NEW EXPERIMENTAL APPROACH FOR PASSING GAP ACCEPTANCE

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ABSTRACT

On two-way two-lane rural highways, drivers need to pass slower vehicles to drive at their desired speed, by travelling in the opposing lane during the maneuver. Drivers make a decision before performing the maneuver, in order to accept or reject each observed gap in the oncoming traffic flow.

A gap can be defined as the time or the distance between two consecutive vehicles in traffic flow. In relation to passing process, gaps can be evaluated from external points of view (static gaps measured on fixed positions) or by the driver of the passing vehicle (dynamic gaps until crossing an opposing vehicle). Both definitions are discussed and compared.

However, if gaps are measured only by taking into account an opposing vehicle, it is possible to evaluate a gap with an opposing vehicle which is further than the maximum available sight distance. Then, the measured gap is longer than the actual gap considered by drivers.

This new approach considers the effect of limited sight distance conditions, and the existence of road markings which indicates the end of passing zones. These factors have been added and a new function of probability of acceptance and rejection has been obtained, based on collected data from an instrumented vehicle in 103 maneuvers on three different road segments.

Results show that longer gaps have to be replaced by their equivalent virtual gaps, which are computed until crossing an opposing vehicle which could appear at the end of the visible area, before the real vehicle comes.

INTRODUCTION

The operational efficiency of many two-lane rural roads depends on the opportunity for faster drivers to pass slower drivers. Where faster drivers encounter a slower one and are unable to pass, platoons form and the level of service of the two-lane highway decreases. This is why passing zones are considered in the design of two-lane rural roads to provide opportunities for faster drivers to pass where gaps in opposing traffic permit. To do so, passing sight distance (PSD) has to be taken into account.

PSD is the distance that drivers must be able to see along the road ahead to safely and efficiently initiate and complete passing maneuvers of slower vehicles on two-lane highways using the lane normally reserved for opposing traffic.

The 2004 Green Book (1) incorporates several assumptions about driver behavior during a passing maneuver. Those assumptions and field data were used for developing the passing sight distance criteria. The minimum PSD is defined as the sum of the following four distances:

- \( d_1 \): distance traveled during perception and reaction time and during the initial acceleration to the point of encroachment on the left lane. Duration of this initial maneuver is estimated as within 3.6 to 4.5 s range.
- \( d_2 \): distance traveled while the passing vehicle occupies the left lane. Duration of passing vehicles occupying the left lane is estimated as within 9.3 to 11.3 s range.
- \( d_3 \): distance between passing vehicle at the end of its maneuver and opposing vehicle (clearance distance). Its minimum is estimated to vary from 30 to 90 m.
- \( d_4 \): distance traversed by an opposing vehicle for two-thirds of the time the passing vehicle occupies the left lane, or 2/3 of \( d_2 \).

Over the last three decades, researchers have questioned the premises of the Green Book model and/or suggested revisions to this model. Most of them agree that PSD should be based on a critical position (2, 3, 4). Several definitions for this location have been given. However, ability to pass is not only influenced by highway geometry, particularly available sight distance, but also by human factors such as driver-reaction time and gap acceptance characteristics.

Passing is commonly modeled as a binary choice in which drivers either accepts or rejects an available gap in traffic on opposing lane. Passing gaps are defined in terms of distance or time.

Gap is usually defined as the distance (or time) between consecutive vehicles on the oncoming traffic (static definition). It has been also defined as the time until crossing an opposing vehicle when a passing vehicle is starting a passing maneuver (dynamic definition). Farah et al. (5, 6) obtained from a simulator test than the mean dynamic accepted gap was 19.6 seconds and the mean rejected gap was 15.5 seconds. Based on their developed model, they stated that critical passing gaps and passing gap acceptance decisions are affected by variables that describe the situation a driver is faced with (in addition to the size of the available gap): acceptance probabilities increase with speed of passing vehicle and decrease with following distance from a vehicle in front.

Pollatschek and Polus (7) quantified driver’s impatience during passing maneuvers. They found that the critical gap decreases with an increase in two-way hourly volume.

Toledo and Farah (8) investigated and compared different definitions of passing gaps and used these definitions to develop different passing gap-acceptance models. Three different models were developed and calibrated based on data of passing maneuvers collected with a driving simulator. The results show that there was a significant impact of the passing gap definition on the models’ capability to explain drivers’ passing behavior.

Alternatives to the AASHTO design model for passing process (1) require actual data to calibrate and determine design values. Several researchers collected data of passing behavior by continuous videotaping from fixed observation points (9, 10, 11). Data has been also collected from an instrumented vehicle (12, 13) in order to characterize evolution of passing vehicles along the maneuver.

Passing gap acceptance is an important driving behavior that has important implications on both traffic flow and safety in two-lane rural roads. However, detailed data, that can be used to explain passing behavior, are difficult to collect in the real-world, partly because passing maneuvers...
may take place at any point on the road. In part, this is why little research has been conducted to
develop models for passing gap acceptance behavior.

OBJECTIVES

One of the main parameters to perform passing maneuvers is gap acceptance. However, it is difficult
to model or estimate because of the lack of available data. Passing maneuver is scattered distributed
along the road; so, data collection is a difficult task and it is usually done by volunteers or on driving
simulators.

Moreover, there are different definitions for passing gap but all of them only consider
vehicles on the opposing lane.

The purpose of this paper is to present a new methodology to analyze passing maneuvers
based on gap acceptance. This methodology is based on the definition of different passing gaps,
including not only the interaction between vehicles but also available sight distance and location of
road markings and vertical signs. The hypothesis is that gap acceptance and rejection distributions, as
well as critical gaps, would be different if these actual characteristics of highways are considered.

The results presented in this paper have been obtained by applying this methodology on three
road segments, where passing maneuvers are allowed. Data have been collected using an instrumented
car as impeding vehicle. It was a regular passenger car; and devices were not visible from outside;
which minimizes influence on drivers’ behavior.

A NEW METHODOLOGY TO ANALYZE PASSING MANEUVERS

A new methodology to analyze passing maneuvers based on gap acceptance has been developed.
Firstly, different passing gaps have been defined. Then, the most important passing gaps among
different scenarios have been stated. Therefore, the new methodology has been applied to the different
theoretical passing scenarios.

Passing gap definitions

Time-space diagrams are used to describe the passing maneuver. In these diagrams, time and space
are represented on horizontal and vertical axes, respectively. Typically, three vehicles are involved on
a passing maneuver: passing vehicle; impeding vehicle; and opposing vehicle. The trajectories of the
tyhree vehicles are represented on a time-space diagram with lines: passing vehicle with solid line;
impeding vehicle with dotted line; and opposing vehicle with dashed line.

As seen on Figure 1, five points of the passing maneuver are defined:

• $t_0$: start of the gap. It could be defined by either the end of a no-passing zone or the
crossing between the passing and a previous opposing vehicle.
• $t_1$: first encroachment point on the left lane of the passing vehicle.
• $t_2$: abreast position of the passing and impeding vehicle.
• $t_3$: end of left lane occupation.
• $t_4$: crossing between the passing and opposing vehicle.

The definition of these five points establishes the different phases of the passing maneuver.
The first phase is the time between the start of a passing opportunity ($t_0$) and the beginning of the left
lane occupation ($t_1$). The second phase corresponds to the left lane occupation by the passing vehicle
while it is overtaking the impeding vehicle. Consequently, it starts at $t_1$ and ends when the rear left
wheel of the passing vehicle crosses the center line ($t_3$). Both first and second phases are determined
by the decision to pass; and the passing vehicle could accept or reject the gap at every moment. The
last phase of the maneuver is the clearance between the passing and opposing vehicles at the end of
the pass; it starts at $t_3$ and it ends at the abreast position of the passing and the opposing vehicle ($t_4$).
This phase reflects the safety of the maneuver: the longer the third phase is, the higher the time until
the passing and opposing vehicle crossing is.

This approach includes not only completed passing maneuvers but also rejected passing gaps.
One gap is rejected if the driver decides not to initiate or complete the passing maneuver. Gap
acceptance is checked at any moment of the maneuver. If the driver had already occupied the left lane
prior rejecting the gap, it is defined as aborted maneuver.
Passing models use passing gaps to analyze the maneuver; which can be calculated on both time and distance. Static time gap (SG) is defined as the time between two consecutive opposing vehicles passing through one section of the roadway. This time can be measured by an external observer. However, static time gap cannot consider the time to complete the maneuver or its risk.

Dynamic time gaps (DG) are proposed as the time until crossing between the passing vehicle and the opposing vehicle (8); and they can be calculated in every section during the passing maneuver. Therefore, four dynamic time gaps are highlighted (Figure 1):

- \( DG(t_0) \): time gap between the beginning of the passing possibility and the crossing of the passing and the opposing vehicle. It can be calculated as \( t_4 - t_0 \).
- \( DG(t_1) \): time gap between the first encroachment point and the crossing of the passing and opposing vehicle. It is defined as \( t_4 - t_1 \); and it is usually named “time to collision” (TTC).
- \( DG(t_2) \): time gap between the abreast position of the passing and impeding vehicle and the crossing of the passing and the opposing vehicle. It can be calculated as \( t_4 - t_2 \).
- \( DG(t_3) \): time gap between the end of the occupation of the left lane and the crossing of the passing and opposing vehicle. It can be calculated as \( t_4 - t_3 \). This gap defines the safety of the maneuver and it is equal to the third passing maneuver phase duration.

In the literature (5, 6, 8), dynamic gaps have been calculated between the passing vehicle and the opposing vehicle; which is accurate in sections with unlimited sight distance. However, actual two-lane rural highways have limited available sight distance. Under this condition, opposing vehicles may be blocked by lateral obstacles, such as trees, buildings or cuttings, or the alignment itself; so, one opposing vehicle could appear after sight distance limit. Consequently, drivers also consider time gaps between their vehicle and available sight distance limit in case one opposing vehicle comes out. Figure 2 shows the passing maneuver with limited available sight distance. This time gap is shorter than the usual gap between both vehicles on unlimited available sight distance zones. Thereafter, a new dynamic time gap, virtual dynamic gap (VDG), is proposed as the time between the passing

![Diagram of passing maneuver with unlimited available sight distance](image)
vehicle and one virtual opposing vehicle that could appear at the available sight distance limit. As
available sight distance profile is not constant, this virtual opposing vehicle does not appear at the
same point; and it should be checked at every position of the passing vehicle during the maneuver, as
seen in Figure 2.

Drivers are not aware of opposing vehicle speed while considering VDG. Opposing vehicle
speed can be assumed to be equal to the operating speed on that section. Individual speeds should be
collected in order to calculate the 85th percentile of vehicles under free-flow conditions. Continuous
speed profiles can be obtained using GPS trackers or video recordings. Besides, spot speeds could be
measured on different sections to estimate continuous speed profile at the segment. If no data
collection is possible, operating speed models could be used to approximate speed profile.

Virtual dynamic time gap should be considered until an opposing vehicle comes out. Then, dynamic time gap to the opposing vehicle should be calculated.

According to design guidelines (1), enough passing sight distance (PSD) should be provided
at frequent intervals on two-lane highways in order to allow drivers to pass slower vehicles. Marking
standards (14, 15) determine passing zones and no-passing zones; which consider shorter PSD values
than design guidelines. Passing maneuver can be safely performed along passing zones. Therefore,
drivers usually limit the passing maneuver to passing zones; and no-passing zone sign demarcates the
opportunity to pass. Consequently, no-passing zone sign location should be also considered on the
analysis of passing maneuvers. Another dynamic time gap, sign dynamic gap (SDG), is defined as the
time spent by the passing vehicle to reach to the no-passing zone sign (Figure 3).

Time gaps can be easily transformed into distance gaps using the time-space diagram. Distance gaps have also been used previously in the literature to analyze the passing gap acceptance
(16, 17). The most important distance gaps are: distance between the passing vehicle at \( t_0 \) and the
opposing vehicle; and distance between the passing vehicle at \( t_0 \) and the virtual opposing vehicle just
located at the sight obstruction. Consequently, passing distance gap is the minimum of both distances.
Passing scenarios
The new approach can be applied to the different passing scenarios depending on: presence of opposing vehicle; available sight distance; and distance to no-passing zone. At each scenario, the minimum gap of the passing maneuver has been determined. Figure 4 shows the flow diagram.

The approach must be applied for every accepted and rejected gap. However, for rejected gaps only the values at the start of the gap can be considered, because the maneuver is not performed.

![Diagram showing passing scenarios]

**FIGURE 4 Passing scenarios**
FIELD STUDY

Site selection
For the research, three road segments were selected according to the following criteria: include one passing zone previously studied (11); uniform design speed; uniform cross section; constant posted speed limit; no intersections; uniform traffic volume on the roadway segment; and length shorter than 10 km. Length of studied sections was limited, in order to concentrate the sample in fewer passing zones.

A previous study (11) scanned the road network to detect zones with higher probability of passing maneuvers with design speed from 80 to 120 km/h. For this research three road segments which included 24 passing zones were selected. Four of them were recorded on the previous study using a traffic mobile laboratory. Table 1 shows the characteristics of those road segments, and the number of observations in each case.

<table>
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<th>CV-35</th>
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<td>90</td>
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<td>Length of passing zones (m)</td>
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<td>600 - 800</td>
<td>250 - 1100</td>
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<td>50 - 60</td>
<td>60 - 70</td>
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<td>Duration of observation (h)</td>
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</table>

**TABLE 1 Road segments selected for the study and number of observed maneuvers**

Data collection
To collect data of passing maneuvers, an instrumented car was used. The car was equipped with four digital cameras and one GPS tracker connected to a VBOX data logger. The GPS tracker recorded latitude, longitude, heading, time and date 10 times per second. The digital cameras were installed inside the vehicle and were not perceived by other drivers. In order to record complete maneuvers, one camera was installed on the rear of the vehicle; two cameras on the left side; and one camera on the front. The provided software allowed correlating video and GPS data.

Once the vehicle was equipped, a calibration of the references was performed. Three rectangles were delimited with traffic cones at known distances. Then, relative distances could be obtained from the video based on perspective restitution (18). Absolute distances were deduced using the GPS data.

The instrumented vehicle performed as an impeding car. Speed of the instrumented vehicle was controlled using cruise control and it varied between 50 and 90 km/h. For each highway section, several speed levels were fixed, according to the observed speeds of impeding vehicles during the previous study (Table 1). Therefore, the previous conditions were copied; so, no modifications on regular traffic flow were introduced. Speed of the impeding car was constant along the entire highway section; and so let faster vehicles pass. Drivers and passing vehicles’ data were collected by the co-driver. Age, gender, number of passengers, car model, and car plate were noted down; as well as the time of the passing maneuver.
Tests were performed during morning period between 9:00 a.m. and 2:00 p.m., on a working day and with good weather conditions.

**DATA REDUCTION**

Field data was processed in order to evaluate and estimate the different definitions of passing gap. Data obtained from the instrumented vehicle contained video images of both passing and opposing vehicles and positioning of the impeding (instrumented) vehicle. Each maneuver and the following process before it were identified with video images.

The time spent following began when a passing vehicle arrived behind the impeding vehicle or the last vehicle of the platoon, and the time gap between them was less than 2.5 s. This value was deduced for this paper after observing video data. Then, each passing gap was identified, measured and classified among the previously defined cases. When a platoon of vehicles was observed on the oncoming lane, only the gap against the lead vehicle was considered.

Different variables were evaluated directly from video images and GPS-position data, as defined previously:

- Acceptance or rejection of the gap.
- Time at the start of the gap or passing opportunity, $t_0$.
- Time at the crossing with next opposing vehicle, if it is visible, $t_d$.
- Time at the start of maneuver, $t_1$ (only for accepted gaps).
- Time at the end of maneuver, $t_3$ (only for accepted gaps).
- Position of the instrumented vehicle at each moment.

Dynamic gaps are easily measured by time difference between $t_d$ and $t_0$. Position of passing vehicle along the whole passing gap was estimated to calculate dynamic gaps when passing and opposing vehicle crossing took place outside the visible area. Relative position of the passing vehicle behind or in front of the instrumented car was obtained from video images by using perspective restitution software (18). Considering position GPS data of the impeding car, the position of the passing vehicle during the pass was deduced.

After that, the passing vehicle was placed in the highway section, and distances to the start of no-passing zones were calculated. Time to arrive to the start of no-passing zone was also calculated using that distance and the observed speed of the passing vehicle.

Trajectories of passing and opposing vehicles were extrapolated from the known data when $t_d$ was not visible. Then, static and dynamic gaps were deduced. Speed of passing vehicle could be obtained from collected video data only during the maneuver. From the end of the maneuver that speed was estimated by comparing it with the 85th percentile of free flow operating speed (assumed as desired speed). It was considered that if speed of passing vehicle during the maneuver was different to desired speed, this vehicle will accelerate or decelerate until it reaches that speed. Speed of opposing vehicle was estimated also by the 85th percentile of free flow operating speed. Estimation of speed of opposing vehicle represented also the same estimation process made by the driver which was about to pass, without information of the actual speed of that vehicle.

Continuous speed profiles were available on one of the road segments. They were collected by installing GPS-trackers on different vehicles for a previous research (19). On the other road segments, an estimation of speed profiles was carried out based on prediction models (19) and validated with observed spot speed data from the previous study (11).

In order to define virtual passing gaps, available sight distance along each point of every passing zones was estimated. A combination of high resolution aerial photography, video images from driver’s point of view, and GPS elevation data along the trips made by the instrumented car were used. Sight distance estimation was done on tangent sections where passing was allowed, according to marking and signing.

Once the available sight distance profile on each point was known, virtual passing gaps (both passing sight distance and static gaps) were obtained by calculation of trajectories of passing and virtual opposing vehicles. Every dynamic virtual gap ended when passing vehicle crossed with the virtual opposing vehicle.
ANALYSIS

Passing gap acceptance behavior of a sample of 103 maneuvers was analyzed according to the proposed methodology. A total number of 581 gap observations were considered, among accepted and rejected passing opportunities. Rejected gaps were only considered if the vehicle eventually performed the passing maneuver, which ensures the desire to pass of the sample of drivers. No aborted maneuvers were observed.

For each passing opportunity, the following variables were obtained:

- Time static gap between consecutive opposing vehicles, \(SG\).
- Time dynamic gap considering the next opposing vehicle, \(DG(t_0)\).
- Virtual dynamic gap considering an opposing vehicle which appears from the limit of available sight distance \(VDG(t_0)\).
- Time to end of the marked passing zone \(SDG(t_0)\).
- Passing distance gap considering the next opposing vehicle or the virtual opposing vehicle \(PSD(t_0)\).

Time dynamic gaps and distance gaps were also computed at the start and at the end of completed passing maneuvers: \(VDG(t_1)\) and \(VDG(t_2)\) when the gap was accepted.

For each gap, a comparison between the three possible dynamic gaps was made at \(t_0\): 1) dynamic gap until the next opposing vehicle \((DG)\); 2) virtual dynamic gap \((VDG)\); and 3) time to the end of the passing zone \((SDG)\). Figure 5 shows the different distribution of gaps. According to their cumulative probability distribution, the higher gaps were with a real opposing vehicle, rather than virtual gaps.

![Figure 5 Comparison between different types of accepted gap.](image)

In each case, the available dynamic passing gap was the minimum of the three possible gaps. In consequence, different distributions of accepted and rejected gaps were obtained if only the existence of opposing vehicle was considered, or if no-passing zones marking and sight distance limitations were included in the analysis.

Figure 6 shows the cumulative probability functions of acceptance or rejection of dynamic gaps (measured at the start of the gap, \(t_0\)). Acceptance (or rejection) cumulative probability at point X was defined as the probability to accept (or reject) a gap under X.
Dashed lines represent dynamic gap distribution considering only the next opposing vehicle on left lane, even if it was outside the visible area. Solid lines show the modified distribution, when virtual dynamic gaps and times until the end of the passing zone were considered. It means that solid lines represent the new proposed distribution of dynamic gaps.

According to Figure 6, the consideration of marking of no-passing zones and virtual opposing vehicles introduced a significant change in accepted and rejected passing gap distributions. If a gap was longer than the available sight distance, it will be replaced by the shorter of the equivalent virtual dynamic gap or the time until the end of the passing zone.

Gaps which were accepted by 50% of drivers are 8 s lower if sight distance restrictions and marking of no-passing zones were considered. Accepted or rejected gaps longer than 30 seconds were not significant in those cases, because sight distance was limited and longer gaps cannot be observed by drivers when they were on the highway. Equivalent analysis using distance gaps changed the passing sight distance accepted for 50% of drivers from 730 m to 575 m.

Accepted Passing Sight Distance can be related to existing marking criteria (14). According to these criteria based on the posted speed limit, passing zones starts if the sight distance was over 395 m on the studied roads. It was found that only 22% of drivers have accepted a distance gap under that value.

In addition to the represented passing acceptance and rejection functions, an evolution of dynamic gaps along completed passing maneuvers (also named time to collision) was analyzed. After the start of each accepted gap ($t_0$), times to collision at the start ($t_1$) and at the end ($t_3$) of the pass are represented in Figure 7.

Figure 7 shows the average behavior of the driver of a passing vehicle. White area is the time required to complete the maneuver. Light gray area shows the safety margin assumed by the driver, considering both real and virtual opposing vehicles, and the possibility of arriving to the end of the passing zone. This safety margin is the clearance time which will be measured after the distance travelled on the left lane and until the crossing with the opposing vehicle ($t_4$-$t_3$) or the arriving at the end of the passing zone.

If sight distance limitation and road marking were not considered, the safety margin would be increased by the dark gray area, which includes the accepted gaps measured when only an opposing vehicle.
vehicle was considered. Therefore, an extra safety margin, which cannot be ensured, is assumed because an opposing vehicle could appear from the limit of available sight distance at any time.

**FIGURE 7 Evolution of dynamic gap along a single passing maneuver.**

**CONCLUSIONS AND FURTHER RESEARCH**

Passing gap acceptance has been analyzed from a new approach. The presented methodology includes new factors to the study of passing process, in order to explain its actual conditions along two-way two-lane rural roads. The methodology was applied to observed field data of three different road segments.

A passing maneuver is affected only by opposing traffic if the passing zone is very long and there is no sight obstruction. But, in most cases, rural highways do not accomplish those conditions and other factors are affecting the passing process.

Design and marking criteria consider the effect of limited sight distance, in order to establish the location of no-passing zones. However, these criteria are not always based on an experimental observation of the process.

Some past studies about passing gap acceptance have only considered unlimited sight distance conditions and have presented an acceptance or rejection probability in order to calibrate a model of passing decisions or to estimate the critical gap. Moreover, those studies were usually based on driving simulators. The proposed approach is applied to collected data from existing rural highways.

The results have shown how probability distribution changes if the real conditions of highways are considered. Longer accepted gaps can be measured but they cannot be observed by the drivers which want to pass. Consequently, these longer gaps are replaced by its corresponding virtual gaps, if a vehicle appears from the limit of available sight distance at any time. In addition to a possible appearance of an opposing vehicle, the sign which indicates the end of a passing zone has an influence on the passing decision. Drivers could not accept a gap if a no-passing sign is visible and it is not enough distance to complete the maneuver. With these considerations, a passing gap which is accepted by 50% of drivers decreases from 24 to 16 s. Higher differences were found between gaps over the 50% of probability of acceptance.
The new proposed gap acceptance distribution affects the calculation of critical gaps, which are used commonly to study the traffic operational characteristics of highways. By taking into account the actual conditions of the road, the critical gap is reduced significantly.

On the other hand, if sight conditions are not included in the analysis, unrealistic safety margins would be considered in maneuvers completed without the presence of a visible opposing vehicle. Time to Collision (or dynamic gap) can be computed also on those maneuvers, which may be potentially unsafe.

Moreover, against PSD models typically used as design and marking criteria, this approach considers a real or estimated (from actual data) speed of opposing vehicles, which is usually different from design speed or posted speed limits.

The purpose of the paper was the establishment of a methodology. In consequence, results are not ready to be directly applied to review or formulate new design or marking criteria. Sample size will be in further work significantly increased. This would allow calculating and analyzing the influence of different factors, such as age and gender of the driver of passing vehicle, or time spent following before the passing maneuver is performed.

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