was parallel with the passing vehicle. This definition has similarly been applied in previous studies by Jenkins & Rilett (2005), Hanley & Forkenbrock (2005), and Toledo & Farah (2011). The size of the accepted gap thus is influenced by flow in the opposite direction. The passing vehicle however, does not utilize the entire accepted gap due to delays in initiating the passing maneuvers. Therefore, another variable is defined as the effective accepted gap (EAG), measured from the point of initiation of a maneuver up to arrival of the opposite vehicle. The EAG was determined from videos.

The average speed of the passing and passed vehicles measured from abreast position is an input variable in the AASHTO (2001) PSD model. From previous studies, these speeds are measured when the passing and passed vehicles appear parallel to each other during the maneuver (AASHTO, 2001; Harwood et al., 2008; Llorca & Garcia, 2011). The speeds were determined from the video data from cameras placed midway the passing zone and computed using the speed trap principle (Gerlough & Huber, 1975). That is, travel time between two reference points at a known distance apart. The centerline markings of 3-meter yellow strips and 9-meter gaps in the passing zone, used as reference points to compute spot speeds as shown in *Eqn. 1*. The length of strips and gaps were verified in the field during data collection. To minimize measurement errors in reading travel time between reference points, a longer distance (24-meters) comprising of two strips and two gaps was used during data processing.

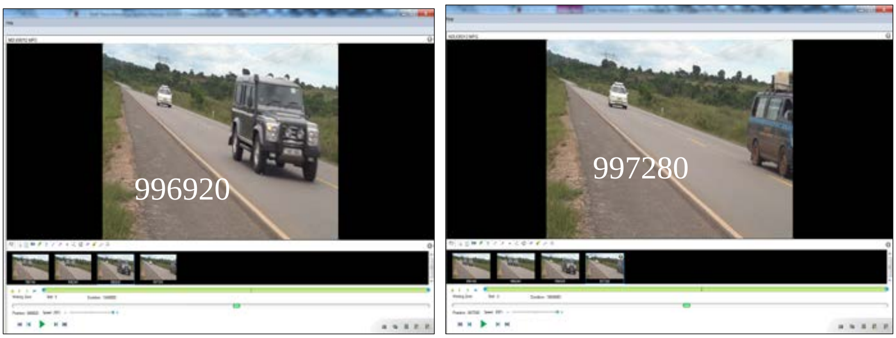
$$S_i = 3.6\left(\frac{d}{t_i}\right) \qquad (1)$$

Where: S_i is the speed of the passing or passed vehicle, (km/h); d the reference distance in the video (24 meters); and t_i the time taken to travel the distance (d) in the video (seconds).

As an illustration, snapshots of passing and passed vehicles recorded using the camcorders positioned midway the passing zone is shown in Fig. 3-5. The centerline strips and gaps are shown in the pictures. The time in microseconds from the video from the start of video recording is superimposed on each of the photos. The duration taken by the passed vehicle to traverse a 24 meter distance is the difference between 997280 (Fig. 3-5d) and 996160 (Fig. 3-5a), which is 1120 microseconds (1.120 seconds). The similar duration for the passing vehicle is 680 microseconds (0.680 seconds). Using *Eqn. 1*, the calculated speeds of the passing and passed vehicles are 127.1 km/h and 77.1 km/h respectively. Note that in *F*ig. 3-5b, the passing and passed vehicles are parallel to each other (at abreast position). This procedure was followed as well to calculate speeds of passing and passed vehicles at the beginning of the passing zone.



a) Passed vehicle reaches end of 24m mark *b) Passing vehicle reaches end of 24m mark*



c) Passing vehicle reaches beginning of 24m mark *d) Passed vehicle reaches beginning of 24m mark*

Fig. 3-5: Calculation of speeds of the passing and passed vehicles

4.0 SUMMARY OF PAPERS

The thesis includes five papers assessing the operation and safety of passing zones on two-lane rural highways. The papers address different but related aspects of the passing zone namely; a review of capacity and safety appraisal of passing zones (*Paper I*), assessment of adequacy of design passing sight distances used in Uganda (*Paper II*), formulation and estimation of a model to predict passing rate using geometric and traffic factors (*Paper III*), risk appraisal based on time-to-collision at the end of passing maneuvers (*Paper IV*), and lastly effect of passing zone length on operation and safety of two-lane rural highways (*Paper V*). A summary of the methodology, results, and applications is presented in Sections 4.1 to 4.5.

4.1 Paper I

Paper I is a review of the literature on how capacity and safety of passing zones are defined and estimated in theory and practice. The paper addresses the first research question (*Q1*) and sets the theoretical foundation onto which other research objectives and questions were derived. The review focused on the effect of passing capacity on safety of passing zones and overall performance of two-lane rural highways, and covered design, marking and operational aspects of passing zones.

The review established that capacity was defined for two-lane highways as 1700 and 3200 passenger cars per hour in one direction and two travel directions, respectively. The capacity values were derived from traffic volumes in one direction measured at a single location, independent of the interactions that often occur at passing zones that are a characteristic of the operation of two-lane rural highways. The lane capacity is therefore not an accurate parameter to measure effectiveness of two-lane rural highways. This fact is supported by the *Highway Capacity Manual* which states that most highways never reach the lane capacity (1700 passenger cars per hour) before they are converted to multi-lane highways (TRB, 2010). In addition, the literature and practice neither define nor quantify passing capacity despite passing zones being major operational features of these highways. The significance of passing capacity on operation and safety of two-lane highways is still largely unknown.

The review further established that operational analysis of two-lane highways uses surrogate measures such as the average travel speeds and percent-time-spent following [PTSF] (TRB, 2000, 2010). Specifically, PTSF is applied as an indirect measure of passing demand estimated considering the proportion of vehicles in one direction travelling with headways of 3.0 seconds or less (TRB, 2000, 2010). The PTSF as a measure of effectiveness has several drawbacks; (*a*) it is difficult to verify in the field (TRB, 2010), (*b*) reportedly yields over estimated values at high directional flows (Cohen & Polus, 2011; Luttinen, 2001), and (*c*) it does not take into account interactions that occur at passing zones but rather rely on macroscopic traffic flow parameters.

Past studies and practice broadly considered safety of passing zones in terms of: adequacy of design and marking PSD to accommodate long vehicles and fast vehicles, and time-to-collision at the end of the passing maneuver. However, there was no direct relation between capacity and safety of passing zones. That is, how safety margins change when passing opportunities dwindle at high opposite traffic volumes.

The paper concludes with a summary of knowledge gaps on capacity and safety estimation of passing zones and recommends further research to address these gaps, which are: (*a*) development of robust passing rate models for individual passing zones; (*b*) estimation of passing zone capacity in magnitude and location based on geometric, environmental and traffic factors of individual passing zones; (*c*) development of criteria to evaluate capacity and safety of passing zones for use by planners and transportation engineers; and (*d*) application of passing zone capacity to evaluate highway sections with several passing zones. The above research gaps have been specifically addressed in this study and are discussed in Paper II; III, IV, and V.

4.2 Paper II

Paper II addresses the first specific objective and the second research question (Q2). The paper discusses two approaches to assess adequacy of the design PSD based on observed passing behavior and operational characteristics of passing zones in Uganda. First, the design PSD threshold required to complete safely passing maneuvers is determined using the inputs of kinematic models in AASHTO (2001) as adopted in Uganda (MOWT, 2010). The PSD thresholds were calculated separately for a passenger car and a long truck as the passed vehicles. The purpose was to determine whether the design PSD threshold used in Uganda (730 meters for a design speed of 110 km/h in a flat terrain) was sufficient for safe completion of passing maneuvers involving a passenger car or long truck as the passed vehicle. The design PSD thresholds were also calculated following the model proposed in the 2011 edition of AASHTO design guide (AASHTO, 2011).

The results suggest that the current design threshold (730 meters) is longer than necessary for safe completion of passing maneuvers. Upholding the 730-meter PSD threshold during design would result in reduced passing opportunities due to fewer marked passing zones on two-lane rural highways. The calculated PSD thresholds are based on assumption that most passing maneuvers commence at the beginning of the passing zone. This is often not feasible due to delays to initiate passing maneuvers resulting from presence of opposite vehicle at the beginning of the passing zone, or high-speed catch-ups between the passing and passed vehicle inside the passing zone.

Secondly, adequacy of PSD was assessed considering difference between design and marking thresholds used in Uganda. The marking PSD thresholds used in Uganda

(MOWHC, 2004c) were adopted from MUTCD of the United States (FHWA, 2009) and are nearly half the thresholds used in design. An implication of the disparity between design and marking thresholds is that the marked passing zones are shorter than the design PSD thresholds on two-lane rural highways in Uganda. Operational characteristics of passing zones were compared to assess adequacy of PSD thresholds based on where passing maneuvers began and ended with respect to the passing zone.

The results showed that long passing zones are good for both operational efficiency and safety of two-lane rural highways. In addition, passing zones 290 (shortest recorded in the study) and 355 (PSD threshold in AASHTO 2011 edition) meters long offer little operational benefits to high-speed two-lane highways due to high passing maneuvers that begin or end in no-passing zone than those that begin and end inside the passing zone.

The paper also discusses some of the key passing behavioral parameters that influence the distance required to complete safely a passing maneuver, namely: the passing duration, the speeds of passing and passed vehicles at abreast position, the average speed difference at abreast position, and the time-to-collision at the end of the passing maneuver. Results showed that it takes longer on average (10.84 seconds) to pass a long truck (4-7 axles) than a passenger car or short truck (2-3 axles) (8.75 seconds). From design perspective, this result means that highways with a high proportion of trucks should be designed with longer passing sight distances. The average speed difference at abreast position (23.59 km/h) is constant irrespective of the speed of the passing and passed vehicles. The speed of the passing vehicle at abreast position increases with the speed of the passed vehicle at a constant rate. This result was consistent with the design assumption used to calculate the passing sight distance that the speed difference between the passing and passed vehicle is constant. Lastly, the time-to-collision at the end of passing maneuvers depends on the size of the accepted gaps. Accepted gaps smaller than 20 seconds resulted in time-to-collisions less than 2.0 seconds characterized by evasive actions by drivers of the passing and opposite vehicles.

The two methods used to assess adequacy of the design PSD were not sufficient to determine the optimal length of passing zone that results in a high percentage of passing maneuvers ending inside the passing zone. A model was thus required to predict the rate of passing maneuvers that end inside the passing zone based on geometric and other traffic related factors. The model is developed and estimated in Paper III. Secondly, it was also not possible in this paper to determine the length of the passing zone that minimizes the passing maneuvers ending in a no-passing zone. Models were developed to predict the probability and the rate passing maneuvers end in the no-passing zone in Paper V. Lastly, the relationship between the time-to-collision with factors such as size of accepted gap, passing duration, and type of passed vehicle are also explored in Paper IV.

4.3 Paper III

Paper III addresses the second specific objective of the study, and the third research question (*Q3*). It discusses the development and estimation of a model to predict the rate passing maneuvers that end inside the passing zone, referred to as the passing rate, using geometric, and traffic factors as explanatory variables. The objective was to illustrate how the passing rate varies with the traffic volume in two directions, and to determine the position of the peak-passing rate referred to as the passing capacity. Two null hypothesis were tested: (*a*) that the passing rate increases at a decreasing rate with traffic volume in two directions, percent of heavy vehicles, and length of passing zone; and (*b*) that the passing rate increases with the directional split, the 85^{th} percentile speed of passenger cars under free flow conditions, the absolute percent vertical grade, and the length of upstream no-passing zone.

The passing rate was modelled as a discrete random variable using Negative Binomial regression and the parameters were estimated using maximum likelihood in R statistical software (R Core Team, 2014) and MASS package (Venables and Ripley, 2002). The model was estimated for a vector of explanatory variables derived from geometric and traffic factors. The paper discusses statistical tests for coefficients of model variables checking for consistency with the null hypotheses.

The results show that indeed the passing rate depends on the length of the passing zone, absolute vertical grade, traffic volume in two travel directions, directional split, 85^{th} percentile speed of free flow vehicles and percent heavy vehicles in the subject direction. Furthermore, the peak-passing rate also known as the passing capacity occurs at 200, 220, and 240 vph in the subject direction for 50/50, 55/45, and 60/40 directional splits, respectively. Beyond these thresholds, the passing rates are reduced at high directional traffic volumes. It was not possible in this study to investigate the passing rate for directional traffic volume more than 254 vph due to lower traffic volumes on the highway sections used in the study.

The results further showed that the passing rate generally increases uniformly at decreasing rate with the length of the passing zone for the four levels of traffic volume in the two travel directions (100, 200, 300 and 400 vph). This is consistent with designing highways with long passing zones for passing efficiency (AASHTO, 2011; MOWT, 2010). It is also consistent with the discussion in Paper II that long passing zones yielded high passing maneuvers ending inside the passing zone. The passing rate however increases marginally for a unit increase of the length of the passing zone beyond 2.50 km. That is, 2.50 km is the optimal length of passing zone that results in high passing rates. Probable explanation is that up to 2.50 km, traffic platoons behind a slow vehicle have been dispersed and passing demand is marginal.

The results also show that the length of upstream no-passing zone was not significant at 95% confidence level although the sign was positive which is consistent with *a*-priori expectations. The length of the upstream no-passing zone represents the extent to which fast vehicles are constrained and indirectly affects the desire to pass prior to arrival at the passing zone. Four factors could reasonably explain this result. Long upstream no-passing zones do not necessarily increase the desire to pass but rather increase prohibited passing maneuvers in absence of strict passing enforcement, as is the case in Uganda. Secondly, the effective length of the upstream no-passing zone in which fast vehicles are constrained by a slow vehicle could be shorter than the overall length. This however is difficult to measure in the field, as one has to monitor the position at which fast vehicles catch-up with slow vehicles to form platoons. Thirdly, the queue length at the beginning of the passing zone behind a slow vehicle is not necessarily comparable with the passing rate since the latter depends on the size of available gap in the opposite traffic stream and the length of passing zone. Lastly, a high proportion (48%) of catch-up maneuvers (passing maneuvers with headways at the beginning of the passing zone more than 3.0 seconds between passing and passed vehicles) in passing rate data could be another probable explanation. This result need to be validated by further studies in different driving environments.

Results show that the passing rate increases to a peak (*passing capacity*) and decreases at higher opposite traffic volumes. This is not sufficient to explain why the passing rate increases from low directional traffic volumes to a peak and decrease at higher directional traffic volumes. From a theoretical point of view, the passing rate decreases because of the reduction in size and proportion of gaps in the opposite direction to complete passing maneuvers safely. To explain this behavior, the relationship between the time-to-collision at the end of a passing maneuver, the passing duration, and the accepted gaps in the opposite direction was explored in Paper IV. An important question is what happens to the operation of passing zones when the passing rate exceeds capacity at high directional traffic volumes? This question was explored further in Paper V.

4.4 Paper IV

Paper IV addresses the third specific objective and the fourth research question (*Q4*). The paper explores the effect on the passing duration and the accepted gap in the opposite direction on the time-to-collision at the end of passing maneuvers. This relationship has not been determined in previous studies despite its significance in explaining the risk associated with accepting shorter than safe gaps in the opposite direction to complete passing maneuvers. The relationship could, or instance, help explain the behavior of the passing rates at high traffic volumes observed in Paper III.

The paper explores the application of time-to-collision (TTC) as a surrogate safety measure to quantify the risk associated with unsafe completion of passing maneuvers. Theoretical basis for model formulation and selection of explanatory variables is presented and discussed. Safe completion of passing maneuvers was evaluated using two TTC thresholds: 2.0 and 3.0 seconds. A logistic regression model was developed with the effective accepted gap in the opposite direction, and the passing duration as explanatory variables. The models were estimated using the MASS package for logistic regression in generalized linear modeling applications (Venables & Ripley, 2002) in R statistical software (R Core Team, 2014).

Results show that TTC-values less than 3.0 seconds involve evasive actions by the drivers of the vehicles involved in the maneuver in the form of reduced speeds, flashing lights, and shifting laterally to the shoulders as observed in recorded videos. Therefore, TTC values less than 3.0 seconds are risky for the drivers involved in the passing maneuvers. As a result, a safety threshold of 3.0 seconds was adopted for sensitivity analysis.

The sign of the coefficient for the effective accepted gap was negative as expected *a*-priori (null hypothesis) implying that the probability of passing maneuvers ending with short TTC decrease with an increase in the size of the effective accepted gap in the opposite direction. Equally, the sign for the passing duration is positive showing that the probability of passing maneuvers ending with short TTC increases with the passing duration.

A sensitivity analysis was conducted for 70% of the observed passing durations involving passenger cars or short trucks (2-3 axles), and long trucks (4-7 axles) as the passed vehicles for TTC threshold of 3.0 seconds. Results show that effective accepted gaps less than 17.00 seconds require the passing vehicle to complete maneuvers with durations below 6.16 seconds in order to end the passing maneuver with TTC greater than 3.0 seconds. Only 15% of observed passing maneuvers, involving passenger cars, or short trucks (2-3 axles) as the passed vehicle were completed with passing durations less than the 6.16 seconds. Moreover, the ability to achieve shorter durations depends on the passing vehicle acceleration capabilities to attain higher speeds, and the speed of the passed vehicle. Therefore, effective accepted gaps less than 17.00 seconds result in a high risk of collision due to high probabilities of passing maneuvers ending with TTC less than 3.0 seconds.

The results further show that the risk of passing maneuvers ending with TTC less than 3.0 seconds for accepted gaps in the range between 17.00 and 29.50 seconds depends on the duration it takes to complete the maneuver. That is, the longer the duration the higher the risk for a given size of the accepted gap in the opposite direction. The risk is especially high if the passed vehicle is a long truck (4-7 axles). Effective accepted gaps greater than 29.50 seconds end with minimal risk of collision for passing durations 13.29 seconds or less. This passing duration threshold was exceeded only by 15% of observed passing maneuvers involving long trucks (4-7 axles), and close to 7% of passenger cars or short trucks (2-3 axles) as the passed vehicles.

The range of effective accepted gaps in the opposite direction presented above where compared with directional traffic volume considering the average headway and the proportion of headways 30 seconds or more. The probability of passing maneuvers ending with TTC less than 3.0 seconds was less than 0.50 for 70% of maneuvers involving a passenger car or short truck (2-3 axles) as the passed vehicles for directional traffic volumes in the range 133-212 vph. The corresponding range for long trucks (4-7 axles) as the passed vehicle is 122-185 vph. This range is also consistent with the behavior of passing rate and capacity presented in Paper III. That is, the passing rate decreases at high opposite traffic volumes because of increased difficulty to find suitable gaps to complete safely passing maneuvers.

Based on the above results, three risk levels were proposed considering the probability to complete passing maneuvers with TTC less than 3.0 seconds for a range of opposite direction traffic volumes. Applications of the proposed risk thresholds to policy, planning and design for highway safety improvements are discussed in the paper.

4.5 Paper V

Paper V addresses the fourth objective and the fifth research question (*Q5*). The paper presents a methodology to assess the effect of passing zone length on operation and safety of two-lane rural highways based on the probability and the rate at which passing maneuvers end in a no-passing zone. The paper addresses the question of what happens to the operation of passing zones when the passing capacity is exceeded. A theoretical framework to explain why passing maneuvers are likely to end in a no-passing zone at high directional traffic volumes and at short passing zones is presented and discussed. Two models are presented for the probability of a passing maneuver to end in a no-passing zone (logistic regression), and the rate passing maneuvers end in a no-passing zone (Negative Binomial).

The results show that 52% of the observed passing maneuvers had headway between passing and passed vehicles at the beginning of the passing zone of 3.0 seconds or less, and 48% of the passing maneuvers had headway of more than 3.0 seconds. Specifically, the proportion of passing maneuvers that end in a no-passing zone was more than double for headways exceeding 3.0 seconds. The proportion increases to 69% for a 6.0 seconds-threshold, which is the limit of free flow conditions. The results show that passing maneuvers frequently commence farther than the beginning of the passing zone with high chances of ending in the no-passing zone.

Sensitivity analysis of the probability of passing maneuvers to end in a no-passing zone showed that passing zones up to 400 meters long confine maneuvers to commence close to the beginning for safe completion inside the passing zone, which is a safety concern. For passing zones 500, 600, and 730 meters long, the probability of individual maneuvers ending in the no-passing zone reached 0.50 when initiation of the maneuver is delayed up to 255, 350, and 465 meters, respectively. These passing zones provide a substantial length for initiation of the maneuvers that can safely end inside the passing zone. The probability of passing maneuvers ending in a no-passing zone reaches 0.50 when the remaining sight distance from the beginning of the passing zone is 245 meters for passenger cars or short trucks (2-3 axles); and 300 meters for long trucks (4-7 axles) as the passed vehicles. These results suggest changes in design and marking of passing zones to enhance safety of two-lane rural highways.

The results from the estimation of the rate of passing maneuvers ending in a no-passing zone showed consistency with *a*-priori expectations. The coefficients for percent absolute vertical grade, traffic volume in two directions, the directional split, length of passing zones, and the percent heavy vehicles had positive signs as expected. The rate at which passing maneuvers end in a no-passing zone was found to increase with traffic volume and unequal distribution of traffic in two directions, absolute vertical grade, and percent heavy vehicles. Specifically, the rate increases with the passing zone length up to 1.30 km and decreases at higher values. These results show that passing zones longer than 1.30 km are good for safety.

In Paper III, the optimal passing zone length was determined as 2.50 km. This shows that passing zones of length 1.30 km to 2.50 km are good for both operational efficiency and safety. However, quite often alignment characteristics permit passing zones shorter than 1.30 km. Results in this paper suggest that safety of passing zones of lengths 0.50-1.30 km could be enhanced with additional signage to indicate the extent maneuvers can be initiated so as not to end in a no-passing zone. Passing zones less than 0.50 km for the type of highway used in the study confine most passing maneuvers to commence close to the beginning of the passing zone and are a safety concern. These passing zones should be avoided for safety reasons. Where passing zones less than 0.50 km exist, additional warning signs should be installed and enforced to help drivers commence maneuvers close to the beginning of the passing zone for safety reasons.

5.0 CONTRIBUTIONS AND FUTURE RESEARCH DIRECTIONS

This section discusses the main contributions of the thesis both from theoretical and practical points of view. The contributions are discussed separately in sections 5.1 and 5.2, respectively. Section 5.3 presents a discussion on the future research directions.

5.1 Theoretical Contributions

This thesis contributes to the understanding of the underlying causal mechanisms that impact crash risk based on observed operations of passing zones on two-lane rural highways. The operation (TRB, 2000, 2010) and design (AASHTO, 2001, 2011; MOWT, 2010) aspects of passing zones have often been considered independently while analyzing capacity and safety of two-lane rural highways. The thesis presented a methodology that evaluates jointly the design and operational aspects of passing zones in relation to capacity and safety. Specific contributions include:

1. Development of passing rate models to predict the rate passing maneuvers end inside and outside the passing zones incorporating geometric and traffic factors, and potential applications (*Paper III & V*). The study developed theoretical model formulation, estimation using empirical passing maneuver data, and applications to highway planning and design.

2. Development of risk appraisal methodology of the passing process based on the time-to-collision at the end of the passing maneuver, effective accepted gap in the opposite direction and the passing duration (*Paper IV*). Three risk levels were proposed to evaluate safety of two-lane highways with applications to highway planning and design.

3. The combined results of models estimated in III, IV and V provide a complete description of operation of passing zones illustrated in Fig. 4-1. The passing rate decreases at high directional traffic volumes because the risk of passing maneuvers ending with TTC less than 3.0 seconds is high. Completion of passing maneuvers becomes increasingly difficult due to reduction in size and proportion of safe gaps in the opposite direction. As the passing rate decreases, the rate at which passing maneuvers end in a no-passing zone increases due to delays to initiate passing maneuvers as sufficient gaps appear later inside the passing zone.

4. A procedure to collect passing maneuver data using ordinary tripod-mounted camcorders as opposed to use of more expensive and inaccessible methods to researchers in developing countries such as the tower-mounted cameras, instrumented vehicles and driving simulators is proposed.

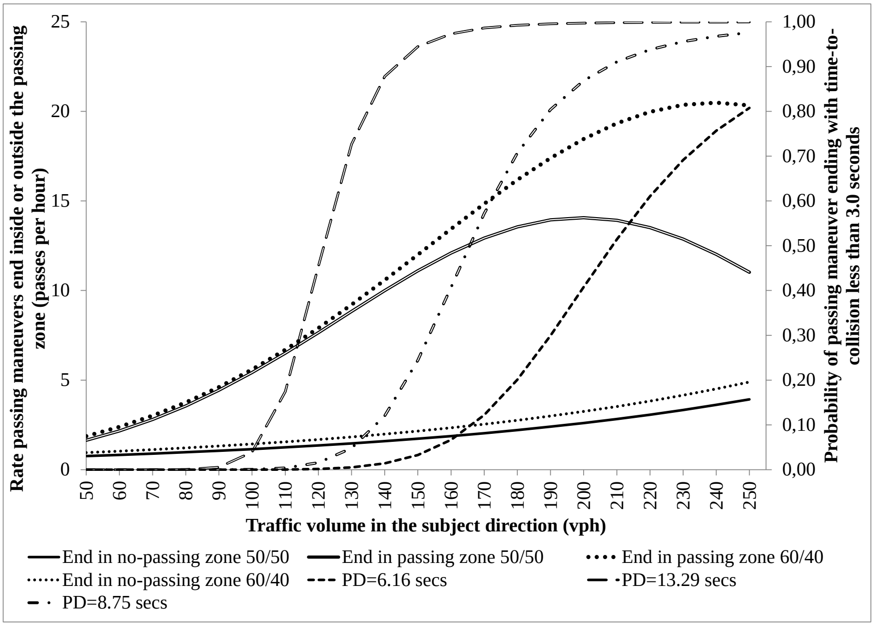


Fig. 4-1: Rate of passing maneuvers that end inside or outside the passing zone and the probability of ending with time-to-collision less than 3.0 seconds as a function of traffic volume in the subject direction

5.2 Contributions to Practice

The thesis contributes to the understanding of how the operations of passing zones can influence design decisions to achieve operational efficiency and safety. For instance, results showed that passing zones 1.30-2.50 km long were good for both operational efficiency and safety. Safety of passing zones 0.50-1.30 km long could be enhanced with additional signage to indicate the extent maneuvers can be initiated so as not to end in a no-passing zone. Passing zones less than 0.50 km should include means to compel drivers to commence passing maneuvers close to the beginning of the passing zone for safety. These passing zones should be avoided during design for this type of highway for safety reasons.

This thesis also contributes to improved design of passing zones for increased operational efficiency and safety. The effect of design factors such as the length of the passing zone, absolute vertical grade, percent of heavy vehicles on the passing rate was determined which could be optimized during design to enhance operational efficiency and safety. Specific contributions to improvement of design and marking of passing zones on two-lane highways in Uganda include:

1. The passing sight distance used in design of highways with design speeds of 110 km/h should be harmonized with the marking thresholds for passing zones.

2. Highways whose traffic consists predominantly of small cars (passenger cars) and short trucks (2-3 axles and length less than 10 meters) should be designed and marked using a minimum threshold of 500 meters. Examples include National Roads off the main export-import routes.

3. Highways with traffic consisting of a high proportion of long trucks (4-7 axles and length between 10 and 23 meters) should be designed and marked using a minimum threshold of 600 meters. Examples include National Roads along the main export-import routes.

4. Installation of additional signs and/or markings inside the passing zone to guide the driver on when a maneuver has high chances of ending in a no-passing zone, where sight distance is limited. The recommended positions where these signs should be installed as illustrated in Fig. 4-2.

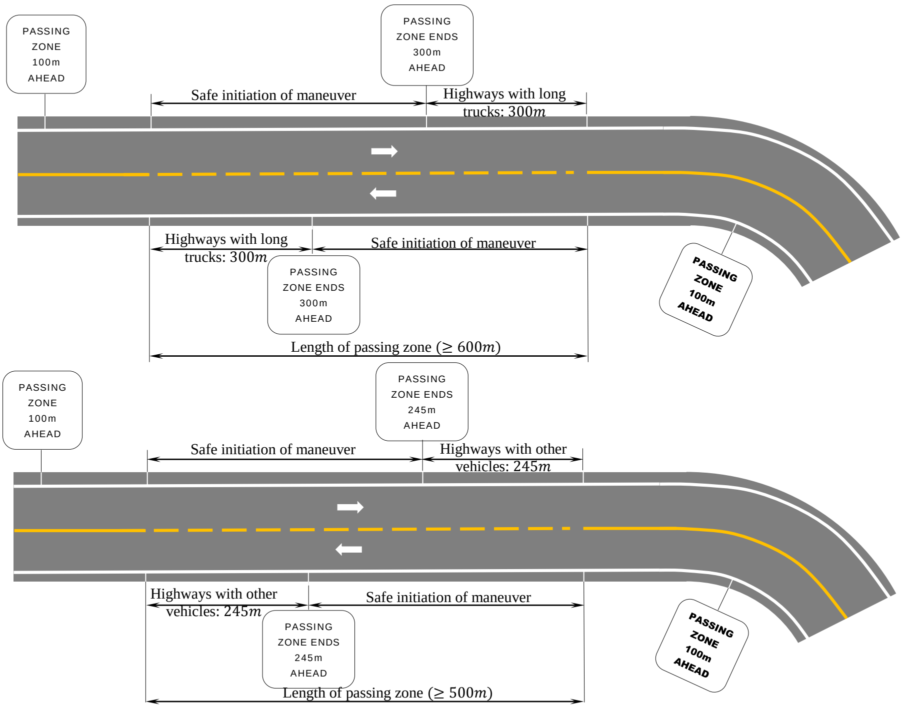


Fig. 4-2: Recommended additional signage in the passing zone

5.3 Future Research Directions

The thesis provides a comprehensive analysis of how design and operational characteristics of passing zones affect the operational efficiency and safety. The study developed models to predict the rates at which passing maneuvers end inside the passing and in the no-passing zone, and risk appraisal based on the probability of completing passing maneuvers with time-to-collision less than 3.0 seconds. A logistic regression model was also estimated to predict the probability that a delayed passing maneuver ends in a no-passing zone. The models were estimated using empirical data collected at 19 passing zones on two-lane rural highways in Uganda. The directional traffic volume used in the study was 44-254 vph.

This study could be extended to validate the methodology and the results using data collected in different driving environments and traffic conditions than in Uganda. Secondly, it would be interesting to compare passing maneuvers ending in the no-passing zone with road traffic crashes that occur downstream the passing zone. This would provide further insights into the safety impacts of delayed passing maneuvers on two-lane highways. It was not possible in the current study to compare traffic crash data with the observed rates of passing maneuvers ending in the no-passing zone due to lack of quality road traffic crash data in Uganda.

Further research could also determine the impact of variables such as lane and shoulder width, pavement frictional resistance, and absolute vertical grades (>4%) on the passing behavior and the operation of passing zones. For instance, it would be interesting to determine passing behavior and operational characteristics of passing zones located in rolling and mountainous terrain. This type of analysis requires data from sites with enough variability in their geometric characteristics, which was not available in the data used in this study.

Passing rates in this study relate to individual passing zones. It was not possible to determine the optimal spacing between passing zones because the length of upstream no-passing zone was not statistically significant in the passing rate model. Therefore, the impact of two adjacent passing zones on the passing rates is another interesting future research direction. The results can be used to determine the optimal spacing between passing zones with applications to highway design.

Lastly, the study could be extended to determine the impact of driver behavior and vehicle factors on the passing rate and passing behavior in Uganda at the microscopic level. Detailed field data collection could determine the vehicle and driver factors of passing vehicles. Empirical data and models developed could be applied as inputs to micro simulations of two-lane highways.

BIBLIOGRAPHY

Aarts, L., & Schagen, I. V. (2006). Driving speed and the risk of road crashes: a review. *Accident; Analysis and Prevention*, *38*(2), 215–224.

Agent, K. R., Pigman, J. G., & Stamatiadis, N. (2001). *Countermeasures for fatal crashes on two-lane rural roads*. Lexington, Kentucky.

Al-Kaisy, A., & Karjala, S. (2010). Car-following interaction and the definition of free-moving vehicles on two-lane rural highways. *Journal of Transportation Engineering: American Society of Civil Engineers, 136*(10), 925.

American Association of State Highway and Transportation Officials. (2001). *A policy on geometric design of highways and streets* (4th Ed.). Washington DC.

American Association of State Highway and Transportation Officials. (2010). Chapter 10-Rural Two-Lane Roads. In *Highway Safety Manual* (1st ed., p. 75). Washington, DC: American Association of State Highways and Transportation Officials.

American Association of State Highway and Transportation Officials. (2011). Elements of Design. In *A policy on geometric design of highways and streets* (6th ed., p. 183). Washington, DC.

Anderson, I. B., & Krammes, R. A. (2000). Speed reduction as a surrogate for accident experience at horizontal curves on rural two-lane highways. *Transportation Research Record: Journal of Transportation Research Board, Washington DC*, *1701*, 86–94.

Bar-Gera, H., & Shinar, D. (2005). The tendency of drivers to pass other vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour*, *8*(6), 429–439.

Benekohal, R. F., & Hashmi, A. M. (1992). Procedures for Estimating Accident Reductions on Two-Lane Highways. *Journal of Transportation Engineering*, *118*(1), 111–129. doi:10.1061/(ASCE)0733-947X(1992)118:1(111)

Bergh, T., Carlsson, A., & Larsson, M. (2003). Swedish vision zero experience. *International Journal of Crashworthiness*, *8*(2), 159–167.

Bonneson, J., & Ivan, J. N. (2013). *Theory, Explanation and Prediction in Road Safety: Promising Directions* (No. Transportation Research Circular E-C179). Washington, DC.

Campbell, R. E., & King, L. E. (1970). The traffic conflicts technique applied to rural intersections. *Accident Analysis & Prevention, Pergamon Press, 2*, 209–221.

Carlson, P., Miles, J., & Johnson, P. (2006). Daytime high-speed passing maneuvers observed on rural two-lane, two-way highway: Findings and implications. *Transportation Research Record: Transportation Research Board, Washington DC*, *1961*, 9–15.

Charmant, J. (2011). Kinovea Version 0.8.15. www.kinovia.org, Accessed September 10th, 2012.

Clarke, D. D., Ward, P. J., & Jones, J. (1998). Overtaking road-accidents: differences in manoeuvre as a function of driver age. *Accident Analysis & Prevention, Pergamon Press*, *30*(4), 455–67.

Cohen, M. A., & Polus, A. (2011). Estimating percent-time-spent-following on two-lane rural highways. *Transportation Research Part C: Emerging Technologies*, *19*(6), 1319–1325. doi:10.1016/j.trc.2011.03.001

Collins, J. M., & Krammes, R. A. (1996). Preliminary validation of a speed profile model for design consistency evaluation. *Transportation Research Record: Transportation Research Board, Washington DC*, *1523*.

Cruzado, I., & Donnell, E. T. (2010). Factors Affecting Driver Speed Choice along Two-Lane Rural Highway Transition Zones. *Journal of Transportation Engineering, American Society of Civil Engineers*, *136*(8), 755.

Diamond Traffic Products. (2006). Apollo counter/classifier: Field unit instruction manual. *Portable Classifiers*. Retrieved from www.diamondtraffic.com

El Khoury, J., & Hobeika, A. G. (2007). Assessing the Risk in the Design of Passing Sight Distances. *Journal of Transportation Engineering, American Society of Civil Engineers*, *133*(6), 370.

El Khoury, J., & Hobeika, A. G. (2012). Integrated Stochastic Approach for Risk and Service Estimation: Passing Sight Distance Application. *Journal of Transportation Engineering*, *138*(5), 571–579.

Elvik, R., Hoye, A., Vaa, T., & Sorensen, M. (2009). *The Handbook of Road Safety Measures* (2nd ed.). Bingley: Emerald Group Publishing Ltd.

Fahlquist, J. N. (2006). Responsibility ascriptions and Vision Zero. *Accident Analysis and Prevention*, *38*(6), 1113–1118. doi:10.1016/j.aap.2006.04.020

Farah, H. (2013). Modeling drivers ' passing duration and distance in a virtual environment. *IATSS Research*, *37*, 61–67.

Farah, H., Bekhor, S., & Polus, A. (2009). Risk evaluation by modeling of passing behavior on two-lane rural highways. *Accident; Analysis and Prevention*, *41*(4), 887–94.

Farah, H., Bekhor, S., Polus, A., & Toledo, T. (2009). A passing gap acceptance model for two-lane rural highways. *Transportmetrica*, *5*(3), 159–172.

Farah, H., & Toledo, T. (2010). Passing behavior on two-lane highways. *Transportation Research Part F: Traffic Psychology and Behaviour*, *13*(6), 355–364.

Farah, H., Yechiam, E., Bekhor, S., Toledo, T., & Polus, A. (2008). Association of risk proneness in overtaking maneuvers with impaired decision making.

Transportation Research Part F: Traffic Psychology and Behaviour, *11*(5), 313–323.

Federal Highway Administration. (1999). Evaluation of design consistency methods for two-lane rural highways, executive summary. *US Department of Transportation, FHWA-RD-99-174*, 4.

Federal Highway Administration. (2009). *Manual on Uniform Traffic Control Devices for Streets and Highways* (2009th ed.). Washington, DC: US Department of Transportation.

Fitzpatrick, K., Elefteriadou, L., Harwood, D. W., Collins, J. M., McFadden, J., Anderson, I. B., … Passetti, K. (2000). *Speed prediction for two-lane rural highways*. Virginia: US Dept. of Transportation, Federal Highway Administration. doi:FHWA-RD-99-171

Gerlough, D. L., & Huber, M. J. (1975). *Traffic flow theory: a monograph*. Washington, DC: Transportation Research Board, National Research Council.

Gibreel, G. M., Easa, S. M., & El-Dimeery, I. A. (2001). Prediction of operating speed on three-dimensional highway alignments. *Journal of Transportation Engineering: American Society of Civil Engineers*, *127*(1), 21–30.

Gårder, P. (2006). Segment characteristics and severity of head-on crashes on two-lane rural highways in Maine. *Accident; Analysis and Prevention*, *38*(4), 652–61.

Hanley, P., & Forkenbrock, D. (2005). Safety of passing longer combination vehicles on two-lane highways. *Transportation Research Part A: Policy and Practice*, *39*(1), 1–15.

Harwood, D. W., Gilmore, K. D., Richard, R. K., Dunn, M. J., & Sun, C. (2008). *Passing sight distance criteria*. *Traffic Safety*. Washington, DC. doi:NCHRP Report 605

Hassan, Y. (2004). Highway design consistency: Refining the state of knowledge and practice. *Transportation Research Record: Journal of Transportation Research Board, Washington DC*, *1881*, 63–71.

Hassan, Y., Gibreel, G. M., & Easa, S. M. (2000). Evaluation of highway consistency and safety: Practical application. *Journal of Transportation Engineering, American Society of Civil Engineers*, *126*(3), 193–201.

Hauer, E. (1971). Accidents, overtaking and speed control. *Accident Analysis & Prevention, Pergamon Press*, *3*(1), 1–13.

Hauer, E. (1982). Traffic conflicts and exposure. *Accident Analysis & Prevention, Pergamon Press*, *14*(5), 359–364.

Hauer, E. (2001). Overdispersion in modelling accidents on road sections and in empirical bayes estimation. *Accident; Analysis and Prevention*, *33*(6), 799–808.

Hegeman, G. (2004). Overtaking prohibition safety effects on two lane roads. *17th ICTCT Workshop*, 1–12.

Hegeman, G. (2008). *Assisted overtaking: an assessment of overtaking on two-lane rural roads*. TRAIL Research School, Delfti University of Technology.

Hegeman, G., Brookhuis, K., & Hoogendoorn, S. P. (2005). Opportunities of advanced driver assistance systems towards overtaking. *European Journal of Transport and Infrastructure Research*, *5*(4), 281–296.

Hirst, W. M., Mountain, L. J., & Maher, M. J. (2004). Sources of error in road safety scheme evaluation: a method to deal with outdated accident prediction models. *Accident Analysis and Prevention*, *36*, 717–727.

Hyden, C. (1987). *The Development of a method for traffic safety evaluation: The Swedish traffic conflicts technique*. Lund.

Islam, M. N., & Seneviratne, P. N. (1994). Evaluation of design consistency of two-lane highways. *Institute of Transportation Engineers*, *64*(2), 28–31.

Jenkins, J. M., & Rilett, L. R. (2004). Application of distributed traffic simulation for passing behavior study. *Transportation Research Record: Transportation Research Board, Washington DC*, *1899*, 11–18. doi:10.3141/1899-02

Jenkins, J. M., & Rilett, L. R. (2005). Classifying passing maneuvers: A behavioral approach. *Transportation Research Record: Journal of the Transportation Research Board*, *1937*, 14–21.

Jurewicz, C., Aumann, P., Bradshaw, C., Beesley, R., & Callaghan, N. O. (2015). *Road Geometry Study for Improved Rural Safety*. Sydney, Australia: Austroads Ltd.

Kanellaidis, G. (1999). Aspects of road safety audits. *Journal of Transportation Engineering, American Society of Civil Engineers*, *125*(6), 481–486.

Kanellaidis, G., Golias, J., & Efstathiadis, S. (1990). Drivers' speed behaviour on rural road curves. *Traffic Engineering and Control, London*, *31*(7/8), 414–415.

Krammes, R. A. (2000). Design speed and operating speed in rural highway alignment design. *Transportation Research Record: Transportation Research Board, Washington DC, 1701*, 68–75.

Krammes, R. A., Rao, K. S., & Hoon, O. H. (1995). Highway geometric design consistency evaluation software. *Transportation Research Record: Transportation Research Board, Washington DC, 1500*, 19–24.

Labi, S. (2006). *Effects of Geometric Characteristics of Rural Two- Lane Roads on Safety*. Lafayette, Indiana: Joint Transportation Research Program, Indian Department of Transportation and Purdue University.

Labi, S. (2011). Efficacies of roadway safety improvements across functional subclasses of rural two-lane highways. *Journal of Safety Research*, *42*(4), 231–9.

Lamm, R., Choueiri, E. M., Hayward, J. C., & Paluri, A. (1988). Possible design procedure to promote design consistency in highway geometric design on two lane rural roads. *Transportation Research Record, Transportation Research Board, Washington DC, 1195*.

Lamm, R., Choueiri, E. M., & Mailaender, T. (1990). Comparison of operating speed on dry and wet pavement of two lane rural highways. *Transportation Research Record: Transportation Research Board, Washington, DC, 1280*, 199–207.

Laureshyn, A., Svensson, Å., & Hydén, C. (2010). Evaluation of traffic safety, based on micro-level behavioural data: Theoretical framework and first implementation. *Accident Analysis and Prevention*, *42*(6), 1637–1646. doi:10.1016/j.aap.2010.03.021

Lin, F.-B. (1990). Flattening of horizontal curves on rural two-lane highways. *Journal of Transportation Engineering: American Society of Civil Engineers*, *116*(2), 181–196.

Llorca, C., & Garcia, A. (2011). Evaluation of passing process on two-lane rural highways in Spain using a new methodology based on video data. *Transportation Research Board: 2011 TRB Annual Meeting*.

Llorca, C., García, A., Perez, A. M., & Moreno, A. T. (2012). New experimental Approach for passing gap acceptance. In *Transportation Research Board 2012 Annual meeting* (p. 14). Washington, DC: Transportation Research Board, Washington DC.

Llorca, C., Moreno, A. T., Sayed, T., & García, A. (2014). Sight Distance Standards Based on Observational Data Risk Evaluation of Passing. *Transportation Research Record: Journal of the Transportation Research Board*, *2404*, 18–26.

Lord, D., Washington, S. P., & Ivan, J. N. (2005). Poisson, Poisson-gamma and zero-inflated regression models of motor vehicle crashes: balancing statistical fit and theory. *Accident; Analysis and Prevention*, *37*(1), 35–46.

Luttinen, R. T. (2001). Percent Time-Spent-Following as Performance Measure for Two-Lane Highways. *Transportation Research Record: Journal of the Transportation Research Board*, *1776*, 52–59. doi:10.3141/1776-07

Marchionna, A., Perco, P., & Falconetti, N. (2011). Application of design consistency evaluation tools for two-lane rural roads: A case study from Italy. *Transportatation Research Board: 2011 TRB Annual Meeting*, 1–19.

Mattar-Habib, C., Polus, A., & Farah, H. (2008). Further evaluation of the relationship between enhanced consistency model and safety of two lane rural roads in Israel and Germany. *European Journal of Transport and Infrastructure Research*, *8*(4), 320–332.

McLean, J., Veith, G., & Turner, B. (2010). *Road safety engineering risk assessment: Relationships between crash risk and the standards of geometric design elements*.

Miaou, S. P. (1994). The relationship between truck accidents and geometric design of road sections: Poisson versus negative binomial regressions. *Accident; Analysis and Prevention*, *26*(4), 471–82.

Miaou, S. P., & Lum, H. (1993). Modeling vehicle accidents and highway geometric design relationships. *Accident; Analysis and Prevention*, *25*(6), 689–709.

Minderhoud, M. M., & Bovy, P. H. (2001). Extended time-to-collision measures for road traffic safety assessment. *Accident; Analysis and Prevention*, *33*(1), 89–97.

Ministry of Finance Planning and Economic Development. (1998). *Statistical abstract*. Entebbe: Republic of Uganda.

Ministry of Works and Transport. (2010). Geometric Design Manual, Vol.1. In *Road Design Manual* (Vol. 1, p. 70). Entebbe, Uganda.

Ministry of Works Housing and Communications. (2004a). *Road safety audit manual*. *Ministry of Works, Housing and Communications; Republic of Uganda*. Entebbe: Republic of Uganda.

Ministry of Works Housing and Communications. (2004b). *The highway code*. Entebbe, Uganda: Uganda Printing and Publishing Corporation.

Ministry of Works Housing and Communications. (2004c). *Traffic Signs Manual*. Entebbe, Uganda: The Republic of Uganda.

Mitra, S., & Washington, S. (2007). On the nature of over-dispersion in motor vehicle crash prediction models. *Accident; Analysis and Prevention*, *39*(3), 459–68.

Montella, A. (2005). Safety Reviews of Existing Roads: Quantitative Safety Assessment Methodology. *Transportation Research Record, Journal of Transportation Research Board*, (1922), 62–72.

Moreno, A. T., Llorca, C., García, A., & Pérez-Zuriaga, A.-M. (2013). Operational Effectiveness of Passing Zones Depending on Length and Traffic Volume. *Transportation Research Record: Journal of the Transportation Research Board*, *2395*, 57–65.

Mwesige, G., Tindiwensi, D., & Bagampadde, U. (2011). Identifying and fixing high crash locations in the road network in Uganda. In *Proceedings of the 2nd International Conference on Advances in Engineering and Technology* (pp. 478–484). Entebbe, Uganda.

Persaud, B. N., Retting, R. a., & Lyon, C. a. (2004). Crash reduction following installation of centerline rumble strips on rural two-lane roads. *Accident Analysis and Prevention*, *36*(6), 1073–1079.

Polus, A., & Cohen, M. A. (2009). Theoretical and Empirical Relationships for the Quality of Flow and for a New Level of Service on Two-Lane Highways. *Journal of Transportation Engineering, American Society of Civil Engineers*, *135*(6), 380–385.

Polus, A., Livneh, M., & Frischer, B. (2000). Evaluation of the passing process on two-lane rural highways. *Transportation Research Record: Journal of Transportation Research Board, Washington DC*, *1701*, 53–60.

R Core Team. (2014). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.r-project.org/

Rozenshtein, S., Polus, A., & Cohen, M. A. (2013). Models for Estimation of Drivers ' Impatience on Two-Lane Rural Highways. In *Transportatation Research Board: 2013 TRB Annual Meeting* (p. 15). Washington, DC: Transportation Research Board, Washington DC.

Shariat-Mohaymany, A., Tavakoli-Kashani, A., Nosrati, H., & Ranjbari, A. (2011). Identifying significant predictors of head-on conflicts on two-lane rural roads using inductive loop detectors data. *Traffic Injury Prevention*, *12*(6), 636–41.

Songchitruksa, P., & Tarko, A. P. (2006). The extreme value theory approach to safety estimation. *Accident Analysis and Prevention*, *38*, 811–822. doi:10.1016/j.aap.2006.02.003

Spring, G. S. (2005). Road Safety: Discussion of State of Practice. *Journal of Transportation Engineering, American Society of Civil Engineers*, *131*(5), 329.

Srinivasan, R., Baek, J., & Council, F. (2010). Safety Evaluation of Transverse Rumble Strips on Approaches to Stop Controlled Intersections in Rural Areas. *Transportation Research Board: 2010 TRB Annual Meeting*.

Tarko, A., Davis, G., Saunier, N., Sayed, T., & Washington, S. (2009). *Surrogate Measures of Safety (White Paper)*. *ANB20(3) TRB Subcommitee on Surrogate Measures of Safety* (Vol. 20). Washington, DC.

Toledo, T., & Farah, H. (2011). Alternative Definitions of Passing Critical Gaps. *Transportation Research Record: Journal of the Transportation Research Board*, *2260*, 76–82.

Transportation Research Board. (2000). Highway Capacity Manual. Washington, DC.

Transportation Research Board. (2003). *Application of European 2+1 Roadway Designs: Research Results Digest* (No. 275). Washington,DC.

Transportation Research Board. (2010). Chapter 15: Two-Lane Highways. In *Highway Capacity Manual* (p. 76). Washington, DC.

Turner, S., & Tate, F. (2009). *Relationship between road geometry , observed travel speed and rural accidents*. *Transport*. Wellington. doi:1173-3764

Tziotis, M., Styles, T., & Turner, B. (2010). *Road Safety Engineering Risk Assessment Part 8: Rural Head-on Crashes*. Sydney, Australia.

Uganda Bureau of Statistics. (2002). *Statistical abstract*. Kampala: Republic of Uganda.

Uganda Bureau of Statistics. (2006). *Statistical abstract*. Kampala: Republic of Uganda.

Uganda Bureau of Statistics. (2008). *Statistical Abstract*. Kampala: Republic of Uganda.

Uganda Bureau of Statistics. (2010). *Statistical abstract*. Kampala: Republic of Uganda.

Uganda Bureau of Statistics. (2014). *Statistical abstract*. Kampala: Republic of Uganda.

Uganda National Roads Authority. (2015). The Roads Magazine, (35), 64.

Van As, S., & Van Niekerk, A. (2004). The operational analysis of two-lane rural highways. In *23rd Annual Southern African Transport Conference, South Africa* (pp. 12–15). Pretoria: SATC.

Venables, W. N., & Ripley, B. D. (2002). *Modern Applied Statistics with S* (4th Edn.). New York: Springer.

Vlahogianni, E. I. (2013). Modeling duration of overtaking in two lane highways. *Transportation Research Part F: Traffic Psychology and Behaviour*, *20*, 135–146.

Vlahogianni, E. I., & Golias, J. C. (2012). Bayesian modeling of the microscopic traffic characteristics of overtaking in two-lane highways. *Transportation Research Part F: Traffic Psychology and Behaviour*, *15*(3), 348–357.

Williams, M. (1981). Validity of the traffic conflicts technique. *Accident Analysis & Prevention*, *13*(2), 133–145.

World Health Organization. (2011). *Global Plan for the Decade of Action for Road Safety 2011-2020*.

Zuriaga, A. M. P., García, A., & Torregrosa, F. J. C. (2011). Study of tangent-to-curve transition on two-lane rural roads with continuous speed profiles. *Transportation Research Board: 2011 TRB Annual Meeting*, 1–16.