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Effect of passing zone length on operation and safety of two-lane rural highways in Uganda

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ABSTRACT

This paper presents a methodology to assess 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 of passing maneuvers ending in a no-passing zone. The methodology was applied using observed passing maneuver data collected with tripod-mounted camcorders at passing zones in Uganda. Findings show that the rate at which passing maneuvers end in a no-passing zone increases with traffic volume and unequal distribution of traffic in the two directions, absolute vertical grade, and percent of heavy vehicles in the subject direction. Additionally, 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 m for passenger cars or short trucks (2–3 axles), and 300 m for long trucks (4–7 axles) as the passed vehicles. These results suggest policy changes in design and marking of passing zones to enhance safety and operation of two-lane rural highways.

1. Introduction

Passing zones on two-lane rural highways provide sight distances for fast vehicles to pass slow vehicles using the opposite traffic lane. This helps to reduced travel delay and queuing of fast vehicles behind slow vehicles according to the Highway Capacity Manual 2010 [HCM 2010] [1]. Despite the apparent operational benefits, there is still limited knowledge on the quantitative effect of the length of passing zones on the operation and safety of these highways. Specifically, the extent passing maneuvers can be delayed from the beginning in order to end inside the passing zone for safety reasons is still unknown. Besides, the sight distance to complete the passing maneuver inside the passing zone decreases with increase in the delay to initiate the maneuver from the beginning of the passing zone.

The delay to initiate passing maneuvers increase the chances of the maneuvers ending in the no-passing zone, where visibility is limited to evade a potential collision with the opposite vehicle [2]. Judgement of the remaining sight distance to complete passing maneuvers inside the passing zone by design rests with the driver of the passing vehicle [3–6]. A previous study observed that drivers are unable to judge accurately the sight distance and speed of the opposite vehicles, which increases the likelihood of passing maneuvers ending in the no-passing zone [7].

The adequacy of the length of passing zones is often assessed considering the sight distance required to complete individual passing maneuvers [5,8–11]. Comparison is often made between the design passing sight distances [PSD] thresholds following '*A policy on geometric design of highways and streets[AASHTO 2001]*' [3], and the marking PSD thresholds by the Federal Highway Administration *[MUTCD 2009]* [12]. These design and marking PSD thresholds were also adopted for design and marking of two-lane highways in Uganda [6,13]. The design PSD threshold is based on a four component kinematic model consisting of distances covered during the perception-reaction and initial maneuver, occupation of the opposite lane, clearance at the end of the maneuver up to meeting the opposite vehicle [3]. Conversely, marking PSD thresholds are based on the 85th percentile speed of all vehicles using the highway under off-peak traffic conditions [12,14].

In practice, the marking PSD thresholds are nearly half of those used in design. Harwood et al. [5] argued that the design PSD thresholds are conservative, and lead to reduced passing opportunities unless the

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highway is re-aligned to create longer passing sight distances. The authors further argued that this may not be cost effective without additional justification of accrued operational and safety benefits. These arguments formed the basis for harmonizing the design and marking PSD thresholds in '*A policy on geometric design of highways and streets [AASHTO 2011]*' [4], implicitly assuming most drivers commence passing maneuvers at the beginning of the passing zone.

However, operating traffic conditions could force passing maneuvers to commence away from the beginning of the passing zone shortening the remaining sight distance to complete passing maneuvers inside the passing zone. This could result from presence of opposite vehicles close to the beginning of the passing zone, or high-speed catch-ups between the passing and passed vehicles [15]. The delay to initiate a passing maneuver contributes to a risk of crash between the passing and opposite vehicles in two ways. First, the delay reduces the remaining sight distance to complete the maneuver inside the zone where it is easier for the passing and opposite vehicles to evade a potential collision. Secondly, it increases the chances of initiating a passing maneuver with the opposite vehicle not in sight. The driver of the passing vehicle is thus unable to gauge the gap in the opposite direction at the time of initiating a passing maneuver.

Passing maneuvers ending in the no-passing zone have been reported at both short (92% for passing zone lengths shorter than 240 m), and long (21% for passing zone lengths 300 m or more) passing zones [5]. Furthermore, a study conducted in Australia (60%) and New Zealand (72%) using traffic crash data from 1999 to 2003 reported high occurrence of passing related head-on collisions in horizontal curves [16]. Therefore, it is essential to study the effect of the length of the passing zone on the chances and rate passing maneuvers end in no-passing zones. This could yield policy measures to enhance design and marking of passing zones for operational efficiency and safety.

The aim of this study is therefore 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 the no-passing zone. In order to achieve this aim, models for estimating the probability and the rate at which passing maneuvers end in no-passing zones are formulated and presented in Section 2. The methods, tools, and data processing are also discussed in Section 3. Section 4 presents results of model estimation and sensitivity analyses. Section 5 discusses the results in comparison with previous studies and practice. Section 6 concludes the paper, and discusses future research directions.

2. Model formulation

This section describes theoretical concepts for the development of models to predict the probability and the rate of passing maneuvers ending in no-passing zones on two-lane rural highways.

2.1. Model formulation of the probability of passing maneuvers to end in no-passing zones

Passing maneuvers that end inside passing zones are safer by design because the sight distances are sufficient for the passing and opposite vehicles to avert potential collisions. The length of a passing zone, the extent of delay to initiate the passing maneuver, and traffic related factors influence the chances of individual passing maneuvers ending inside passing zones or outside passing zones (in the no-passing zone) as illustrated in Fig. 1.

Long passing zones provide adequate sight distances to complete passing maneuvers inside the zone [3,4]. The underlying assumption is that individual passing maneuvers commence close to the beginning of the passing zone. However, quite often passing maneuvers commence away from the beginning of the passing zone due to presence of opposite vehicles or as a result of high-speed catch-ups [15]. Thus, for a given length of a passing zone, the longer the distance up to the initiation of a passing maneuver, the higher the probability of the passing vehicle completing the passing maneuver in the no-passing zone.

The distance up to the initiation of the passing maneuver indirectly depends on the speed of the passing vehicle measured at the beginning of the passing zone, and the time up to the point of initiating a maneuver. Previous design PSD thresholds in AASHTO 2001 [3] also adopted in Uganda [6] explicitly incorporated a distance component for perception-reaction and initial maneuver to account for delays to initiate passing maneuvers. However, this component was removed in AASHTO 2011 [4] leading to short design PSD thresholds. Moreover, marking of passing zones follow even shorter PSD thresholds than those used in design [13], which increases the chance of delayed passing maneuvers ending in a no-passing zone.

The speeds of passing and passed vehicles at the beginning of the passing zone affect the position of initiation of the maneuver inside the passing zone. Additionally, the speed of the passed vehicle has been shown to influence the time it takes to complete the maneuver, also known as the passing duration [17,18]. The passing duration has also been found to depend on other traffic factors; the type of passed

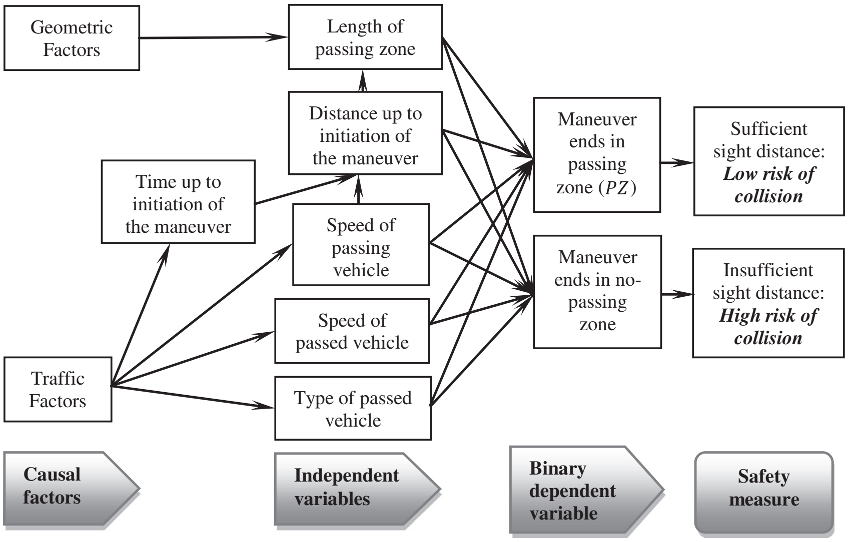

Fig. 1. Theoretical framework of underlying theoretical causal relationships.

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vehicle [8,10,17], and the number of passed vehicles [17]. Observed data of passing maneuvers from previous studies reported that the majority of passing maneuvers involve one passed vehicle [5,19]. Thus, passing maneuvers involving one passed vehicle were considered in this study for practical reasons.

The association between independent and binary dependent variables is modelled by applying logistic regression [20]. The binary dependent variable (Y), illustrated in Fig. 1 is defined as follows:

$$Y = \begin{cases} 1, & \text{Passing maneuver ends in NPZ} \\ 0, & \text{Passing maneuver ends in PZ} \end{cases} \tag{1}$$

The probability of an individual maneuver ending outside the passing zone conditional on a vector of independent variables X, $P(Y=1|X_i)$ is given by:

$$P(Y=1|X_i) = \pi = \frac{\exp(\beta_o + \beta_i X_i)}{1 + \exp(\beta_o + \beta_i X_i)}. \tag{2}$$

Where: β_0 is the intercept; β_i the vector of parameters; and X_i the vector of explanatory variables derived from causal factors.

Parameters of the logit model in Eq. (2) are estimated for a vector of explanatory variables using maximum likelihood techniques [20]. Using Eq. (2) as estimated from observed data, it is possible to carry out sensitivity analysis of the model and assess the effect of passing zone lengths on the probability of individual passing maneuvers ending in the no-passing zone.

2.2. Model formulation for the rate of passing maneuvers ending in no-passing zones

The probability prediction model described in the preceding section is useful to estimate deficiencies of individual passing zones. However, from a decision-making perspective, the frequency of occurrence of passing maneuvers ending in the no-passing zone is necessary to justify policy changes in design or marking of passing zones. In this section, a model is proposed to predict the rate of passing maneuvers ending in the no-passing zone using geometric and aggregate traffic factors.

The model predicts aggregate maneuver counts per hour at passing zones as a function of independent variables derived from general road geometric and traffic factors. The modeling approach is based on the Negative Binomial regression [21–23]. The Negative Binomial regression is preferred over Poisson due to its ability to explain overdispersion in the data [24,25]. The rate of passing maneuvers ending in no-passing zones is thus defined as follows:

$$PV_i = \exp(\beta_i X_i + \varepsilon_i). \tag{3}$$

Where; PV_i is the rate of passing maneuvers ending outside the passing zone (passes per hour); β_i the vector of model parameters; X_i the vector of independent variables derived from causal factors; and ε_i a gamma-distributed random error term.

Model parameters in Eq. (3) are estimated using the maximum likelihood estimation [26], and implemented in statistical software with GLM applications. The mean and variance functions for a vector of explanatory variables are as follows:

$$E[PV_i|X_i] = \lambda_i \tag{4}$$

$$Var[PV_i|X_i] = \lambda_i + \varphi^{-1}\lambda_i^2. \tag{5}$$

Where; φ is the dispersion parameter; and λ is the mean rate of maneuver counts ending in the no-passing zone.

A number of explanatory variables can be used in the model specification: traffic volume in two directions, directional split, length of passing zone, percent absolute vertical grade, and percent heavy vehicles. The traffic flow rate in two directions and the directional split was previously used to model the frequency of maneuvers ending inside the passing zone [27,28]. Traffic volume in two directions has a combined effect on the rate of maneuvers to end in no-passing zones. Traffic volume in the subject direction increases the passing demand, and the likelihood of vehicles desiring to pass at passing zones. Conversely, high opposite traffic volume inside passing zones increases the delay of passing maneuver initiation and the chances of the passing vehicle ending the maneuver outside the passing zone. The *a*-priori expectation is that the rate increases with both the volume and uneven distribution of traffic volume in two travel directions.

The length of the passing zone from a theoretical point of view influences the rate at which passing maneuvers end in the no-passing zone. Short passing zones confine maneuvers to commence close to the beginning of the passing zone with a deviation from this expectation increasing the rate. In contrast, long passing zones result in increased occurrence of delayed passing maneuvers and chances of ending in the no-passing zone in absence of warning signs on the limit of safe initiation of passing maneuvers. The a-priori expectation is for the rate to increase at a decreasing rate with the length of the passing zone. Sufficiently long passing zones lead to reduction of the effect of delayed maneuvers and therefore the rate of maneuvers ending in the no-passing zone.

The rate is also hypothesized to increase with the absolute vertical grade inside the passing zone. Increase in vertical grade leads to reduction of speeds especially of heavy vehicles and is the basis for building climbing lanes on two-lane rural highways [3,4]. Lastly, studies have shown that it takes longer to pass long trucks than passenger cars [8, 10]. The a-priori expectation is for the rate to increase at a decreasing rate with percent heavy vehicles. This is because of both the reduction of passing opportunities and possibilities to merge back at end of the maneuver.

3. Data collection and processing

Data used to estimate the two models was collected at passing zones on two-lane rural highways in Uganda [29]. The highway is part of the continental Northern Corridor serving the Great Lakes Region of East Africa from Kenya through Kampala Capital City in Uganda to Rwanda, Burundi, and the Democratic Republic of Congo. The passing zones were located on rural sections of the highway in a flat terrain in the East, Central, and Mid-western parts of Uganda. Passing maneuver data was collected using a series of camcorders mounted on tripods and positioned by the roadside at the beginning, midway, and at the end of the passing zone as illustrated in Fig. 2.

Several methods have been applied to study passing maneuvers on two-lane highways: helicopter hovering above the passing zone [9]; instrumented vehicle [19,30]; and mobile tower-mounted cameras [5,17]. These methods are quite expensive. This study explores the use of roadside video recording to collect passing maneuver data. Data obtained from camcorders positioned close to the beginning of the passing zone was used to determine the speeds of passing and passed vehicles, and the time up to the position of initiation of the passing maneuver. Data from camcorders positioned inside the passing zone was used to estimate other factors such as the speeds of passing and passed vehicles at abreast positions.

The length of passing zones, lane, and shoulder widths were measured in the field using a measuring wheel. The vertical grade was determined from as-built drawings obtained from the Uganda National Roads Authority. Other traffic variables such as the mean, 85th percentile, and standard deviation of free flow speeds of passenger cars were collected at the beginning of the passing zone using traffic classifiers for purposes of estimating the rate of passing maneuvers ending in no-passing zones. Data collection of observed passing maneuvers require video recording for a period of five hours from 13:00 to 18:00 h at each passing zone on clear dry days. All passing zones had vertical grades in the range of 0–4.2%, which is classified as flat terrain in

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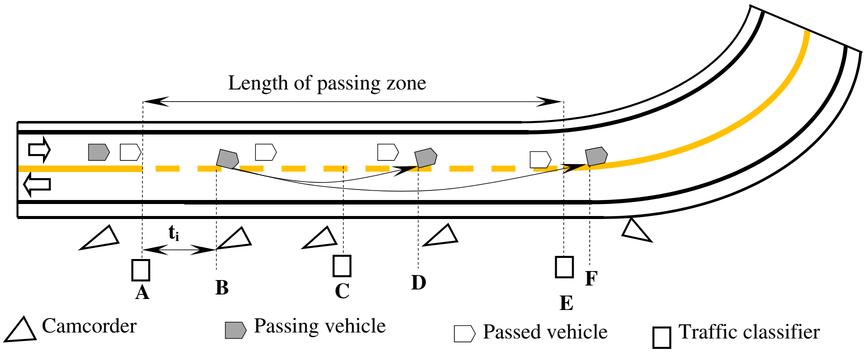

Notation
A: Beginning of the passing zone
B: Position of initiation of maneuver
C: Halfway the passing zone
D: Position of maneuver ending in the passing zone
E: End of the passing zone
F: Position of maneuver ending in the no-passing zone
t_i: Duration up to initiation of the maneuver
Note that driving in Uganda uses the left lane

Fig. 2. Field data collection layout and variable definition.

Uganda with design speed of 110 km/h [6]. The lane and shoulder widths were 3.50 and 2.00 m, respectively. The pavement surface at all passing zones was 50 mm asphalt concrete in good condition.

Video data was processed using the open source video analysis software Kinovea [31]. Time stamps of vehicle positions during the maneuver were manually recorded for all pre-determined reference positions. The type of vehicles involved in the maneuver, time stamps when the maneuver commenced or ended, and the number of passed vehicles was recorded. Additionally, the number of passing maneuvers ending outside passing zones were recorded and aggregated in one-hour intervals.

Lastly, speeds of the passing and passed vehicles at the beginning of the passing zone were computed based on the speed-trap principle [32]. Centerline strips three meters long and spacing between strips of nine meters were applied to compute spot speeds using Eq. (6). The length of strips and gaps was verified in the field during the data collection using a measuring wheel. To minimize measurement errors in reading travel times between reference points, a longer distance (24 m) comprising of two strips and two gaps was applied to compute spot speeds.

$$S_i = 3.6\left(\frac{d}{t_i}\right) \tag{6}$$

Where; S_i is the speed of the passing or passed vehicle at the beginning of the passing zone, (km/h); d the reference distance in the video (24 m); and t_i the time taken by the vehicle to travel the distance (d) from the video (seconds).

4. Results

This section presents the results of model estimation and sensitivity analyses. It comprises five sub-sections: (1) summary statistics; (2) model estimation for probabilities of maneuvers ending in the no-passing zone; (3) sensitivity analysis of the estimated probabilities model; (4) results of estimated rate model; and (5) sensitivity analysis of the estimated rate model.

4.1. Summary statistics

Processed data from 48 h of video in two travel directions yielded 266 passing maneuvers ending in no-passing zones from 19 passing zones ranging in length from 290 to 2985 m. Passing maneuvers ending in the no-passing zone constituted 2.27% by proportion of total traffic volume in the two travel directions, and 14.13% of all observed passing maneuvers. Fig. 3 shows the proportion of observed passing maneuvers (1006) by headway between the passing and passed vehicle at the beginning of the passing zone. Two headway thresholds were applied to categorize the passing maneuvers: 3.0 s applied by HCM 2010 to compute the percent-time-spent following [1]; and 6.0 s representing free flow conditions [33].

The figure shows that 52% of observed passing maneuvers had headway between passing and passed vehicles at the beginning of the passing zone of 3.0 s or less, and 48% of the passing maneuvers a headway more than 3.0 s. Specifically, the proportion of passing maneuvers that end in a no-passing zone more than double for headways more than 3.0 s. The proportion increases to 69% considering a 6.0 s-threshold, representing the limit of free flow conditions. These results show that passing maneuvers frequently commence farther downstream the passing zone than assumed in design with high chances of ending in the no-passing zone. Design and marking of passing zones should therefore take into consideration this delay to initiate passing maneuvers for safety reasons.

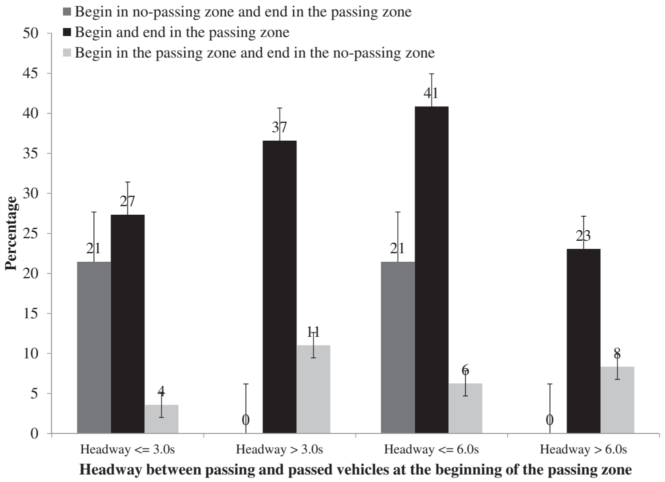

Fig. 3. Proportion of observed passing maneuvers by headway between passing and passed vehicles at the beginning of the passing zone.

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Table 1
Descriptive statistics of model variables.

Variable (unit of measure)	Minimum	Median	Mean	Maximum
Rate estimation variables				
Maneuvers ending in no-passing zone, PV (passes per hour)	0	2.00	2.77	14
Length of passing zone, LPZ (km)	0.29	0.73	0.93	2.99
Absolute vertical grade, AG (%)	0	1.77	1.65	4.2
Proportion of heavy vehicles, P_{HV} (%)	14.46	29.86	31.27	63.11
Mean free flow speed, MFS, (km/h)	63.53	86.39	85.53	102.73
Std. of free flow speed, SD, (km/h)	13	19.01	19.47	32.72
85th percentile speed, S_{85}, (km/h)	79.16	103.58	102.92	125.02
Traffic volume in subject direction, VS, (vph)	44	117	122	254
Traffic volume in opposite direction, VO, (vph)	44	117	122	254
Traffic volume in two directions, VT, (vph)	112	226	244	426
Directional split (DS)	27/73	50/50	50/50	73/27
Probabilities estimation variables				
Passing vehicle speed (km/h)	48.21	85.89	89.26	154.29
Passed vehicle speed (km/h)	21.60	67.50	68.05	108.00
Length of passing zone (m)	290	664	794	1500
Distance up to initiation of maneuver (m)	13	316	391	1370

Table 1 provides a summary of traffic and geometric variables used to estimate the models. The range of passing maneuvers ending in no-passing zones was 0–14 passes per hour with a mean value of 2.77 passes per hour. The passing zones were sections of a highway with design speed of 110 km/h and a posted speed limit of 80 km/h.

Eighty-four passing maneuvers were processed to determine the speeds of passing and passed vehicles at the beginning of the passing zones, the durations up to initiation of the passing maneuvers inside the zones, and the type of passed vehicles. This was necessary to estimate the probability of individual passing maneuvers to end in the no-passing zone. The maneuvers were estimated for passing zones in the range of 290 and 1500 m as shown in Table 1. For some passing maneuvers, it was not possible to determine the point of initiation of the maneuver because of poor video quality or blocked visibility by opposite vehicles. This limitation can be overcome in future studies by using video recording from a vantage point rather than the roadside used in the current study. Nevertheless, the obtained sample size was deemed sufficient to estimate the model. The final sample comprised 27 passing maneuvers ending in no-passing zones and involving private cars or short trucks (2–3 axles) as the passed vehicle, and 24 involving long trucks (4–7 axles) as the passed vehicles. The passing vehicle in the sample was a passenger car.

The mean speed of passing vehicles at the beginning of the passing zone was 89.17 km/h, with a standard deviation of 21.72 km/h. The mean speed of passed vehicles was 68.05 km/h, with a standard deviation of 16.15 km/h. The speed difference between the passing and passed vehicles was in the range of −11.91 to 86.79 km/h. Thus, the sample consisted of passing maneuvers from two categories, high-speed catch-ups inside the passing zone, and close following at the beginning of the passing zone. The mean speed of passing vehicles was 9.17 km/h above the 80 km/h posted speed limit. In contrast, the mean speed of passed vehicles was 11.95 km/h below the posted speed limit. This characteristic is typical of the highways used in the study since it is part of a major import–export route in East Africa with high proportion of long slow trucks.

4.2. Estimation of probability prediction model of maneuvers ending in the no-passing zone

The model was estimated using GLM applications in the R statistical software [34]. Several models were evaluated using different combinations of road geometric and traffic related variables including: the length of the passing zone, the distance up to initiation of the passing maneuver, and the ratio of the distance up to initiation of the passing maneuver and the length of passing zone.

The speed difference at the beginning of the passing zone was not included for two reasons: (*a*) it is correlated with speeds of passing and passed vehicles; and (*b*) the speeds of the passing and passed vehicles affect the distance required to complete a maneuver, and must therefore be included in the model. A summary of the results of the best model is presented in Table 2.

The signs of estimated coefficients were all according to *a*-priori expectations. A negative sign for the variable length of passing zone shows that the probability of individual maneuvers ending in the no-passing zone decreases with the length. Similarly, the higher the speed of the passing vehicle, the less likely that passing maneuvers end in the no-passing zone. This is because higher speeds of passing vehicles result in shorter distance to complete the maneuver. The probability of passing maneuvers ending in the no-passing zone increases with the speed of the passed vehicle and when the passed vehicle is a long truck. The probability increases as well with the increase of the distance up to the initiation of the maneuver.

The model parameter estimates were tested at the 95% confidence level ($\alpha = 0.05$), for the null hypothesis H_O: $\beta_i = 0$ against H_1: $\beta_i \neq 0$. The estimates for the length of the passing zone, distance up to initiation of the maneuver, and speed of the passed vehicle were significant at the 95% confidence level, while the estimates for the speed of the passing vehicle and the type of passed vehicle were not. However, z-values were all greater than one, showing a contribution of these variables to the probability estimation, and thus were retained in the final model. The model was tested for significance and goodness of fit using the likelihood ratio test based on the null deviance (no explanatory variables) and residual deviance (with explanatory variables). The estimated χ^2-statistic was 57.37, which was also significant at the 95% confidence level (p-value < 0.0001). Therefore, the final estimated model for the probability of passing maneuvers ending in the no-passing zone is as follows:

$$P(Y=1|X_i)=\pi=\frac{\exp(1.762-0.024LPZ+0.026DIM+0.087VP_1-0.040VP_2+1.229TP)}{1+\exp(1.762-0.024LPZ+0.026DIM+0.087VP_1-0.040VP_2+1.229TP)}. \tag{7}$$

Where; LPZ is the length of the passing zone (meters); DIM the distance up to initiation of the maneuver (meters); VP_1 the speed of passed

Table 2
Model estimation results of probability of maneuvers ending in the no-passing zone.

Variables (unit of measure)	β-Estimate	Standard error	Z-value	Pr(>|z|)
Intercept	1.762	2.098	0.840	0.401
Geometric variables				
Length of passing zone (meters)	−0.024	0.007	−3.637	0.000
Distance up to initiation of maneuver (meters)	0.026	0.007	3.705	0.000
Traffic variables				
Speed of passed vehicle (km/h)	0.087	0.041	2.116	0.034
Speed of passing vehicle (km/h)	−0.040	0.028	−1.452	0.147
Type of passed vehicle [TP]; TP = 1 for long truck 4–7 axles, and TP = 0 for passenger cars and short trucks (2–3 axles)	1.229	0.963	1.276	0.202
Goodness-of-fit parameter estimates				
Null deviance (df = 83)	105.49			
Residual deviance (df = 78)	48.12			
Chi-square deviance, df = 5, (p-value)	57.37 (0.000)			
Sample Size	84			

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vehicle (km/h); VP_2 the speed of the passing vehicle (km/h); and TP the type of passed vehicle (TP = 1 for long trucks (4–7 axles) and TP = 0 for passenger cars or short trucks (2–3 axles)).

4.3. Sensitivity analysis

The model summarized in Eq. (7) was used to predict probabilities for different combinations of independent variables. Probabilities were computed for recommended design parameters as in AASHTO (2011) for a flat terrain as follows: speed of the passing vehicle equal to 110 km/h, speed of the passed vehicle, 91 km/h, a speed difference of 19 km/h, and the design PSD threshold of 355 meters. This is in order to compare the estimated probabilities with the performance of the design PSD thresholds if they were adopted in Uganda. Probabilities were predicted for passing zones of length 290, 355, 400, 500, 600, and 730 m. 290 m is the shortest length of passing zone used in this study. The 730 m is the design PSD threshold currently recommended in Uganda [6].

Fig. 4a shows the probabilities for different lengths of passing zones with the passed vehicle as a passenger car or short truck (2–3 axles). The passing vehicle is a passenger car. The graph shows that the probability of an individual maneuver to end in the no-passing zone for passing zones of length 290, 355, and 400 m are 0.15, 0.04, and 0.01, respectively. The probability is zero for zones 500 meters or longer. Furthermore, probabilities of individual maneuvers ending in the no-passing zone are 0.50 for zones 290, 355, and 400 m if there is a delay to initiate the maneuvers up to 65, 125, and 165 m from the beginning, respectively.

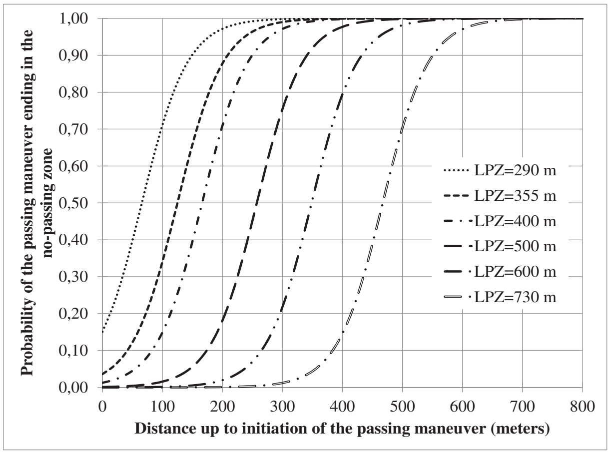
The results show that passing zones up to 400 m long confine maneuvers to commence close to the beginning for safe completion inside the passing zone, which is a safety concern. For passing zones of 500, 600, and 730 m, the probability of individual maneuvers ending in the no-passing zone reaches 0.50 when initiation of the maneuver is delayed up to 255, 350, and 465 m, respectively. These passing zones provide a substantial length for initiation of the maneuvers that can safely end inside the passing zone.

Fig. 4b shows the probabilities when the passed vehicle is a long truck (4–7 axles). The graph shows that at the beginning of the passing zone, the probability of individual maneuvers to end in the no-passing zone are 0.38, 0.11 and 0.04 for passing zones of lengths 290, 355, and 400 m, respectively. For passing zones 500 m or more, the equivalent probability is zero. The probability of ending in the no-passing zone reaches 0.50 if the maneuvers commence at 19, 78, and 120 m from the beginning of the passing zone for lengths 290, 355, and 400 m, respectively. Similarly, the probability of individual maneuvers to end in the no-passing zone is 0.50 for passing zones 500, 600, and 730 m for delays up to 210, 300, and 420 m, respectively.

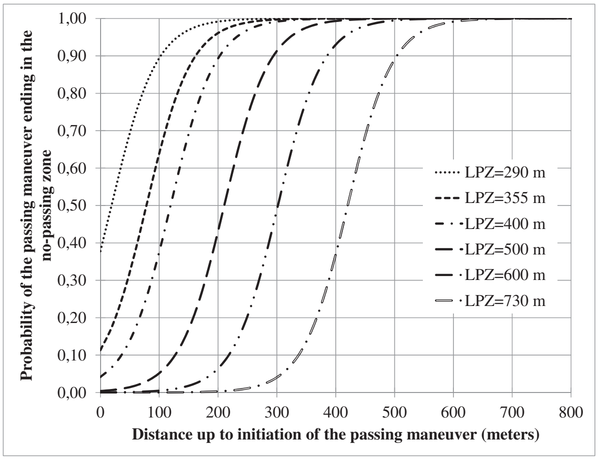
Fig. 4c is a plot of the ratio of distance up to initiation of a passing maneuver, which results in 0.50 probability of ending in no-passing zone to the length of the passing zone against the length of passing zone. The figure shows that for passing zones 500 m or more, and a passenger car or short truck (2–3 axles) as the passed vehicle have at least half the lengths available for safe initiation of passing maneuvers. The sight distance threshold required to complete passing maneuvers inside the passing zone is 245 m. Conversely, if the passed vehicle is a long truck (4–7 axles), passing zones at least 600 m or more have at least half the length available for safe completion of a maneuver, and the sight distance threshold to complete the maneuver inside the passing zone is 300 m.

These results suggest changes in design and marking of passing zones on two-lane rural highways for operational efficiency and safety reasons as follows:

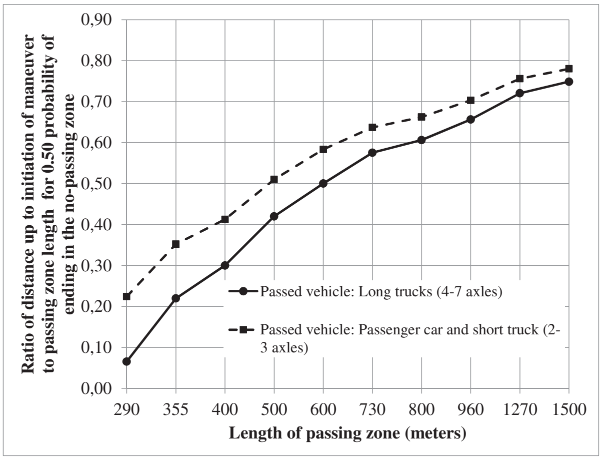
(i) Highways used by long trucks should have passing zones at least 600 m, with the last 300 m set aside for completion of maneuvers.
(ii) Highways used mostly by passenger cars and short trucks (2–3 axles) should have passing zones at least 500 m, with the last 245 m reserved for completion of maneuvers.



a) Passed vehicle is a passenger car or short truck (2-3 axles)



b) Passed vehicle is a long truck (4-7 axles)



c) Extent of delay to initiate maneuver with 0.50 probability of ending in the no-passing zone

Fig. 4. Sensitivity analysis of the probability prediction model and applications.

Passing zones 400 m or less confine maneuvers to commence at the beginning of the zone in order to be completed inside the passing zone. This is not feasible at high directional traffic volumes due to increased chances of meeting opposite vehicles on arrival at the beginning of the

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passing zone. Passing zones that are 400 m or and shorter should have advance-warning signs to compel drivers to commence passing maneuvers at the beginning of the zone. Therefore the marking PSD thresholds (240 m) in the Uganda Traffic Signs Manual for a speed limit of 80 km/h are not sufficient for safety reasons [13]. Additionally, the AASHTO 2011 [4] PSD threshold (355 m for a design speed of 110 km/h) recommended for design and marking of this type of highways is insufficient for safe passing.

4.4. Estimation of the rate of passing maneuvers ending in the no-passing zone

The model for the rate of passing maneuvers that end in the no-passing zone was estimated using the R software [34], and the package MASS for Negative Binomial regression [35]. Model specifications using different combinations of geometric and traffic variables were evaluated for consistency and statistical significance. The variables that were explored included the length of the passing zone, absolute vertical grade, traffic volume in two directions, directional split (percent of traffic volume in one direction to traffic volume in two directions per hour), percent heavy vehicles, and 85th percentile speed of free flowing passenger cars at the beginning of the passing zone including second order effects. The 85th percentile speed of free flowing passenger cars was not significant. Results of the final model estimation are presented in Table 3.

The signs of the coefficients for the respective variables were according to *a*-priori expectations. That is, a positive sign of the coefficients for percent absolute vertical grade, traffic volume in two directions, and the directional split. That is, passing maneuvers ending in the no-passing zone increase with traffic volume and uneven directional split. This is because these conditions lead to an increase of passing demand in the subject direction, and reduced passing opportunities in the opposite direction. Signs of the coefficients for the length of passing zones, and the percent heavy vehicles show an increase of maneuvers ending in the no-passing zone at decreasing rate.

Wald tests on parameter estimates indicate that traffic volume in two directions and the directional split are significant at 95% confidence level. Parameter estimates for the length of the passing zone, absolute vertical grade, and heavy vehicles were not significant at the 95% confidence level but had high z-values. The percent heavy vehicle and its square term were significant at 90% confidence level. Based on the magnitude of z-values, the length of passing zone, and absolute vertical grade were retained in the final model shown in Table 3.

Table 3
Model estimation results of the rate passing maneuvers end in the no-passing zone.

Variable	β-Estimate	Standard error	Z-value	Pr(>$\lvert z\rvert$)
Intercept	−2.883	1.138	−2.533	0.011
Geometric variables				
Length of passing zone (km)	0.644	0.460	1.399	0.162
square of length of passing zone (km^2)	−0.253	0.160	−1.578	0.115
Absolute vertical grade (%)	0.086	0.070	1.219	0.223
Traffic variables				
Traffic volume in two directions (vph)	0.004	0.001	4.748	0.000
Directional split	0.022	0.010	2.228	0.026
Percent heavy vehicles	0.080	0.047	1.687	0.092
Square percent heavy vehicles	−0.001	0.001	−1.713	0.087
Goodness-of-fit parameter estimates				
Dispersion parameter	4.03			
Null deviance, LL(0)	137.79			
Residual deviance, LL(β)	100.66			
2 log likelihood at zero	−410.23			
2 log likelihood at convergence	−378.96			
Likelihood ratio test (χ^2, df = 7) *(p-value)*	31.27 *(0.000)*			
ρ^2	0.27			
Sample size	96			

A dispersion parameter of 4.03 was obtained showing support for the Negative Binomial regression model form. The estimated model was compared with the null model using the likelihood ratio test [21, 36]. Using the analysis of variance procedure in R, a χ^2-value of 31.27 with seven degrees of freedom was obtained, which was significant at the 95% confidence level (p-value = 0.000).

This result showed that the estimated model explained better the rate at which passing maneuvers end in the no-passing zone than the null model. The ρ^2-value (analogous to R^2 in ordinary least squares regression) was computed as $(1 - LL(\beta) / LL(0))$ [21], and resulted in a value equal to 0.27, showing that the model explains 27% of data variability. This low value stems from the fact that the likelihood of individual maneuvers ending in the no-passing zone also depends on the position of initiation of individual maneuvers and the time it takes to complete the maneuvers. This is difficult to estimate for aggregate data that was used for the rate estimation. A summary of the estimated model is as follows:

$$PV = \exp\begin{pmatrix} -2.883 + 0.644LPZ - 0.253LPZ^2 + 0.086AG + 0.004VT \\ +0.022DS + 0.080PHV - 0.001PHV^2 \end{pmatrix}. \tag{8}$$

Where: PV is the rate passing maneuvers end in the no-passing zone (passes/h); LPZ the length of passing zone (km); AG the absolute vertical grade (%); VT the traffic volume in the two travel directions (vph); DS the directional split expressed as 50 for 50/50; and PHV which is the percent of heavy vehicles.

4.5. Sensitivity analysis of the rate prediction model

The estimated model summarized in Eq. (8) was used for sensitivity analysis using a combination of independent variables. Fig. 5a shows a graph of the observed and predicted rates at which passing maneuvers end in the no-passing zone against traffic volume in two travel directions. The graph was plotted for passing zones of lengths 0.290, 0.355, 0.730 and 1.000 km; average directional split (50), 35% percent heavy vehicles; and 1.0% absolute vertical grade. The figure shows that the rate at which passing maneuvers end in the no-passing zone increases with traffic volume in the two travel directions. This is because as traffic volume in the two travel directions increases, the passing demand in the subject direction increases while the passing opportunities in the opposite direction decrease. This leads to increased frequency of delayed passing maneuvers, and higher chances of passing maneuvers ending in the no-passing zone.

Fig. 5b shows a graph of the rate against the length of passing zones for traffic volumes in the two-travel directions 150–400 vph. Input values for the directional split, absolute vertical grade, and percent heavy vehicles were maintained as previously defined in Fig. 5a. The graph shows that the rate increases to a peak at 1.30 km and decreases at higher values of the length of passing zones. The explanation for this result is that at very long passing zones; passing vehicles find gaps in the opposite direction earlier in the zone. This reduces the frequency of passing maneuvers initiated towards the end of the passing zone. Secondly, long passing zones also reduce chances of occurrence of catch-up maneuvers that occur later in the passing zone.

Fig. 5c presents the rate against the percent heavy vehicles, with traffic volume in two directions, 300 vph, and other model inputs maintained as in Fig. 5a. The graph shows that the rate of passing maneuvers ending in the no-passing zone increases to a peak at 35% heavy vehicles and decreases at higher values. The possible explanations for this result are: (*a*) at higher percentages of heavy vehicles above 35%, the number of passing attempts goes down due to reduction in proportion of fast passenger cars; and (*b*) growth in platoons of heavy vehicles makes it difficult to initiate and complete passing maneuvers.

Lastly, Fig. 5d is a graph of the rate against the percent absolute vertical grade, with traffic volumes in the two travel directions, 300 vph,

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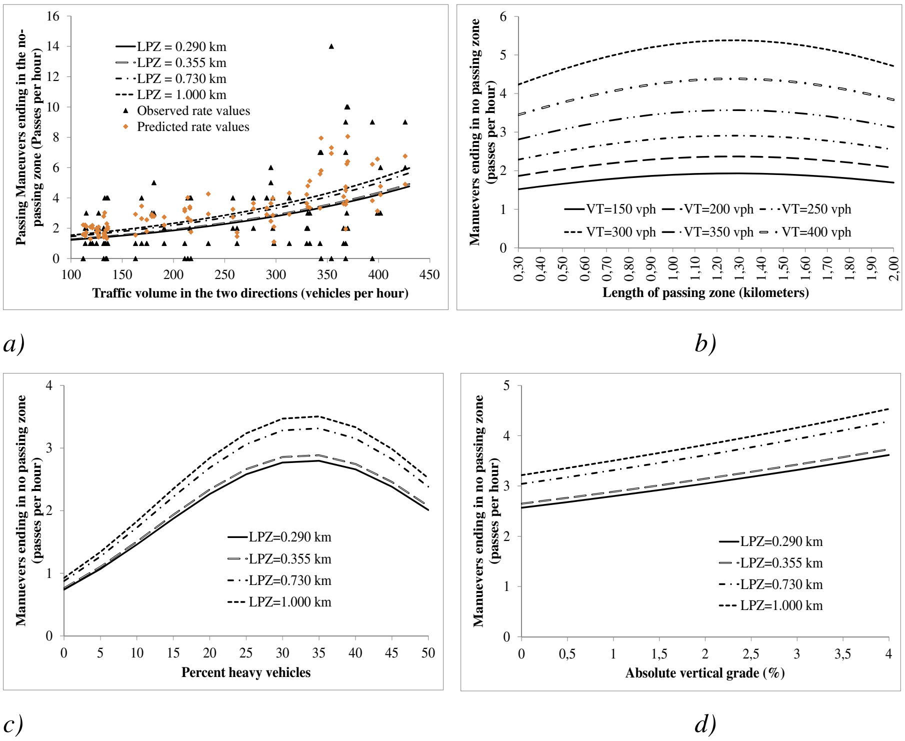

a) b)

c) d)

Fig. 5. Sensitivity analysis of the model for the rate of passing maneuvers ending in the no-passing zone.

and other inputs maintained as in Fig. 5a. The graph shows that the rate increases with an increase in the absolute vertical grade, with higher results at long passing zones. The percent absolute vertical grade contributes to reduction in the speeds of slow vehicles, and increases catch-ups occurring inside the passing zone.

5. Discussion

The methodology and results presented in the preceding sections provide a new approach to evaluate the operational efficiency and safety of two-lane rural highways based on the length of the passing zone. Previous studies assessed the adequacy of the design PSD considering the distance required to complete individual passing maneuvers assuming they commence at the beginning of the passing zone [5,8–11]. As such, design PSD thresholds were based on distance required to complete a passing maneuver but not adequacy of the passing zone lengths to break up platoons which is necessary for operational efficiency and safety [1]. Observed data in this study provides evidence that passing maneuvers frequently commence farther downstream from the beginning of the passing zone with high chances of ending in the no-passing zone. These results suggest that passing zones should be longer than the critical distance required to complete individual passing maneuvers for safety reasons.

A recent study by Llorca et al. [37] used reliability analysis based on limit state design to evaluate the design and marking PSD standards in Spain. The authors estimated the difference between the assured sight distance based on the available length of the passing zone, and the computed PSD to assess reliability of design values. The proportion of negative differences was used as a measure of non-compliance. The authors determined that the Spanish marking standard had 85% non-compliance rate, while the design standards had non-compliance rates between 15 and 30%. The Spanish study however, did not consider the impact of delayed maneuvers while estimating non-compliance of individual passing zone.

Results of the current study show that the design PSD thresholds in AASHTO 2011 [4] are sufficient for safe completion of passing maneuvers that commence at the beginning of the passing zone, and involve a passenger car as the passed vehicle. Moreover, they are insufficient for passing maneuvers involving long trucks (4–7 axles) as the passed vehicles. The AASHTO 2001 [3] PSD design thresholds currently used in Uganda, provide sufficient sight distance to complete individual maneuvers and more than half the length is available for safe initiation of the maneuvers. Moreover, when it comes to design of passing lanes, the AASHTO 2011 [4] recommends lengths more than 0.50 km to reduce platooning, with optimal lengths between 0.80 and 3.20 km.

The results also show that passing maneuvers ending in the no-passing zone are not random, but vary systematically with volume and uneven distribution of traffic in the two travel directions, the length of passing zone, percent absolute vertical grade, and percent heavy vehicles. Most important for safety is the fact that the rate passing maneuvers end in the no-passing zone increase with traffic volume in two directions. This increases accident risk since drivers may end passing maneuvers with insufficient sight distance to avert potential collisions. It is proposed that additional signs should be placed inside the passing zones to limit the occurrence of passing maneuvers towards the end of the passing zone.

The length of the passing zone and absolute vertical grade affects the speeds of heavy vehicles, which would lead to increase in late catch-ups inside the passing zone. The AASHTO 2011 [4] states that upgrades of 2–4% would result in 10–20 km/h speed reduction of trucks after 500 m if the entry speed is 110 km/h. Lastly, the AASHTO 2011 [4] considers provision for climbing lanes on two-lane highways when the proportion of heavy vehicles reach 10%. It was not possible to find past studies that modeled the rate of passing maneuvers ending in the no-passing zone for comparison.

6. Conclusion

The paper presented a methodology to assess the effect of passing zone length on operational efficiency and safety of two-lane highways based on the probability and the rate of passing maneuvers ending in the no-passing zone. A logistic regression model was estimated to

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predict the probability of individual passing maneuvers ending in the no-passing zone taking into account the impact of the length of passing zone, distance up to initiation of the maneuver, speeds of passing and passed vehicles, type of passed vehicle as significant model explanatory variables.

Sensitivity analysis of the estimated model showed that passing zones of 400 m or less have higher chances of individual maneuvers ending in the no-passing zone if they do not commence at the beginning of the zone. For operational efficiency and safety reasons, passing zones at least 500 m should be considered for highways predominantly used by passenger cars or short trucks (2–3 axles), and the last 245 m of the zone should be used only to complete the maneuvers. Conversely, highways with long trucks (4–7 axles), passing zones at least 600 m long should be considered with the last 300 m reserved for completion of maneuvers.

A Negative Binomial regression model was developed to predict the rate of passing maneuvers ending in the no-passing zone with volume and distribution of traffic in two-directions, length of passing zone, percent absolute vertical grade, and percent heavy vehicles as explanatory variables. Sensitivity analysis of the model showed that the rate of passing maneuvers ending in the no-passing zone increase with the zone length up to 1.30 km, and decrease at higher values. Furthermore, the rate increases with volume and uneven distribution of traffic in two travel directions. This is safety concern of the operation of passing zones at higher traffic volumes due to increased passing demand and reduced passing opportunities.

This study could be extended to validate the methodology and the results under different traffic and geometric conditions than in Uganda, and consider variations of passing speeds for different times of the day. It is also interesting to compare the passing maneuvers ending in the no-passing zone with road traffic crashes that occur immediately after 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.

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