Passive railroad-highway grade crossings

Relevant human factors and effects of safety measures

Søren Underlien Jensen

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Trafitec
Research Park Scion-DTU
Diplomvej 376
2800 Kongens Lyngby
Denmark
www.trafitec.dk

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Executive summary

Empirical knowledge about human factors related specifically to road users at passive railroad-highway grade crossings with fast trains is very limited today. There exists no precise information about:

- Road users judgment of speed and distance of trains,
- road users acceptance and rejection of lags to trains (time-to-arrival), and
- real clearance times for motorized vehicles, especially for large trucks and agricultural vehicles with trailers at passive railroad-highway grade crossing of different gradients and pavement type and quality.

There is no doubt that road users underestimate train speed, when it runs more than 30-40 mph. But the significance of this underestimation is unknown in relation to the accident rate at passive railroad-highway grade crossing, where trains run 60-75 mph. Road users percentual underestimation of trains time-to-arrival at grade crossings become larger the closer trains are at crossings. This is due to systematic illusions within the human vision.

It is unknown whether perceptual fix points like signs along the rail line, ditch lights on trains or train design may reduce the underestimation of train speed and its influence on accident rate. Ditch lights on trains reduce the rate of accidents at passive grade crossings, but whether this is due to better recognition of train presence or better judgment of speed and distance is also unknown.

Danish standards for passive railroad-highway grade crossings appear inexpedient in poor sight conditions due to weather like fog, heavy rain, etc. Current Danish standards for sight distances are shown in section 2.3. The sight distance standards are not obeyed at several passive railroad-highway grade crossings, even far from.

If passive railroad-highway grade crossings are to exist in many years ahead then it would be relevant to know the basic relevant human factors in order to set up more cost-efficient safety measures. It is also relevant with regulatory guidelines for train speed if sight distances are not obeyed and during poor sight conditions due to weather.

The literature shows that several technical safety measures exist, which actually improve safety at passive railroad-highway grade crossings. Even driveways and dirt roads with poor pavement conditions are possible to make safer at railroad grade crossings at low costs e.g. by creating a perpendicular crossing, reducing gradients, increasing sight distances, etc. Besides technical safety measures, both campaigning and education may improve safety at grade crossings.

1. Introduction

The purpose of this literature study is to describe road users' judgment of speed and distance, especially in relation to trains at passive railroad-highway grade crossings. Passive crossings have no active traffic control devices like flashing light signals, automatic gates and traffic control signals. The study also includes references to improve safety at passive railroad-highway grade crossings. During the study it has been found natural to include other topics like accepted / rejected lag to trains, clearance times and accident models. The study is based on recent literature on these topics. The Danish Road Directorate has initiated and financed this study with a particular interest in getting situations with trains running 60-75 mph described.

Road users' combined judgment of speed and distance is often studied on the basis of time intervals. Such studies often measure differences between road users perceived and the actual ”time-to-contact” (TTC).

TTC is the time an object like a train or a car needs to run in order to hit you under the assumption that speed and direction of the object is kept constant. TTC refers sometimes to ”time-to-collision”. Road users' ability to control TTC and thereby avoid an accident depends among others of their skill to judge speed and distance.

The road user actually judges / perceives TTC both for him self and for the counterpart in many cases. At a passive railroad-highway grade crossing the road user must judge both his owns' and the trains' TTC, i.e. time needed to get to the actual crossing / area of conflict. The counterpart, i.e. the train, time interval to the crossing is often referred to as the ”time-to-arrival” (TA).

There are two very different situations in relation to road users' crossing of a passive railroad-highway grade crossing. One situation is when a road user is driving or riding before the crossing. The other situation is when a road user starts from a standstill at the crossing.

The driving or riding road user is very dependent of sight conditions before the passive railroad-highway grade crossing. This road user must assess the needed time interval to get to and cross the railroad. In this situation there may arise the dilemma, where the road user must decide for an evasive braking maneuver or to continue possibly speeding up in order to cross before the train arrives. These situations primarily occur at passive crossings without closed manual gates but with long sight distances to trains seen from approaching road users. These situations are according to Danish standards only allowed at passive railroad-highway grade crossing with train speed of maximum 47 mph.

From a standstill the situation is different. Here are no dilemma zone situations. The road users’ judgment of the time to cross the railroad is very different. It may for some be more difficult, because it involve start-up, acceleration and movement out of conflict area instead of a constant speed over a judged distance. The road user view is also different, because only the sight conditions close to the railroad are important. Situations with crossing road users from a standstill often occur at passive railroad-highway grade crossings secured with manual gates, which often occur at train speeds of 47-75 mph in Denmark.

In both situations, moving and standstill, a number of topics are interesting:

- ”Lag acceptance” (LA), i.e. acceptance or rejection of lags (time interval) before train arrival. Similar to gap acceptance at intersections.
- ”Base critical lag” (BCL), which is an expression for a lag time interval that an equal number accept and reject.
- ”Clearance time”, which also is called ”time-to-line-crossing” (TTLC). TTLC is the time interval needed to cross the conflict area.
- ”Safety margin”, which is the time interval from a road user has left the conflict area and to a train arrives to the conflict area.

LA at railroad-highway grade crossing are different compared to intersections, because a trains brake distance is much longer than cars, and the engine driver may only avoid the collision by braking or whistling the train horn. A road users underestimation of TTLC or overestimation of TA in relation to LA is therefore not a critical at an intersection compared to a railroad-highway grade crossing.

2. Human factors at grade crossings

No studies of judgment of speed and distance of trains have been found. Nor has such studies of cars driving considerably more than 50 mph been found. This means that no precise results of judgment of speed and distance at passive railroad-highway grade crossings with trains running 60-75 mph can be shown.

There are studies of judgment of speed and distance to cars driving 20-50 mph in real traffic, simulators and experimental trials. In the forthcoming is the most relevant information of these studies elaborated. Besides judgment of speed and distance are relevant clearance time, lag / gap acceptance studies, etc. mentioned.

2.1 Judgment of speed and distance

More than 20 years ago Leibowitz (1985) a respected research of human visual perception hypothesized about the many accidents at railroad-highway grade crossing. Leibowitz claimed that speed of large objects like trains was underestimated by the observers due to a normal deficiency of human visual perception. It was proved later on the basis of experimental trials that Leibowitz actually was right (Cohn and Nguyen, 2003).

The relation between object size and misestimating of speed is just one of many systematic illusions that are part of visual perception. Based on many dozens of studies of visual perception Changizi et al. (2006) show that it is possible to systematically organize more these illusions and they demonstrate that …

1) smaller sizes,
2) slower speeds,
3) greater luminance contrast,
4) farther distance,
5) lower eccentricity,
6) greater proximity to the vanishing point, and
7) greater proximity to the focus of expansion,

… all tend to have similar perceptual effects, namely to …

A) increase perceived size,
B) increase perceived speed,
C) decrease perceived luminance contrast, and
D) decrease perceived distance.

This way there exists seven times four or 28 systematic illusions. On the basis of this and studies of judgment of speed and distance in road traffic one may say that a large and fast train running 60-75 mph will …

- seem smaller than it is,
- seem slower than it runs, while
- distance to the train presumably is reasonably correctly perceived.

Overall this leads to road users' overestimation of the train's time-to-arrival, TA, to the crossing. This overestimation of TA will increase with higher train speed. In other words, the risk (both accident rate and severity) will increase the faster the train runs. Accident models also show that this is true.

Carthy et al. (1995) conducted a series of video experiments with 181 participants who were to judge time-to-arrival of cars respectively 20 and 60 meters away and driving 20, 25, 30, 35, 40 and 45 mph. The experiments were performed by letting a seven second video clip go to black screen precisely when the car on the screen was 20 or 60 meters away. After this the participant had to push a button at the moment when he perceived the car to be right in front of him. It turn out that participants were fairly poor to judge speed of the cars but better to judge distance to the cars. The participants judged TA of cars correct when they drove 20 mph at a 20 meter distance, but overestimated TA by about 1 second when cars drove 45 mph at the same distance. At a 60 meter distance TA was underestimated by about 3.1 seconds with 20 mph fast cars, but overestimated by 1.3 seconds with 45 mph fast cars. The study is therefore in line with the previous mentioned systematic illusions. Participant skills to judge speed and distance were primarily related to the mathematical-spatial intelligence. If judgments of 60 and 75 mph at a 60 meter distance were performed, then TA would probably been overestimated by 1.5-2.3 seconds at 60 mph (corresponds to an error of 42-64 meters) and 1.8-2.5 seconds at 75 mph (60-83 meters). This is due to a tremendous underestimation of the cars speed.

2.2 Base critical lag and clearance time

David Ragland at University of California at Berkeley is currently conducting a study of base critical lag (lag acceptance / rejection) at railroad-highway grade crossings. However, it has no been possible to obtain preliminary results.

An American study (Zwahlen and Schnell, 1999) gives empirical values for how close cars pass in front of trains. Two new signs respectively Buckeye Crossbuck and Standard Improved were compared to the Old Crossbuck in this before-and-after study. Locomotives were to use the horn when the train was 1,600 feet away from the passive railroad-highway grade crossing to the train reached the crossing. Video cameras filmed onboard the trains when the horn was activated. Many trains runned relatively slow, and some cars passed the crossing illegally while the horn whistled. A few cars passed the crossing just 2 seconds before train arrival. TA was less than 20-26 seconds for half of the illegal passages depending on type of sign, i.e. this may be interpreted as base critical lags. The paper authors stated that they have proven that the new signs were better than the Old Crossbuck, because a smaller share of the cars passed at small TA. However, viewing the actual figures it seems that this is primarily due to a lower minimum speed of trains in the after period with the new signs compared to the before period with the Old Crossbuck.

The above study illustrates the important phenomenon “false alarms” or “cry wolf” in relation to passive railroad-highway grade crossings. Locomotive horns will in the above situations be perceived as a signal, which indicate that trains are far both in distance and time from the crossing, because road users’ experience is that the horn whistles long time before the train arrives. It’s the same case when warning bells or flashing light are activated too long time before train arrival.

The locomotive horn is only used as a short whistle in Denmark, not a very long whistle all the way to the crossing as in USA. A short whistle results in only few noise nuisances for neighboring residents while it may be difficult to judge direction of. The whistles may not necessarily be heard by road users especially by drivers of agricultural vehicles, where health and safety at work acts sometimes rules the use of hearing protection, and in cars with loud music. A short whistle creates the same cry wolf phenomenon as a long whistle.

To cross a road or a railroad may be split into a set of different processes, e.g. observation-judgment-decision-start up-acceleration-driving. The process time depends on many issues such as the persons’ cognitive, perceptual and psychical skills and the vehicles’ acceleration performance.

Responsetime or reactiontime, which include both time for observation, judgment and decision, may vary very much from split second response to processes including long hesitation. Oxley et al. (2005a) found in a simulator study that roadcrossing pedestrians’ responsetime varied from 0.15 to 8.01 seconds. The variance and average of responsetime became greater with increasing pedestrian age. Pedestrians during one’s working life accept gaps in traffic, which are of a shorter distance, compared to older pedestrians. But the older pedestrians are much poorer judging the speed of cars and their on time-to-line-crossing, i.e. time spent to cross the road, compared to younger pedestrians. Therefore the safety margin between the car and pedestrian is smaller among older pedestrians especially at high car speeds, at wide roads and for cars running at the far side of the road. Children are also poorer judges of car speed compared to adults (Connelly et al, 1998).

Time used for start-up and acceleration does vary from action to action and from person to person. In another simulator study of cyclists crossing of roads Plumert et al. (2004) found that 10-year-olds used more time on start-up and acceleration than 12-year-olds who then again used more time than adults. At the same time the variation in time used for start-up and acceleration was largest among 10-year-olds and smallest among adults. Acceleration was more powerful and lasted longer among adults who also cycled faster than children. The study showed that children's base critical gap was the same as adults regardless of car speed. This means that cycling children's safety margin is smaller than adults when they cross roads, because of their less powerful acceleration and slower speed.

There have been made many studies of children, adults and elderly base critical gap, responsetime, start-up time, acceleration and speed in relation to crossings of roads. It will be too extensive to mention all in the manner as above. Instead is a short synthesis proposed. The synthesis is based on the following references: Carthy et al. (1995), Connelly et al. (1998), Jensen and Hummer (2002), Middleton et al. (2004), Oxley et al. (2004; 2005a; 2005b), Plumert et al. (2004), Schiff et al. (1992), Scialfa et al. (1991), and also Vaughan and Bain (2001).

Children's and elderly traffic performance is poorer than adults, which primarily is due to their shorter safety margins. But backgrounds for the poorer performance are very different. Children's skills and experiences in relation to traffic are not fully developed, and that leads to poorer performances. The variation in performances between children is as modest as adults, but individual children are more unstable in performance than adults, and therefore the variation in performances is larger among children compared to adults.

Elderly poorer traffic performance is primarily due to failing skills among a group of the elderly, which as a share of population increases with age. The individual older persons failing skills also increase in magnitude with age. Variation in performances among elderly is therefore larger compared to adults. The performance among elderly with severe failing skills is also more unstable, which primarily seems to be caused by impatience in relation to a long base critical gap – which is shorten in frustration by selecting too short gaps, because there is too long time to a adequate gab that fits their perceived needs for a safety margin. It seems that differences in performance are larger between adults and elderly on foot and bicycle than in cars presumably because elderly with severe failing skills do not drive cars.

The base critical gap of elderly in cars depends on speed of counterpart cars and the situations complexity. In simple situations with high counterpart speeds an older car driver selects shorter gaps than a young or middle-aged driver. The opposite is true at low speeds in complex situations.

Transport mode and age	Gap in meters	Responsetime	Time for start-up and acceleration	Speed
Walking – children	Longer	Longer	The same	Slower
Walking – elderly	Longer	Longer	Longer	Slower
Bicycling – children	The same	The same	Longer	Slower
Cycling – elderly	Longer	Longer	Longer	Slower
Car driving – elderly	Shorter-longer	Longer	Longer	The same

Table 1. Synthesis of children's and elderly performances relative to adults in relation to crossing a road.

If Table 1 is viewed in relation to passive railroad-highway grade crossing with train speed of 60-75 mph then perhaps especially older drivers have problems, because they heavily underestimate train speed in this simple situation and choose smaller lags than other road users and they use more time for start-up and acceleration. But it might be that older car drivers compensate more for their failing skills at passive railroad-highway grade crossings.

2.3 Sight distances

The Danish standards operate with clearance times of 18 seconds for road traffic and 12 seconds for path traffic (pedestrians and bicyclists) at railroad-highway grade crossings (Road Directorate, 1993). This gives the following minimum requirements for sight distances along railroad from crossing (7 meters from the nearest rail):

Train speed	Roads	Paths
47 mph	375 meters	250 meters
56 mph	450 meters (408 meters)	300 meters
62 mph	500 meters (453 meters)	350 meters
75 mph	600 meters (544 meters)	400 meters

Table 2. Sight distances along railroad from crossing according to Danish Standards (Road Directorate, 1993). Comparable American sight distances in brackets.

Basis for clearance times and sight distances is not explicitly given in the Danish standards. However sources behind the standards state that 18 second clearance time for road traffic was calculated by Danish State Rail on basis of trails driving with agricultural vehicles. The calculation make use of an 18 meters long vehicle with an acceleration of 1 m/sec^2, which starts 7 meters in front of the nearest rail and the must pass the latest rail by 10 meters with the vehicle's rear end.

The American standards operate with slightly different sight distances (AASHTO, 2001). The shown sight distances in Table 2 corresponds to a clearance time of 16.3 seconds and is calculated on the basis of a 20 meters long truck.

If we consider paths it is reasonable to say that the older pedestrian determines the sight distances. A reasonable set of times and speed would be:

- response and start-up time: 2.5 seconds
- walking speed: 1.0 meter /second

On 12 seconds the slow older pedestrian will only walk 9.5 meters.

It is important to state that even though road and path users misjudge the trains time-to-arrival, TA, it should not influence the choice of clearance times and sight distances, because road and path users underestimate train speed. If they on the other hand overestimated train speed it would improve safety to operate with longer clearance times and sight distances.

It is not possible at the current state to assess the clearance time and sight distance for road traffic. Clearance times will probably heavily depend on e.g. pavement quality and gradients. It is therefore necessary to conduct new drive trial in order to reassess the basis.

In foggy weather the sight conditions are poorer leading to a greater proximity to the vanishing point, which then leads to a more correct estimation of train speed. However the very long sight distances is a problem in fog, which results in safety problems if measures are not taken, e.g. lower train speed, use of locomotive horn or temporary closure of passive railroad-highway grade crossing.

3. Risk studies and safety measures

This section focuses on studies of selected safety measures and risk studies, which show differences in accident rate depending on railroad-highway grade crossing layout and traffic control.

3.1 Risk studies

The risk at the various types of railroad-highway grade crossings is very different according to Cedersund (2006), see Table 3. The Swedish study in Table 3 does not take into account the non-linear relationship between accident rate and traffic flow. Intersections with much traffic have a lower accident rate than intersections with less traffic. Cedersund later state that two of three railroad-highway grade crossings have been closed or transformed into grade separated crossings within the past 25 years. The type of grade crossing was in the same period changed in most remaining grade crossings. And lastly the accident rate has diminished for the individual type of railroad-highway grade crossing over the years.

Type of railroad-highway grade crossing	Rate 1973-1977	Rate 1999-2004
Automatic fully skirted gates	0,53	0,20
Half gates	1,10	0,27
Warning bells and flashing lights	10,41	9,01
Signs	34,31	23,97
Unregulated	-	25,06

Table 3. Accident rate at railroad-highway grade crossings - number of accidents divided by number of cars and trains (Cedersund, 2006).

The *Railroad-Highway Grade Crossing Handbook* (Tustin et al., 1986) shows the developments in American accident models for railroad-highway grade crossings. *Peabody Dimmick Formula* from 1941 is a relationship between the expected number of accidents in a 5-year period on one hand and volumes of cars and trains and additionally a protection coefficient on the other hand. The relative risk at different types of railroad-highway grade crossing can be determined by the protection coefficient; signs (0.61), bells (0.56), flashing lights (0.46) and automatic gates (0.37). Automatic gates were in 1941 only about 1.6 times safer than signs (Old crossbucks).

The *New Hampshire Index* was a more complex accident model. The protection coefficient was also different; signs (1.00), flashing lights (0.20-0.60) and automatic gates (0.10-0.13). The automatic gates were in this model about 10 times safer than signs.

NCHRP 50 Hazard Index from 1968 is simpler and looks like accident models known from road traffic. The protection coefficient is; signs (3.06 in urban areas and 3.08 in rural), flashing lights (0.23 in urban areas and 0.93 in rural) and automatic gates (0.08 in urban areas and 0.19 in rural). The automatic gates were in this model 38 times safer than signs in urban areas and 16 times in rural areas.

The latest American model is the *USDOT Accident Prediction Equations*. This three step model does not operate with protection coefficients. Instead models for specific types of railroad-highway grade crossing are used, and it is therefore not possible to directly list a relative risk for the various types.

Oh et al. (2006) describes a Korean accident model for railroad-highway grade crossings. The model shows among others that speed humps on the road prior to the crossing resulted in fewer railroad-highway accidents.

Another model by Austin and Carson (2002) shows that trains during nighttime, pavement type and layout between rails, road markings, traffic light signals and warning bells have an influence on accident rate.

3.2 Single safety measures

This section shows safety effects related to measures implemented at railroad-highway grade crossings based on a number of sources and studies.

Washington and Oh (2006) indicate effects of 18 measures on the basis of 32 studies. Table 4 shows effects of 9 relevant measures.

Safety measure	Safety effect
Speed hump (speed reducing measure on the road)	36-40 %
Creation of a perpendicular railroad-highway crossing	29-45 %
Prewarning of railroad-highway crossing	0-50 %
Reduction in road gradients at railroad-highway crossing	39-47 %
Longer sight distance along highway from crossing	0-50 %
Longer sight distance along railroad from crossing	10-41 %
Construction of pedestrian gate	0-50 %
Construction of road lighting	15-45 %
Stop signs	38-46 %

Table 4. Mean effects of safety measures at railroad-highway crossings shown as a percentual decrease in accident rate. (Washington and Oh, 2006)

Saccomanno et al. (2006) also indicate effects of 18 safety measures based on 91 previous studies. Table 5 shows safety effects of 14 relevant measures.

Safety measure	Safety effect
Grade separation / closure	100 %
Yield sign	19 %
Stop sign	35 %
Stop ahead sign	35 %
Stop line sign	28 %
Illumination – road lighting	44 %
Pavement markings	21 %
From signs to flashing lights	54 %
From signs to 2Q-gates	72 %
Installing traffic signal	64 %
Elimination of whistle prohibition	53 %
Improve sight distance	34 %
Improve pavement condition	48 %
Reduce posted speed limit	20 %

Table 5. Mean effects of safety measures at railroad-highway crossings shown as a percentual decrease in accident rate. (Saccomanno et al., 2006)

A study from New Zealand of four types of safety measures in relation to railroad-path grade crossings was done by Lobb et al. (2003). The safety measures purpose were to reduce boys' illegal crossing of railroads on the journey to and from school. The measures were respectively awareness campaigns, education, punishment for every unsafe crossing (continuous punishment – Friday detention) and punishment occasionally for unsafe crossing (intermittent punishment). The number of illegal crossing was reduced slightly by awareness campaigns (about 13 %), whereas the reduction implementing the other three safety measures was statistical significant with drops in illegal crossings of 35, 76 and 69 % respectively using education, continuous and intermittent punishment.

Mok and Savage (2005) describe effects of a series of measures. The estimation of safety effects is based on analyses of the railroad-highway accident developments in USA 1975-2001 and is therefore related to large uncertainties. The study shows that two-fifths of the decline in accidents and fatalities and railroad-highway grade crossings is due to a general improvement in safety such as reduced drunk driving, wider use of safety belts, safer vehicles, etc. A fifth of the decline is due to installation of gates and / or flashing lights. The Operation Lifesaver public education campaign and the installation of ditch lights each led to about a seventh of the decline in accidents and fatalities. Finally may the last tenth of the decline be due to closure of railroad-highway grade crossings. The authors transform this into effects of the safety measure. Closure of 10 percent of the railroad-highway grade crossing will lead to a decrease of 5.1 percent in accidents and 2.7 percent in fatalities. The explanation for the lower safety benefits than 10 percent is that closure of crossings leads to accident migration to other crossings nearby. Installation of gates and flashing lights reduce accidents and fatalities by respectively 48 and 31 percent. Operation Lifesaver has resulted in a reduction of 15 percent in accidents and 19 percent in fatalities at all railroad-highway grade crossings. The corresponding figures for ditch lights are respectively 29 and 44 percent.

Noyce and Fambro (1998) evaluated a prewarning sign with strobe light, which was activated by driving cars. The sign warning about the railroad-highway grade crossing ahead and a supplemental sign stated ”Look for train at crossing”. The strobe light was placed above the sign. The sign was placed 175 meters from a crossing in Texas, USA. The loop detector, which activated the strobe light for 8 seconds, was placed 170 m before the sign. At the crossing there was both before and after the change an Old crossbuck sign. The evaluation shows that car speed was reduced particularly at nighttime and at a distance of 50-200 meters from the crossing. The authors believes on the basis of a behavioral and questionnaire survey amongst drivers that the sign and strobe light has increased drivers awareness of the crossing and caused drivers to approach the crossing with more caution especially at nighttime.

The use of locomotive horns at night at railroad-highway grade crossings was prohibited for certain trains in Florida, USA. The prohibition led to increases of 140-280 percent in nighttime accidents at the crossings (FRA, 2000). Later studies show that prohibition of use of locomotive horns in daylight led to increases of respectively 84 and 62 percent (FRA, 2000). Locomotive horns often result in major noise nuisances for the railroad neighbors. A study of automatic horns placed at the railroad-highway crossing instead of on the locomotive shows that it is possible to lower noise nuisances considerably (Gent et al., 2000). Another report shows that crossing horns, which whistle 17 seconds before train arrival, instead of locomotive horns, actually lower noise nuisances by 65-85 percent and reduce the number of illegal crossings by road users while the horns whistle with 68 percent (Raub and Lucke, 2003).

Stephens and Long (2003) evaluated supplemental x-box pavement markings applied at locations near signalized intersections, where it is hazardous or inexpedient to stop especially for long vehicles. The evaluation shows that x-box markings reduced stops at these locations by 36-39 percent and reduced stops on crossings and rails by 42-60 percent.

Ward and Wilde (1995) studied effects of stop signs at passive railroad-highway grade crossings. The study shows that car speed was reduced and drivers spend more time on looking for trains especially about 20 meters from the crossing after the stop signs were installed. The share of drivers that stopped at the crossing remained unchanged.

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