Capacity and Safety of Passing Zones on Two-Lane Rural Highways: A Review of Theory and Practice

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***Abstract*—Passing zones are primary operational features of two-lane rural highways where fast vehicles pass slow vehicles using a lane reserved for traffic in opposing direction. The operation of these zones has an effect on the overall safety of two-lane rural highways especially when passing opportunities reduce considerably at higher flows. This paper presents a review on capacity and safety of passing zones on two-lane rural highways. Despite stated importance of passing zones to the operational performance of two-lane rural highways, passing zone capacity has not been estimated and its impact on safety is still not known. Safety evaluations mainly compare adequacy of design and marking passing sight distances to complete passing maneuvers as well as parameters derived from the passing process namely; passing duration, speed difference between passing and passed vehicles, and clearance between passing and opposing vehicle at the end of the maneuver. There is need for further research to address gaps in current capacity and safety evaluation methods of two-lane rural highways with focus on; (a) development of robust passing rate models for individual passing zones based on geometric, environmental and traffic factors, (b) estimation of passing zone capacity, (c) development of criteria to evaluate capacity and safety of passing zones for use by policy makers, planners and transportation engineers and (d) application of passing zone capacity to evaluate rural highway sections with several passing zones.**

***Index Terms*—capacity, safety, passing zones, two-lane highways**

I. Introduction

Two-lane highways generally form a large portion of the road infrastructure in the world and specifically developing countries where play a cardinal role in local freight and passenger transport. They are characterized by intermittent zones marked with a broken centerline marking to permit fast vehicles pass slow vehicles using a lane for traffic in opposing direction. The zones are operationally referred to as passing zones by the '*American Association of State Highway and Transportation Officials [AASHTO]'* [1] and Harwood, *et al*. [2]. Passing zones provide sufficient sight distance for a driver to initiate and complete a passing maneuver safely to avoid a collision or evasive actions with traffic in opposing lane [1]. The objective is to reduce the time fast vehicles travel behind slow vehicles due to inability to pass and enhance overall operational efficiency of two-lane rural highways [2]. Passing zones are therefore fundamental to operational performance of two-lane rural highways with impacts on both capacity and safety. Specifically, the passing process involves risky maneuvers that increase the likelihood of occurrence of fatal and/or serious injury accidents as passing opportunities dwindle. This paper presents a review of theory and practice on capacity and safety of passing zones on two-lane rural highways. The focus is on the effect of capacity on safety of passing zones and overall performance of two-lane rural highways.

II. Capacity of Passing Zones

A. Definition

The Highway Capacity Manual 2010 [HCM] defines capacity of a facility as 'the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic and control conditions' [3]. For a two-lane highway, this capacity is 1700 and 3200 passenger cars per hour in one direction and two travel directions, respectively [3]. The above capacity values were derived from arrival demand measured at a single location, independent of the interactions at passing zones that are a characteristic of the operation of two-lane rural highways [4].

A simulation study by Kim and Elefteriadou with 80% passing zones of a highway section concluded that capacity was neither affected by passing zones nor opposing traffic flow rate [4]. This finding was not surprising since capacity estimation was derived from arrival demand independent of traffic interaction effects. Moreover, the HCM states that the quality of service deteriorates at very low volume-to-capacity ratios and few highways ever operate at or close to capacity before expansion to multi-lane highways [3].

The above lane capacity is therefore not a complete parameter to measure effectiveness of two-lane rural

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highways. Moreover, published literature neither defines nor quantifies passing zone capacity despite its recognition as a major operational feature for these highways. The HCM 2010 and its predecessor editions adopted two parameters to measure effectiveness of two-lane highways namely; average travel speed [ATS] and percent time spent following [PTSF].

The ATS is expressed as the average free flow speed in the traffic stream has been shown to decrease with directional flow per hour. Free flow speeds decrease with directional flows due to lack of freedom by drivers to choose desired speeds. It is used as an indicator for reduction in quality of service and was used to create LOS thresholds for Class *I* highways [3]. That is, LOS A for ATS ranges greater than 88 km/h and at most 64 km/h for LOS E.

The PTSF takes into account the proportion of vehicles following slow vehicles due to inability to pass and is the most widely used performance measure for two-lane rural highways. Lower PTSF values represent freedom of maneuver, driver comfort and travel convenience in the traffic stream [3]. Equation (1) shows the HCM base PTSF model, presented graphically in Fig. 1. The model shows increasing PTSF with flow in the subject direction for different flows in the opposing direction.

$$BPTSF_b = 100\left[1-\exp\left(aV_d^b\right)\right] \tag{1}$$

where, $BPTSF_b$ is the base PTSF in the subject direction (%), V_d is flow in the subject direction (pc/h), a and b are coefficients for different flows in opposing direction. For instance, a=-0.0014 and b=0.973 for opposing flows at most 200 pc/h, and a=-0.0062 and b=0.817 for opposing flows at least 1600 pc/h.

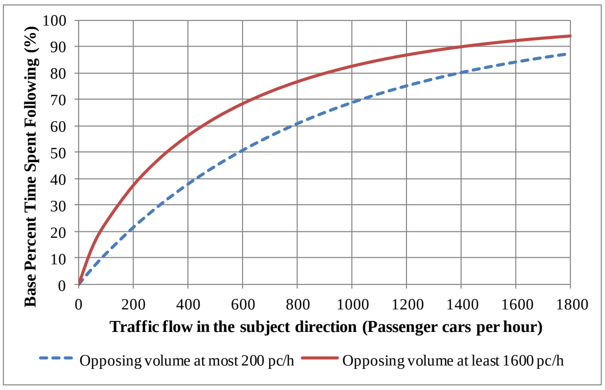


Figure 1. Plot of base PTSF with flow in the subject direction in HCM 2010.

For Class *I* highways, PTSF thresholds at LOS A and E are 35% and 80%, respectively. Capacity exists at the boundary of LOS E and F. Furthermore, lane capacity is adjusted for the vertical grade and proportion of heavy vehicles as well as PTSF and ATS to account for prevailing traffic flow conditions.

There are several drawbacks to the use of PTSF as a measure of effectiveness namely; (a) it is impossible to observe in the field and as such it is estimated from the proportion of vehicles travelling at headways at most 3.0 seconds [3], (b) it reportedly yields over estimated values at higher directional flows [5, 6] and (c) does not take into account passing interactions at passing zones but rather relies on macroscopic traffic flow parameters.

To overcome over estimation problems in the PTSF model, Luttinen [5] proposed a multivariate regression model incorporating both geometric and traffic factors (2). Model derivation similarly did not incorporate passing interactions at passing zones and the PTSF was estimated using 3.0 seconds threshold as well. Cohen and Polus proposed a modification based on the queuing theory that yields lower values than the HCM model (3) [6]. The authors used average headways within and outside platoons to compute PTSF values using a 3.0 seconds threshold.

$$p_w = 1-\exp((-0.00144-0.00042P_{np}+0.00009\mu_{L(80)})q_a - (0.00732-0.00156w_s)\sqrt{q_o}); \left(R^2 = 0.195\right) \tag{2}$$

$$PTSF = \begin{cases} 100.\dfrac{\bar{Q}}{\bar{N}+\bar{Q}}, \pi = 0 \\ 100.\dfrac{\bar{Q}-1}{\bar{N}+\bar{Q}-1}, \pi = 1-\rho \\ 100.\dfrac{\bar{Q}^2/\bar{Q}-1}{\bar{N}+\bar{Q}^2/\bar{Q}-1}, \pi = \Pr ob\left\{Q=2\right\} \end{cases} \tag{3}$$

where; P_w and PTSF are percent time spent following (%), q_o is flow in opposing direction (vph), q_a is flow in subject direction per hour (vph), $\mu_{L(80)}$ mean speed for 80 km/h speed limit highways, P_{np} is the proportion of upstream no-passing zones (%), W_s is the width of shoulders (meters), Q is the number of headways inside a platoon, $\bar{Q}$ is the average number of headways inside a platoon, $\bar{N}$ is the average number of headways between two platoons, π is the probability that a slow vehicle has no following platoon and ρ is the traffic intensity.

Van As and Van Niekerk [7], and Al-Kaisy and Karjala [8] proposed use of 'follower density' as an alternative to PTSF given by Equations (4) and (5), respectively. Follower density was similarly estimated using 3.0 seconds headway threshold.

$$K_F = P_F \frac{Q}{NU} \tag{4}$$

$$F_D = 0.01041V_s - 0.00022V_o - 0.03057P_{HV} + 0.005P_{NPZ} + 2.12739\sigma_s; \left(R^2 = 0.96\right) \tag{5}$$

where; K_F and F_D are follower densities defined as the number of vehicles traveling with headways at most 3.0 seconds in one direction per hour, V_s and Q are flows in subject direction (vph), N is number of lanes, U is the mean speed of all vehicles (km/h), P_F is percent followers (%), V_o is flow in opposing direction (vph), P_{HV} is the proportion of heavy vehicles (%), P_{NPZ} is the proportion of no-passing zones (%), and σ_s is standard deviation of free flow speeds (mph).

The PTSF and follower density are surrogate measures of passing demand which is the desire of a fast vehicle to pass a slow vehicle. Estimation of passing demand from macroscopic traffic flow parameters was first proposed by Wardrop in a model based on traffic flow characteristics (6) [9]. The model reportedly yields overestimated values in comparison with empirical data [10]. Passing demand cannot be observed due to its latent nature and therefore making a comparison with passing rate is erroneous as the latter depends on available opportunities to pass. However, passing rate would be a better measure of effectiveness since it is a measure of satisfied demand for the available passing opportunities.

$$P_D = 0.56\left(\frac{Q^2\sigma_s}{\mu_s^2}\right) \quad (6)$$

where; P_D is the number of passings in square passenger car units per kilometer hour, Q is the flow in the subject direction (vph), σ_s is the standard error of space mean speed (km/h), μ_s is the space mean speed (km/h), vph is vehicles per hour, and km/h is kilometers per hour.

B. Passing Rate Models

Few studies in the literature have developed empirical passing rate models. The earliest cited is a negative exponential model developed by Daganzo with flow in two directions as the independent variable and a 50/50 directional split (7) [11]. Fig. 2(a) shows a plot of Daganzo's passing rate model against flow in two directions. The model predicts high passing rates at low traffic volume and diminishes to zero at 400 vph. Theoretically, passing rate should increase at low flows and decrease at higher flows due to reduction in passing opportunities in opposing traffic stream.

$$\mu = 637\exp\left(\frac{-q}{153}\right) \quad (7)$$

where; μ is the passing rate in passings per hour, and q is flow in two travel directions (vph).

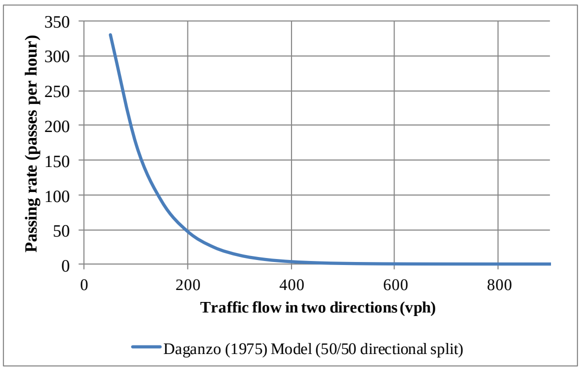
Morrall and Werner introduced the concept of overtaking ratio between achieved overtakings to the desired overtakings estimated at continuous passing lanes [12]. The authors illustrated that the supply of gaps in opposing traffic that are sufficient for a safe overtaking maneuver decrease with volume. However, no mathematical model was developed to explicitly explain how passing varies with volume in two directions.

Hegeman developed a power model relating the observed passing maneuvers to flow in the subject and opposing directions (8) [10]. The model was truncated at 1700 passenger cars per hour per lane, which is the flow at capacity in one direction as indicated earlier. Fig. 2(b) shows a plot of Hegeman's model for 50/50 and 60/40 direction splits. The plot shows that passing rate peaks close to 600 vph for 50/50 directional split.

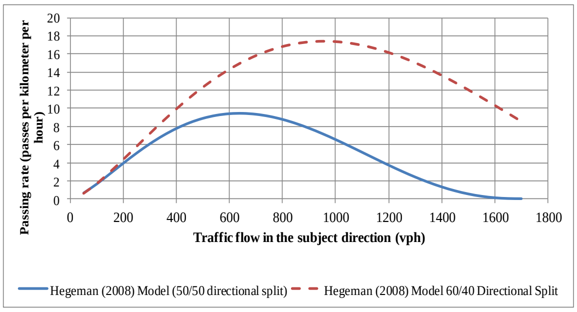
$$OF = 1.6*10^{-11} * q_a^{1.5}(1700 - q_o)^{2.5}; (R^2 = 0.67) \quad (8)$$

where; OF is passing rate in passings per kilometer per hour, q_a is flow in subject direction (vph) and q_o is flow in opposing direction (vph).

However, the average headway at 600 vph is 6.0 seconds which is not sufficient to initiate and complete passing maneuvers involving two vehicles [1], [2]. The probable reason for this peak location is inclusion of passing maneuvers made by motorbikes (12.50%) in passing rate data. Motorbikes require shorter headways to initiate and complete passing maneuvers. However, the model fits theoretical expectation of changes in passing rate with directional flows.



(a)



(b)

Figure 2. Plot of passing rate models by (a) Daganzo (1975) and (b) Hegeman (2008).

The above discussion points to the fact that passing zone capacity has neither been defined nor estimated in published literature. Its significance in operational and safety evaluation two-lane highways is also not known. Capacity of two-lane rural highways has been defined and estimated based on throughput derived from arrival demand measured from one location without considering traffic interactions at passing zones that affect greatly the quality of service [3].

Secondly, the ATS and PTSF are used as surrogate measures of effectiveness with the PTSF being the most popular albeit with problems of overestimation at higher directional flows and difficulty to measure in the field. In addition, modifications proposed by Luttinen [5], and Cohen and Polus [6] to overcome overestimation as well as the follower density [7, 8] have dependent variables derived similarly as in HCM model.

Thirdly, existing passing rate models have different model forms; power [10] and exponential [11]. Moreover, both models do not include geometric and other traffic variables related to speeding characteristics and directional volumes. Lastly, Hegeman's model demonstrated that it is possible to define and estimate passing zone capacity from passing rate data collected at passing zones. However, issues still remain pertaining to appropriate model form and explanatory variables that need to be explored in future studies.

III. Safety of Passing Zones

Safety of passing zones is discussed in the literature under three broad perspectives namely; design, marking and operation. These perspectives are presented in detail in subsequent sub-sections.

A. *Design*

The main safety concern on the operation of passing zones has been adequacy of passing sight distance [PSD] for different traffic and environmental factors. The design PSD comprises of four parts; perception reaction time [PRT] and initial acceleration (d_1), occupation of the right lane (d_2), clearance between passing and passed vehicle at the end of the maneuver (d_3), and opposing vehicle up to the end of the maneuver (d_4) illustrated in Fig. 3. The derivation of minimum design PSD was based on five major assumptions of a passing maneuver involving two passenger cars; (a) a passing vehicle reduces speed and trails a slow vehicle prior to reaching the passing zone, (b) the slow vehicle maintains constant speed during the maneuver, (c) the passing vehicle gauges available sight distance ahead and gap in opposing traffic to initiate a maneuver, (d) the maneuver is executed by what is termed as '*delayed start'* and '*hurried return*' while maintaining a speed difference between the passing and passed vehicle 10 mph [16 km/h], and (e) at the end of the maneuver, there is a sufficient clearance between the passing and opposing vehicle.

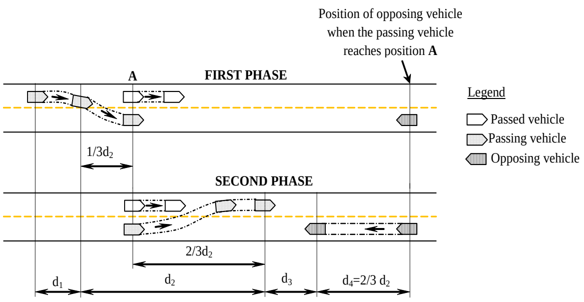


Figure 3. Components of passing sight distance (*Adapted from AASHTO*).

The first assumption accounts for only accelerative passing maneuvers involving two passenger cars. However, studies have shown other types of manuevers; flying pass where the passing vehicle catches up with a slow vehicle and decides to pass without following, those involving more than one passed vehicle, and where the passed vehicle is a truck [13]–[15]. For instance, flying pass maneuvers are characterized by high speeds of passing vehicle and start from any position of catch-up in a passing zone requiring even longer PSD to complete.

Secondly, the four distance components were derived based on kinematic models first developed by Valkenburg and Michael [14], Glennon [15] and later extended by Hassan [16] and Wang and Cartmell [17]. The overall PSD derived from the four distance components has been criticized for being too conservative [2], [18]. For instance, according to the AASHTO design guide, highways with a design speed of 110 km/h, the minimum design PSD is 730 meters for a passing duration of 11.30 seconds and average speed of passing vehicle 99.80 km/h. This minimum PSD is more than sufficient for a driver to safely initiate and complete a passing maneuver from field observations. Passing zones with lengths less than minimum PSD for the design speed are common on most two-lane highways and study has shown that they are less safe than those above the threshold. Therefore, upholding design PSD threshold reduces the frequency of passing zones and increase driver frustration due to inability to pass and reduce overall LOS.

Thirdly, the location of abreast position used to compute the distance travelled by opposing vehicle while the passing vehicle occupies the opposing traffic lane (d_4) is different than one-third assumed in AASHTO design guide when compared with 41% and 56% of the passing distance in opposing traffic lane observed by Harwood, *et al*. [2], and Llorca and Garcia [19], respectively. These values yield a shorter distance travelled by opposing vehicle while passing vehicle occupies the opposing traffic lane than assumed in AASHTO design guide.

Lastly, the assumption of 16 km/h speed difference between the passing and passed vehicle has been found to be too low compared with field data; 19 km/h [2], 21.40 km/h [13] and 23 km/h [19]. A higher speed difference leads to an overall reduction in PSD due to a shorter passing duration.

TABLE I. RECOMMENDED MINIMUM DESIGN AND MARKING PASSING SIGHT DISTANCES

AASHTO (2001)		MUTCD (2009)		Proposed Revision by Harwood et al. (2008)	
DS (km/h)	PSD (meters)	OP or SL (km/h)	PSD (meters)	DS (km/h)	PSD (meters)
30	200	40	137	30	120
40	270	48	152	40	140
50	345	56	167	50	160
60	410	64	183	60	180
70	485	72	213	70	210
80	540	80	244	80	245
90	615	88	274	90	280
100	670	97	305	100	320
110	730	105	335	110	355
120	775	113	365	120	395
130	815			130	440

DS=Design speed, PSD=Passing sight distance, OP=Operating speed, SL=Speed limit. Source: AASHTO (2001), MUTCD (2009) and Harwood, *et al.* (2008)

In conclusion, the design PSD values are long enough to safely initiate and complete a passing maneuver. Moreover, the highway terrain often allows much longer PSD than the design thresholds. Harwood, *et al.* [2] proposed new design PSD values based on modified assumptions of the passing process shown in Table I as follows; (a) speed of passing and opposing vehicles equal to the design speed, (b) speed difference between passing and passed vehicle is 19 km/h, (c) abreast position is reached at 40% of the passing duration where the probabilities to complete or abort the maneuver are equal, (d) length of passing and passed vehicles is 5.80 meters (e) perception reaction time, (f) final headway between passing and passed vehicles, and (g) clearance between passing and opposing vehicles at the end of the maneuver one second, respectively. The new design PSD thresholds are nearly half those that have been used in practice for a long time. The revision is consistent with findings by El Khoury and Hobeika that it is possible to lower existing design PSD thresholds and maintain acceptable risk levels [18]. Where, risk levels were determined based on the time clearance at the end of the maneuver between the passing and opposing vehicles.

B. Marking

Marking is intended to communicate the design to the driver by ensuring that there is sufficient sight distance for a safe passing maneuver. The most cited reference for highway marking is the '*Manual on uniform traffic control devices for streets and highways [MUTCD]*' [20] and has been adopted by many countries. Marking PSD values in MUTCD depends on the posted speed limit or 85th percentile speed of vehicles of a similar highway as shown in Table 1. The PSD values are approximately half of those recommended in design. As an example, the length of passing zone corresponding to a posted speed limit of 80 km/h is 244 meters which is only close to 270 meters for a design speed of 40 km/h in AASHTO design guide [1].

The difference between design and marking PSD values has been a subject of research related to capacity and safety. Harwood and Glennon for instance observed that passing zones less than 268 meters were associated with safety and operational deficiencies [21]. A study by Hassan concluded that marking PSD values were sufficient for design speed in the range 50-60 km/h and passing maneuvers involving only two passenger cars [16]. The author further noted that the deficiency in PSD increased with design speed up to 36% at 120 km/h. El Khoury and Hobeika observed that the MUTCD PSD thresholds fall within acceptable risk levels for passing maneuvers involving two passenger cars [18]. A recent study by Harwood, *et al*. observed that passing zones 120-240 meters long do not contribute significantly to the operational efficiency of two-lane highways [2]. The study recommended that passing zones shorter than 240 meters should not be included on two-lane highways with speed limits in the range 89-97 km/h.

C. Operation

Safety considerations in the operation of passing zones relate to the passing process, driver and vehicle factors. The factors are evaluated in relation to the likelihood of occurrence of rear-end collision due to close following before the maneuver, long passing distance requirements than the marked PSD, and lack of sufficient clearance between passing and opposing vehicles at the end of the maneuver that increases the risk of head-on accidents.

a) Passing process

Safety of the passing process is evaluated in most studies with respect to AASHTO design guide taking into account safety risks associated with respective design parameters. These include; PRT, and headway between passing and passed vehicles at the start of the maneuver (3.60-4.50 seconds), passing duration (9.30-11.30 seconds), headway between passing and opposing vehicle at the end of the maneuver (30-90 meters), speed difference between passing and passed vehicle (16 km/h), and location of abreast position where it is presumed the probabilities to complete or abort a maneuver are equal [15], [16].

A study conducted by Polus, *et al.* determined that the mean PRT for passing a passenger car was 1.45 seconds, and between 1.20 and 1.36 seconds for passing a truck in flying and accelerative passing maneuvers, respectively [22]. Hegeman observed that the PRT of 50% of passing vehicles was at most 0.50 seconds [10]. The PRT values obtained in the two studies were shorter than the assumed design guide range. The safety implications are that drivers react quickly and follow more closely in a maneuver which increase the risk of rear-end collisions.

Polus, *et al.* observed that the mean passing duration involving two passenger cars and for passenger cars and trucks were 10.00 and 11.50 seconds, respectively [22]. Other researchers similarly established passing durations of 10.00 [2], 7.80 [10], 7.60 [19] and 9.80 [13] seconds. These values are similar to those assumed in the design guide.

The headway between passing and opposing vehicles at the end of the passing maneuver is used to assess the risk of a head-on collision. Empirical research indicates that this headway is in the range 0.30-5.80 seconds [2, 10, 19, 22]. Specifically, Hegeman observed that 10% of observed passing maneuvers ended with the clearance below 3.0 seconds [10]. However, the risk estimation criteria based on time headway does not take into account the effect of flow in opposing direction. The expectation is that the time clearance should decrease at higher flows in opposing direction adding to the risk of a head-on collision. Therefore an appropriate measure of risk should correlate the clearance with flow in opposing direction.

b) Driver factors

Driver factors relate to the behavior and characteristics that impacts the passing process. These include; the desire to pass, accepted gap in opposing traffic, age and gender. A study by Bar-Gera and Shinar evaluated the tendency for drivers to pass vehicles using data of young drivers collected from a driving simulator [23]. The authors observed that 50% of the drivers tend to pass vehicles in front even when moving faster than their average speed and the tendency to pass was as a result of drivers' own speed variability. They concluded that reducing speed variances was crucial to improving overall roadway safety.

A study by Jenkins and Rilett observed that the increase in speed of the passing vehicle decreases with increase in speed difference between passing and passed vehicles [24]. The authors further observed a weak linear relationship between passing vehicle speed reduction and clearance time between passing and opposing vehicles at the end of the maneuver.

Farah, *et al*. developed a passing gap acceptance model at passing zones of two-lane highways [25]. The study involved 64 male and 36 female drivers with at most five years driving experience; aged between 22 and 70 years and using a driving simulator. The authors noted that young male drivers accepted shorter gaps in opposing traffic stream than older male drivers. Furthermore, experienced drivers accepted shorter gaps and the critical gap decreased with the speed of passing vehicle. They established that the mean accepted gaps in opposing traffic using logit and maximum likelihood estimation were 26.20 and 23.50 seconds, respectively.

Lastly, Farah and Toledo developed a passing behavior model incorporating the desire to pass and gap acceptance [26]. The authors observed that critical passing gaps vary substantially with driver characteristics related to age but not gender. The size of available gap in opposing traffic affects gap acceptance and that aggressive drivers were more likely to desire to pass and to accept shorter gaps.

c) Vehicle factors

The most widely reported vehicle factor in the literature is the effect of truck length on PSD requirements compared with those of passenger cars using kinematic PSD models. The earliest reported is a model developed by Lieberman with passed vehicle speed, length and acceleration as explanatory variables [27]. The author concluded that longer PSD was required to pass a truck than a passenger car. Glennon included length of passed vehicle as one of input variables in his model and concluded that passing long trucks increased the PSD requirements by 28%-36% [15]. Similar increase in PSD with trucks as passed vehicles have been reported; 8% [16], 38% [17], and 14% [22]. Jenkins and Rilett observed that the passing duration and distance were significantly greater when the passed vehicle was a truck than a passenger car [28].

The above discussion points to a general consensus amongst researchers that truck length increase PSD requirements compared to passenger cars. However, the proportion of trucks in traffic stream or their physical characteristics has never been adopted as criteria for selecting the design PSD in practice. The probable reasons are; (a) design PSD values are long enough to cater for maneuvers involving trucks and (b) highway terrain often allows for long passing zones than design thresholds increasing the opportunity to pass long trucks.

In summary, there is general agreement that design PSD values are more than sufficient for safe completion of passing maneuvers and nearly double the marking PSD thresholds. Secondly, all assumed design parameters of the passing process are consistent with field observation save for PRT and the speed difference between passing and passed vehicles. Furthermore, the length of the passed vehicle and specifically trucks significantly impacts the required PSD to complete a maneuver. Lastly, the desire to pass and gap acceptance depend largely on driver factors such as age, driving experience, and individual driver's speed variability. However, there is no direct relation between capacity and safety of passing zones. That is, how safety margins change when passing opportunities dwindle at high traffic flows.

IV. Need for Further Research

Surrogate measures of ATS and PTSF have been used for performance evaluation of two-lane rural highways. The measures still have problems of over estimation, difficulty to estimate empirically and failure to take into account passing characteristics at individual passing zones. Specifically, passing zone capacity has neither been suitably defined nor estimated and its impact on safety and quality of service is largely unknown. This has made it difficult to determine precisely when passing zones are operationally ineffective due to reduction in passing opportunities at higher directional flows. This would help to guide policy makers, planners and transportation engineers when to widen the two-lane highways on the basis of lack of passing opportunities. This therefore calls for further research to develop theoretical frameworks to estimate passing zone capacity and its impact on overall safety.

Estimation of passing zone capacity should commence with development of passing rate with appropriate explanatory variables to capture both passing demand and opportunities based on geometric, environmental and traffic factors. The theoretical expectation is that passing rate increases with flow in the subject direction and decrease at higher flows due to reduction in sufficient gaps in opposing traffic to initiate and complete a maneuver [3]. This trend is graphically illustrated by Hegeman (2008)'s model in Fig. 2(b).

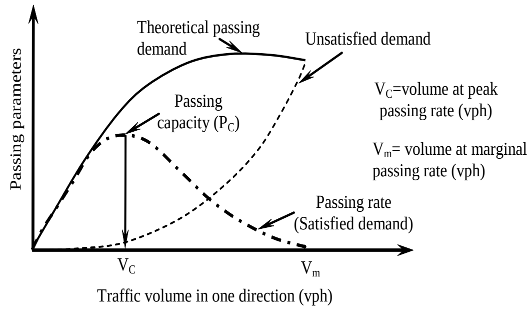


Figure 4. Variation of passing demand and rate with flow in one direction.

On the other hand, passing demand increases indefinitely with flow in the subject direction. As such, the difference between passing demand and passing rate is the unsatisfied passing demand illustrated in Fig. 4. The unsatisfied demand should theoretically increase with flow in the subject direction due to reduction of gap opportunities in opposing traffic stream. The unsatisfied demand can be estimated from field data of aborted, evasive and manuevers that end outside the passing zone. There is need to develop empirical models to predict the number of manuevers that end in and outside the passing zone so as to estimate capacity and safety thresholds. Therefore future research efforts should be directed towards the following;

- Development of a model to predict passing rate at individual passing zones taking into account the discrete nature of passing maneuver counts and incorporating both geometric, traffic and environmental factors (9). Models for discrete events are best handled in the literature under Generalized Linear Modeling using Poisson and Negative Binomial Regression techniques [29].

$$P_r = f(\beta X) + \varepsilon \qquad (9)$$

where, P_r is the passing rate, β is a vector for model parameters, X is a vector for explanatory variables derived from geometric, traffic and environmental factors, and ε is a random error term with an appropriate probability distribution.

- Estimation of the magnitude and location of passing zone capacity from the passing rate. Theoretically, passing zone capacity (P_c) is the maximum expected passing rate for given geometric, environmental and traffic factors (10).

$$P_c = \max\{P_r\} \qquad (10)$$

- Development of criteria to guide policy makers, planners and transportation engineers on capacity and safety evaluation of individual passing zones. This should take into account passing rate variation with flows as well as where manuevers start and end in the passing zone.
- Explore application of passing zone capacity to evaluate highway sections with several passing zones. For instance, the design guide recommends having frequent passing zones on a highway to increase passing capacity and enhance the overall quality of service [1]. The benefits of having frequent passing zones on a section have not yet been determined.

V. Conclusion

A review of theory and practice on capacity and safety passing zones on two-lane rural highways is presented. Literature shows that passing zone capacity has neither been adequately defined nor estimated despite its significance to the operational performance of two-lane rural highways. Performance evaluation depend on average travel speed and percent time spent following albeit with problems of over estimation and difficulty to verify empirically. Safety evaluations make comparisons between required passing sight distance with design and marking thresholds. However, generally there is no criterion to guide planners and transportation engineers on safety evaluation of passing zone.

Future research is required to address the above gaps and should focus on the following; (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 evaluation of highway sections with several passing zones.

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