This is the accepted version of the publication Qian Meng, Li-Ta Hsu, Integrity for autonomous vehicles and towards a novel alert limit determination method, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering (Volume 235 Issue 4) pp. 996-1006. Copyright © 2020 IMechE. DOI: 10.1177/0954407020965760

Integrity for Autonomous Vehicles and Towards a Novel Alert Limit Determination Method

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Abstract. Integrity is one critical performance indicator for navigation in safety-critical applications such as autonomous vehicles. Alert limit is one of the representive parameters in integrity monitoring which defines the maximum tolerable positioning error for an operation to safely proceed. But the integrity requirements for global navigation satellite system (GNSS) assessment are quite different from those for other applications. For autonomous vehicles, a reasonable alert limit needs to ensure the vehicle security and take full advantage of the space between vehicle and lane as much as possible. Based on the analysis of integrity application differences from civil aviation to autonomous vehicles, an improved alert limit determination method is proposed in this paper. The kinematic model is firstly introduced into the online determination of alert limit. The integrity risk on two sides are allocated optimally respect to the road geometry and kinematic model. The fixed cuboid bounding box is replaced by a subversive fan-shaped bounding box which is more reasonable to cover the safety-critical areas. The discussion compared with the Ford model also verified the superiority of the proposed method. Finally the paper also gives the alert limits calculated based on the Chinese standards and hopefully it could provide some references for the navigation integrity assessment for autonomous vehicles.

Keywords: Integrity; Autonomous Vehicles; Alert limit; Navigation.

1. Introduction

Autonomous vehicles are the next technology revolution in transportation and will greatly improve the safety, efficiency and intelligence. However the complexity and diversity of surrounding environment aggravate the requirements for monitoring and controlling [1]. In order to promote the progress steadily, Society of Automotive Engineers (SAE) [2] suggests six levels for driving autonomy, which is shown in Figure 1. From Level 0 to Level 2, the driver needs to be responsible for monitoring and controlling the vehicle all the time though some automated features or functions have been involved in the system. It is a milestone from Level 2 to Level 3 as the driving system starts to replace the driver to monitor the environment and control the vehicle in certain circumstances. Starting from Level 4, the role of autonomous system exceeds that of driver clearly. Level 5 is full automation, which is the final target of autonomous vehicles. The system is capable of performing all dynamic driving tasks all-time and all-circumstance. From lower level to higher level, the autonomy is growing up while the ability and obligation of driver is constantly decreasing.

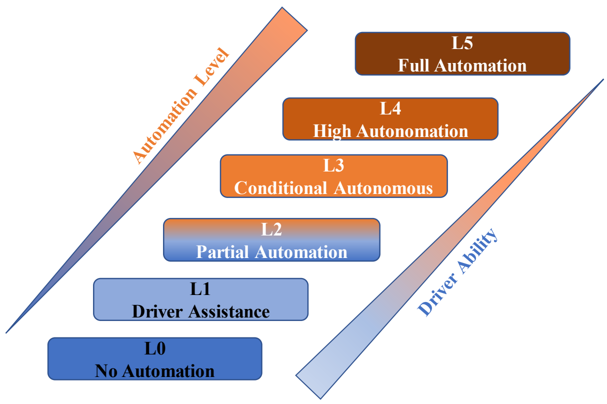


Figure 1 Society of Automotive Engineers (SAE) levels of road vehicle autonomy

With the growing levels of autonomy, the requirements of autonomous vehicles on navigation become much more stringent than traditional applications. Particularly for traditional applications, the navigation system is an assistant tool for the human rather than a decision system. The navigation doesn't need to be responsible for the safety and reliability of positioning results. Applications such as autonomous vehicles of Level 3+ is defined as safety-critical application in positioning, navigation and timing (PNT). To make its way towards production-ready maturity, most automobile manufacturers and research institutes are committed to an extremely accurate, robust, and reliable navigation system to guarantee the mission accomplishment and operation safety [3, 4].

As autonomous vehicles require decimeter-level even centimeter-level positioning accuracy, most of the current researches focus on the robust and reliable navigation solution based on multi-sensor[5, 6]. It results that the performance assessment system is got less attentions in above safety-critical application. To some extent, the navigation safety requirements are much more important as they determine the status of safety and define the performance of sensor solutions at scale [7, 8]. Besides the accuracy, integrity is another representative indicator among navigation applications. Different from the traditional fault detection technology, integrity puts more emphasis on the measure of trust that can be placed in the correct position and the ability to provide timely alert when the navigation system should not be used for navigation. Integrity was firstly introduced in global positioning system (GPS) and accepted by the civil aviation as one of the crucial criteria for satellite navigation system [9, 10]. The corresponding concepts such as probability of hazardous misleading information (PHMI), alert limit (AL) and protection level (PL) are defined and used for integrity evaluation. Actually as a representative quantifiable criterion, integrity has been introduced and researched in many fields.

Based on the successful and mature application in civil aviation, the definition of integrity risk and protection level have been initially introduced into autonomous vehicles to evaluate the safety [11, 12]. However as mentioned above, most of the research literatures focus on the user algorithms to meet the integrity requirements while the integrity requirements are transplanted from the civil aviation easily. The research on integrity requirements of autonomous vehicles attracted less attentions [13]. Especially the application differences such as driving scenario, integrity requirements, navigation information are not analysed in detail. The detailed algorithm and solutions are full of uncertainty. For example, the principles for alert limit determination are almost not mentioned in the current papers. Only the localization requirement model proposed by the Ford Motor Company (referred to 'Ford model' hereinafter) introduced a baseline method for evaluate the alert limit [14].

The Ford model exactly did pioneer work in integrity for autonomous vehicles. However the principle of baseline method is still slightly limited in civil aviation. The Ford model made full use of bounding box in global navigation satellite system (GNSS) position of civil aviation. A fixed cuboid box is defined for allowed position error and the corresponding protection levels are then determined. The mode needs to find a trade-off between the lateral and longitudinal alert limits. It is easy to understand that the balance needs to fall to the lateral component as it is more stringent. However, different from the civil aircraft, whose trajectory is smooth and the route in flight is relatively vast, the challenge that autonomous vehicle facing is the complexity and limitation of lanes. In most cases, the width of lane is less than 4 meters. With the road curvature increasing, the size of the cuboid box the lane can contain is drastically decreased. Actually the size of box is severely limited in curved road, resulting in a more restrict and conservative alert limits in final vehicle operation. But for integrity, conservative alert limits will affect the availability of navigation system. What's worse, the model results show that the vehicle have to drive off the centerline in curved road and close to the inner side to guarantee the biggest box. The added complexity and uncertainty to the control and navigation system make the loss outweighs the gain. Last but not least, the difference in vehicle kinematic model is not considered in Ford model.

A comprehensive and detailed review of integrity application differences between civil aviation and autonomous vehicles is given in this paper, which has never been concluded from the aspect of user algorithm in the existing literature to the authors' knowledge. Based on that, a novel online alert limit determination method is proposed to improve the weakness of the current research. The vehicle kinematic model is introduced into the integrity evaluation firstly and the fan-shaped bounding box is pioneered to improve the integrity risk allocation. The discuss results are encouraging for the decimeter-level positioning requirements in autonomous vehicles. Section 2 describes the significance of integrity and the alert limit for safety-critical navigation application. Section 3 gives the review of integrity application differences and difficulties between civil aviation and autonomous vehicles. Section 4 proposed the online alert limit determination method enhanced by the kinematic model. Section 5 compares and discusses the alert limit performance of the proposed and baseline Ford model under different vehicle types and road grades. Section 6 is the conclusion.

2 Integrity Risk Evaluation in Civil Aviation

Since little literature talked about the significance and importance of alert limits, even the differences between integrity and accuracy or fault detection. In this section, we'll start from the integrity requirements for the navigation system and analyze the impact of alert limits on integrity risk evaluation.

2.1 Integrity Requirements for Navigation System

Integrity, including accuracy, continuity and availability, are all representive performance indexes for navigation system. Their relationship is shown in Figure 2. There exists layer upon layer relations between each other. For integrity evaluation, the promise is that the accuracy of navigation results should meet the requirements firstly. The continuity of a system is the ability of the total system to perform its function without interruption during the intended operation. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation. The availability of a navigation system is the percentage of time that the services of the system are usable by the navigator. Availability is an indication of the ability of the system to provide usable service within the specified coverage area. Signal availability is the percentage of time that navigation signals transmitted from external sources are available for use. It is a function of both the physical characteristics of the environment and the technical capabilities of the transmitter facilities [15].

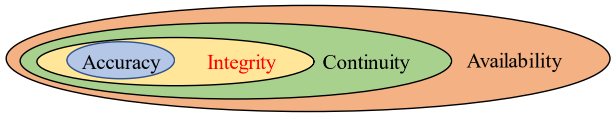


Figure 2 Performance requirements for navigation

Both the accuracy and integrity focus the positioning errors in a certain probability. For example, as shown in Figure 3, we often define the required accuracy as the biggest position error in 95% time which corresponds to 2σ in normal distribution. Integrity risk is a much stricter probability which is defined less than 10^{-7}~10^{-8} in most cases.

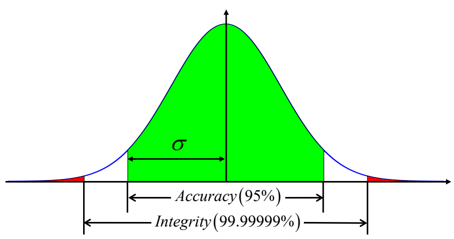


Figure 3 Relationship between accuracy and integrity

However it does not mean that integrity is a stricter accuracy in positioning results. They have obvious distinctions in function implementation.

Firstly, integrity is an index that focuses on safety-critical application. Compared to the accuracy which focuses on the best 95% test statistics (shows as the green part in the figure), the integrity risk emphasizes the impact of vehicle on hazardous situations due to the navigation system (as shown as the red part in the future). The probability of this scenario is pretty small but the impact is unacceptable for human safety.

Secondly, it is a difference between offline and online. For navigation system or sensors, accuracy is a performance index that tested and determined offline before use. Integrity is a criterion of real time online processing for particular operations. Accuracy determines whether we use this navigation system for this application. Integrity determines whether we rely on the navigation results at this epoch during this operation.

Finally, integrity includes the function of fault detection and exclusion and the ability to provide alarms when the navigation results are not reliable. Accuracy doesn't include such functions. Last but not least, the performance of integrity also affects the performance continuity.

2.2 Alert Limit in Integrity Evaluation

As we mentioned in above subsection, integrity risk emphasizes the impact of vehicle on hazardous situations due to the navigation system. For specific operation, integrity risk $PHMI$ is defined as the probability of providing a normal operation signal that is actually out of tolerance without warning the user in a given period of time. Here the maximum tolerable positioning error for an operation to safely proceed is called alert limit. Correspondingly the protection level is a statistical error bound computed to guarantee the probability of error exceeding the bound is smaller than the defined integrity risk [16]. So the integrity risk bounded by the protection level can be expressed as:

$$P\left(\left|\hat{\mathbf{X}}-\mathbf{X}\right| > AL \& PL < AL\right) \leq PHMI \tag{1}$$

where $\mathbf{X}$ and $\hat{\mathbf{X}}$ are the actual position and estimated position, respectively. The above equation is also the basic principle for integrity evaluation.

The classical Stanford diagram lists the relationship between PL, AL, and positioning error (PE), which is shown in Figure 4. As in the circumstance $PL > AL$, the system will always trigger the alarm. And the scenario 'Misleading information' doesn't change the determination that the navigation result is reliable. For result-oriented view, the Stanford diagram can be simplified into Figure 5, which is simpler to understand. The integrity outputs can be divided into two options:

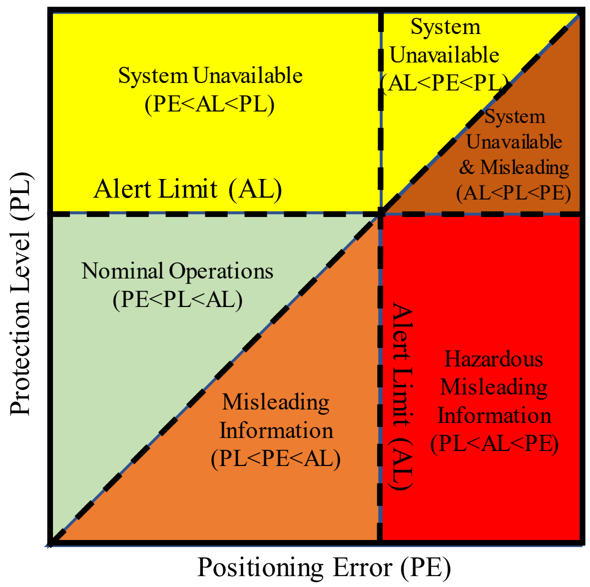


Figure 4 Stanford diagram

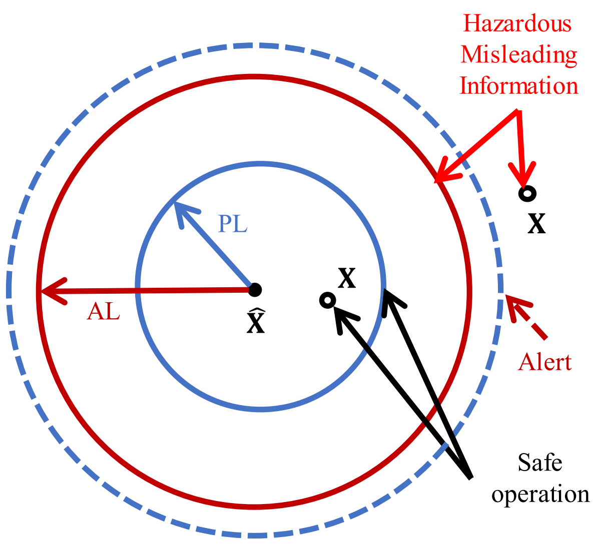


Figure 5 Result-oriented relationship between PL, AL and estimated position

1) $PL > AL$. The relationship is shown as the dotted blue circle and red circle in the figure. It is easy to understand that when PL exceeds AL, the alert will be triggered immediately, no matter whether the positioning error exceeds the AL or not.

2) $PL < AL$. The relationship is shown as the solid blue circle and the red circle in the figure. It is an ideal circumstance and the integrity output is that the navigation position is reliable. In fact only the circumstance that the PL can cover the position error, it is reliable status definitely. When the integrity output is reliable but the positioning error exceeds the AL, the navigation position at this epoch is defined as the hazardous misleading information.

In most integrity-related researches, the works focus on the positioning algorithm and protection level computation to guarantee the availability of GNSS. What we do in integrity research is to keep this kind of integrity risk is small enough to meet the required PHMI. On the other side, the research on AL determination is relatively few. However, as shown in Figure 5 and equation (1), the alert limit plays an important role in integrity evaluation. If the defined AL is too large, then the calculated PL is easy to meet the requirements, the navigation results will be evaluated as reliable in most time no matter whether the positioning result has been damaged by measurement outliers or hazardous situations. It is unacceptable in safety-critical applications. On the contrary, if the defined AL is too small. The calculated PL is easy to exceeds the AL and trigger the alert. The navigation system will be identified as unavailable frequently due to false alarms. It doesn't reflect the real situation and is disadvantageous for the technology application. The result is that the alert limit should be objective, reasonable and reflect the navigation requirements as far as possible.

3 Integrity application from Civil Aviation to Autonomous Vehicles

There are a lot of similarities between civil aviation and autonomous vehicles in view of navigation. Both of them are safety-critical applications. Their perfect working mode is autopilot in all conditions. Strictly the civil aircraft is one of the few means of the transportation that have achieved autonomous driving in cruise mode. GNSS provides absolute positioning results in this point-to-point service. It results that it is feasible to introduce integrity and alert limit to evaluate the measure of trust of the navigation system.

The importance of alert limit determination has been analyzed in above section. Actually the alert limit requirements in civil aviation is defined with the flight operations. As shown in Table 1, the alert limit is relatively simple due to the vast route before non-precision approach. In fact the unit of alert limit is nautical mile (NM). Even entering the precision approach, the alert limit is still as large as tens of meters due to the wide runway. Particularly the alter limit is a constant during one certain operation. Of course it is no longer applicable for alert limit determination in autonomous vehicle. The next subsection will introduce the differences in detail.

Table 1 Alert limit requirements in civil aviation

Operation	Oceanic en-route	Continental en-route	Terminal	Non-precision approach	APV-I	APV-II	Category I
HAL	7.4km (4NM)	3.7km (2NM)	1.85km (1NM)	556m (0.3NM)	40m (130ft)	40m (130ft)	40m (130ft)
VAL	N/A	N/A	N/A	N/A	50m (163ft)	20m (66ft)	35~10m (115~33ft)

To implement the integrity evaluation for autonomous vehicles, it’s believed that all factors related to the integrity parameters (integrity risk, positioning errors, alert limit and protection level calculation) need be considered effectively. A review of integrity application difference is given in this section. From civil aviation to autonomous vehicles, we conclude the differences in four aspects: Driving scenario, Integrity requirements, Navigation solution and Sensor availability. These four aspects affect every integrity parameter more or less. Table 2 only lists the strong relationship between influence factors and integrity parameters. The symbol ‘√’ represents the strong relationship. The detailed information of influence factors is shown in Table 3.

Table 2 Strong relationship between influence factors and integrity parameters

Integrity parameter / Influence factor	Integrity Risk	Alert Limit	Positioning Errors	Protection Level
Driving scenario	√	√	√	√
Integrity Requirements	√	√		√
Navigation Solution	√		√	√
Sensor Availability	√		√	√

For driving scenario, it is the most open-and-shut difference between the two applications. It is also the difference that affect all integrity parameters. Comparing with that of civil aviation, the trajectory of autonomous vehicles is complex. The road grades can be divided into freeway, street road, interchange, tunnel and so on. They have different road parameters and various traffic regulations. One common characteristic is that the road lane is narrow compared to the size of vehicles, which results the safe space is extremely limited. Besides that, the civil aircraft is sensitive to the weather only in take-off and terminal approach. It will further avoid the impact of severe weather by airport scheduling system [17]. However the autonomous vehicles will face the severe weather such as rainstorm and snow directly. The difference in driving scenario determines that autonomous vehicles need to assess the four integrity parameters online and real-time.

For integrity requirements, it affect the integrity risk and alert limit determination. It includes the integrity risk unit, risk quantization, alert limit definition and determination. Compared to civil aviation which has established a whole performance requirement for integrity, most of the above factors for autonomous vehicles are to be determined (TBD) disappointingly and need to be solved urgently.

Table 3 The differences of integrity evaluation between civil aviation and autonomous vehicles.

Aspect	**Item**	**Civil Aviation**	**Autonomous Vehicles**
Driving Scenario	Trajectory	Smooth	Complex
	Route/Lane	~km	<4m
	Relative space	Vast	Narrow
	Weather impact	Little	Obvious
Integrity Requirements	Integrity risk unit	/h; /approach	/mile;/h
	Risk quantization	10^{-6}~10^{-8}	TBD
	Alert limit range	~kilometer-~10 m	TBD
	Bounding box	Simple, Cylinder	TBD

Navigation Solutions	Navigation sensors	GNSS(GPS)	GNSS/INS/LiDAR/Camera
	Navigation method	GNSS only	Multi-sensor fusion
	GNSS position model	Single point	RTK/PPP
	Aided information	SBAS/GBAS/ILS	HD map; V2X
Sensor Availability	Measurement	Pseudorange	Pseudorange/Carrier/Point Cloud…
	Positioning model	Absolute	Absolute; Relative
	Measurement performance	Similar among satellites	Diversity and complexity
	Integrity risk allocation	Equally among satellites	TBD

For navigation solutions, it is the key technology and research hotspot that most automobile manufacturers and research institutes have spent huge fund and human resources on [18]. The navigation system must output the positioning errors as small as possible and have the ability to detect outliers, faults, interfere, spoofing, and so on. Sensors which can provide high accuracy positioning results, like RTK (Real - time kinematic), PPP (Precise Point Positioning), Inertial navigation system (INS), Light imaging detection and ranging (LiDAR), radar and camera, are involved in the navigation solution for autonomous vehicles. However none of them is able to complete the whole task independently due to their vulnerability to interferences and limitations to application scenarios [19] [20] [21]. To satisfy the above navigation requirements and evade the drawbacks of single sensor, multi-sensor information fusion technology is widely adopted in autonomous vehicles navigation solutions with the assist of high definition (HD) map or vehicle-to-everything (V2X) technology [22] [23]. By contrast, the navigation solution and positioning model in civil aviation is simpler and more mature.

For sensor availability, it can be regarded as the extension of navigation solution aspect but directly affect the integrity risk and positioning errors. The above sensors can provide various types of navigation information such as absolute or relative positioning output, range or positioning observations. However, multi-sensor information fusion can improve the robustness and universality, so does the integrity risk probability of decreasing the navigation accuracy and reliability due to sensor faults and performance degradation of single sensor [24 25]. Furthermore, as the performance of satellites is similar, the problem of integrity risk allocation is not serious in civil aviation. However in autonomous vehicles, the integrity risk needs to be allocated to different sensors based on their availability and impact on the final navigation results. No sensor can be regarded as absolute safe and reliable.

Based on the analysis of these four aspects, the integrity evaluation of autonomous vehicle is much more complex and difficult compared to that of civil aviation. The resulting integrity solution should be more rigorous due to human safety. Particularly among the above four aspects, the integrity requirement-related work needs to be paid more attentions while there have not been some progresses compared to the other three aspects to some extents. Among the integrity requirement, the importance of alert limit is self-evident. It plays an important role in user algorithm to determine the final decision is normal operation, false alarm or missed detection.

4 Alert Limit Determination in Autonomous Vehicles

The significance and urgency of alert limit for integrity application in autonomous vehicles have been reviewed in above section. In this section, the current alert limit determination technology is introduced and a novel method is proposed in detail.

4.1 Baseline Alert Limit Determination

Actually little literature mentioned the alert limit determination in autonomous vehicles. Ford model is the first model that proposed a detailed algorithm for alert limit determination of autonomous vehicles. The baseline procession of Ford model can be summarized in Figure 6. The input parameters include road geometry and vehicle dimension. The absolute alter limit is a trade-off in turns and the final alert limit is a relative one considering the attitude compensation. The core steps include two: Trade-off in turns and Orientation error rotation.

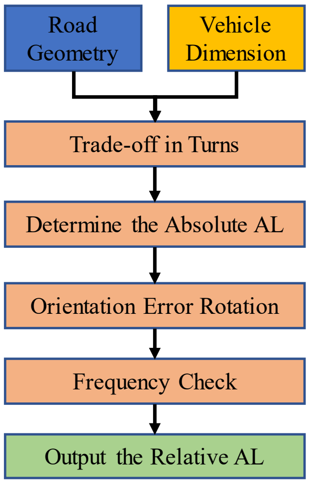


Figure 6 Functional diagram of Ford model

As shown in Figure 7, in most cases the bounding shape of alert limit for autonomous vehicles is defined as a cuboid box considering the vehicle dimension. The bounding box can be divided to lateral, longitudinal and vertical directions. The problem is that once the car drives into a turn, the size of the bounding box is changing due to the radius, which is shown in Figure 8. A longer longitudinal alert limit will result in a shorter latitude alert limit and vice versa. The relationship between latitude and longitudinal alert limit can be expressed in the following equation:

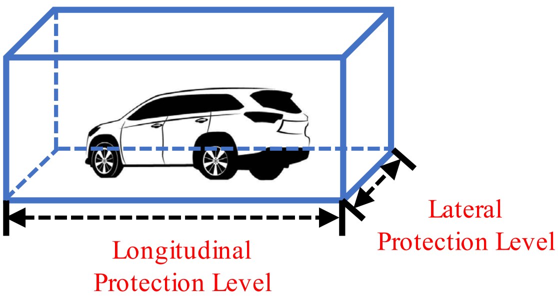


Figure 7 Bounding box definition for autonomous vehicles

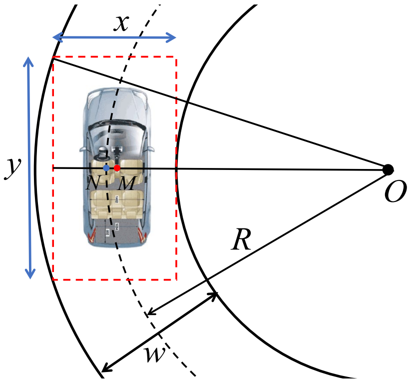


Figure 8 Bounding box geometry in a turn

$$\left(\frac{y}{2}\right)^2 + \left(R - \frac{w}{2} + x\right)^2 = \left(R + \frac{w}{2}\right)^2 \qquad (2)$$

where x and y are latitude and longitudinal alert limit, respectively. R and w are radius and the width of the turn. For a certain radius and width, a trade-off must be made to calculate the outputs of alert limits. There are no definite trade-off principles. The sacrifice is inevitable in one direction.

Another problem is that to meet the ideal bounding box calculated in above equation, the car needs to drive off the centreline in curved road and close to one side of the road. As shown in Figure 8, at the current epoch, the centreline of road is point N, where the center of the car, also the center of the bounding box, is point M. The distance between M and N can be calculated as:

$$MN = ON - OM = \frac{w-x}{2} \qquad (3)$$

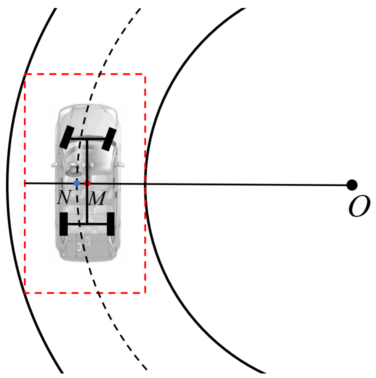
where this distance is dynamic and changing due to the road type and radius. The added complexity and uncertainty to the control and navigation system make the loss outweighs the gain.

Focus on the orientation error rotation. It is easy to understand that it needs to modify and compensate the attitude error for a moving car positioning. However it should be noted that according to the definition of alert limit, it is an absolute bounding box under the maximum tolerable positioning error. Thus the attitude error should be involved in this bounding box rather than shrinking the box. In other words, attitude error is one kind of positioning error, and it has no relationship with the determination of alter limit.

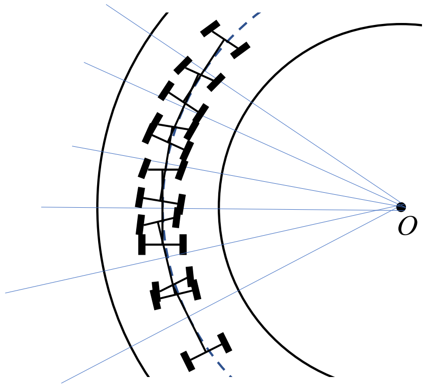
Furthermore, to compensate the attitude error, a lot of assumptions and compromises are made in Ford model such as: The sum of allowable longitudinal and vertical errors for freeway operation be approximately half the vehicle length; Orientation error for freeway operation is 1.5 degrees and for local streets is 0.5 degrees. These behaves conversely reduces the preciseness of the algorithm.

4.2 Online Alert Limit Determination enhanced by kinematic model

Based on the introduction of integrity and the analysis of Ford model, one important parameter not considered in civil aviation and Ford model is the vehicle kinematic model. As shown in Figure 9 (a), when going around a curve, the direction of vehicle driving will have an apparent angle compared to the direction of head, especially in turning and roundabout. It is also another difference between civil aircraft and autonomous vehicle. Under this scenario, compared with the steering wheel and wheels, the designed cuboid box aligning with the head will not fully reflect the driving characteristic of the autonomous vehicle. Take the car head as an example, the advantage of cuboid box is to allocate the integrity risk to the left and right sides equally. However, the car has a trend to turn to the inner side due to the kinematic model. Just shown in Figure 9 (b), the outer wheels will run a bigger circle than that of the inner wheels when the car goes around a turn. The integrity risk on two sides are not balanced.



(a)



(b)

Figure 9 Kinematic model in turns

Overall, a realistic and reasonable model for integrity alert limit determination method enhanced by kinematic model is proposed. A flexible bounding box with respect to the kinematic model will replace the fixed cuboid box. In straight road, the road geometry is simple and the vehicle kinematic model is clear. A cuboid box based on the width of lane is determined using the method similar to Ford model. On the other hand, in curved road, a fan-shaped box is designed to bound the vehicle appropriately. The box is determined by the radius, the width and the design speed of the road. These parameters are easy to access from the high definition (HD) map, which means the alert limit can be calculated online. Figure 10 shows a demo of HD map, the radius, width of the lane can be outputted with the running vehicle simultaneously. But it should be noted that the accuracy and covariance error must be considered in the final integrity risk evaluation, which is similar to the orientation error.

Figure 10 HD map in Google Earth

With a small inner side and big outer side, the fan-shaped box is much more fit for the vehicle kinetic model. The vehicle can keep drive along the centerline of the lane to guarantee the optimum control. Starting from the fan-shaped box, it can still get the lateral and longitudinal alert limits to evaluate the localization performance. As the aim of bounding box is to avoid the vehicle itself from hazardous circumstance, the longitudinal and lateral alert limits can still be defined as the distance from the vehicle body straight to the box laterally and longitudinally, respectively. Finally, the fan-shaped bounding box is the blue shadow area in Figure 11. Focus on the positioning point N, the alert limit is shown as the red shadow area in Figure 12, where NE and NF are the lateral and longitudinal alert limit, respectively. It should be noted that the area '$ABCD$' in Figure 12 is the alert limit of positioning point, not the bounding box of the vehicle in Figure 11.

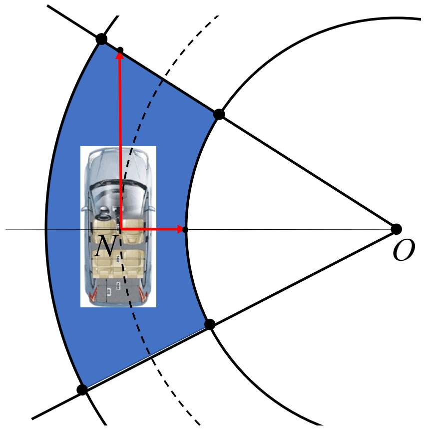


Figure 11 Fan-shaped bounding box for vehicle

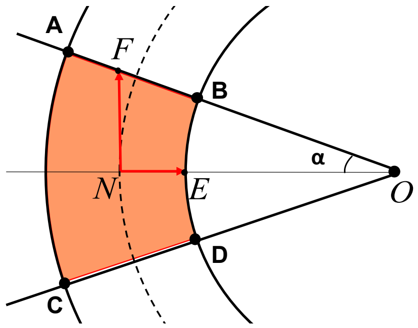


Figure 12 Alert limit based on fan-shaped box

For the calculation of lateral and longitudinal alert limit, it is easy to find that the lateral alert limit is determined by the width of the road and the width of the vehicle:

$$Lat.AL = NE = \frac{w - w_v}{2} \qquad (4)$$

where w_v is the width of the vehicle.

$$Lon.AL = NF = R\arctan\alpha \qquad (5)$$

where α is determined by the design speed of the turn and the positioning interval time T.

$$\alpha = \frac{v_d}{R}T \qquad (6)$$

Hence the shape of the bounding box is not necessary to be immutable and the alert limit can be calculated online by the road geometry, width of the vehicle directly without any trade-off and compromises.

5 Discussion

To verify the superiority of the proposed alert limit determination method. The output comparison between Ford model and the proposed model are tested and discussed based on the American road design standard [26]. Then the alert limits based on the Chinese design specification for highway alignment are given in detail [27].

5.1 Comparison based on American Road Design Standard

Table 4 and Table 5 show the alert limits based on America standard road types and vehicle types. Particular the road widths used in freeway operation and local road are 3.6m and 3.0m, respectively. The radiuses of turns are 150m and 20m, respectively.

Table 4 Alert limits for America freeway operation

Vehicle Type	Ford Model		Proposed Model	
	Lat.AL/m	Lon.AL/m	Lat.AL/m	Lon.AL/m
Mide-Size	0.72	1.40	0.86	2.78
Full-Size	0.66	1.40	0.83	2.78
Standard Pickup	0.62	1.40	0.80	2.78
Passenger Vehicle Limits	0.57	1.40	0.75	2.78
6-Wheel Pickup	0.40	1.40	0.59	2.78

As the tables shown, compared to those calculated by Ford model, the lateral alert limits determined by the proposed model are broadened by 20%~50%. The longitudinal alert limits are broadened about two times. The safe spaces between the vehicle and the lane are maximized to the full. It is significant for the autonomous vehicle navigation with relatively less stringent alert limits.

Table 5 Alert limits for America local road

Vehicle Type	Ford Model		Proposed Model	
	Lat.AL/m	Lon.AL/m	Lat.AL/m	Lon.AL/m
Mide-Size	0.44	0.44	0.58	0.83
Full-Size	0.38	0.38	0.53	0.83
Standard Pickup	0.34	0.34	0.50	0.83
Passenger Vehicle Limits	0.29	0.29	0.45	0.83

5.2 Alert limit based on Chinese Design Specification for Highway Alignment

According to the Chinese design specification for highway alignment, the road can be divided into five grades with different design speed and road width. The vehicles can be divided into five types according to the vehicle size. Table 6 gives the detailed lateral and longitudinal alert limits based on road grade and vehicle type, where the lateral alert limit is in front of the longitudinal one.

Table 6 Alert limits based on Chinese design specification for highway alignment

Road grade / Vehicle Type	Freeway	first-class highway	second-class highway	third-class highway	forth-class highway
passenger car	0.98m/2.78m	0.98m/2.22m	0.85m/1.67m	0.85m/1.11m	0.73m/0.83m
passenger bus	0.60m/2.78m	0.60m/2.22m	0.48m/1.67m	0.48m/1.11m	0.35m/0.83m
articulated bus	0.63m/2.78m	0.63m/2.22m	0.50m/1.67m	0.50m/1.11m	0.38m/0.83m
Truck	0.63m/2.78m	0.63m/2.22m	0.50m/1.67m	0.50m/1.11m	0.38m/0.83m
articulated vehicle	0.60m/2.78m	0.6m/2.22m	0.48m/1.67m	0.48m/1.11m	0.35m/0.83m

5.3 Superiority of proposed alert limit determination method

Compared to the classical alert limit defined in civil aviation, the pioneering work in the novel alert limit determination method proposed for autonomous vehicles include: Firstly, different from the alert limit in civil aviation which is determined offline by operations and common among every types of aircrafts, the alert limit for autonomous vehicles need to be determined online and real-time calculated. It is a variable with the road and vehicle information. Then, the alert limit in civil aviation is only divided into vertical alert limit and horizontal alert limit. The priority of vertical component is higher than the horizontal one. But for autonomous vehicles, the horizontal alert limit is prior than the vertical one and needs to be refined to lateral alert limit and longitudinal alert limit to meet the safety requirements. Thirdly, the bounding box of aircraft is a constant cylinder, where the bounding box used in the proposed method is dynamic fan-shaped considering the integrity risk allocation. Finally, as the route is vast and the trajectory is smooth, the aircraft kinematic model is not considered in the alert limit determination. To improve the integrity risk allocation, the kinematic model is introduced into the alert limit determination.

Besides the fan-shaped bounding box and kinematic model, compared to the Ford model, the proposed method also shows superiorities in the following aspect: Firstly, there’s no trade-off and compromises in calculation. The processing is more direct and rigorous. Then, compared to the Ford model, the proposed method shows respect to the virtual driver system where the control and routing do not need to make sacrifices to enlarge the alert limit. Furthermore, the alert limit is clarified as the absolute safe space by definition, rather than the relative space, which results that the positioning and altitude errors are not considered in the alert limit determination.

6 Conclusion

The importance of integrity and alert limit in safety-critical navigation application is firstly analysed. A review of integrity application differences from civil aviation to autonomous vehicles is given in detail after that. To improve the research weakness, a novel alert limit determination method enhanced by the kinematic model is proposed in this paper. The integrity risk on two sides are allocated respect to the road geometry and kinematic model. A fan-shaped bounding box is more reasonable to cover the safe-critical areas. The experiment test results compared with those of the Ford model also verified the superiority of the proposed method. The alert limits calculated based on the Chinese standards will give some references for the navigation integrity for autonomous vehicles.

The authors are working on developing the online system for alert limit determination with the HD map. We believe it is great help to assess the integrity of multi-sensor navigation system and improve the integrity application in autonomous vehicles.

Acknowledgments

This research is funded by the Hong Kong Polytechnic University project "Security Enhancement of Positioning Sensors on Connected Autonomous Vehicles", the grant number is P0013910 (ZVP9).

References

1. Kassas ZM, Closas P, Gross J. Navigation Systems Panel Report Navigation Systems for Autonomous and Semi-Autonomous Vehicles: Current Trends and Future Challenges. *IEEE Aerospace and Electronic Systems Magazine* 2019; 34: 82-84.
2. SAE International. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles (J3016B). 2018.
3. Koopman P, Wagner M. Autonomous vehicle safety: An interdisciplinary challenge. *IEEE Intelligent Transportation Systems Magazine* 2017; 9: 90-96.
4. Jiao X, Yang D, Jiang K, Yu C, Wen T, Yan R. Real-time lane detection and tracking for autonomous vehicle applications. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of automobile engineering* 2019; 233:2301-11.
5. Li X, Zhang W. Reliable integrated navigation system based on adaptive fuzzy federated Kalman filter for automated vehicles. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 2010;224:327-46.
6. Meng Q, Liu J, Zeng Q, et al. Neumann-Hoffman Code Evasion and Stripping Method For BeiDou Software-defined Receiver. *Journal of Navigation* 2017; 70:101-119.

7. Venkita SR, Willemsen D, Alirezaei M, Nijmeijer H. Switching from autopilot to the driver: A transient performance analysis. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 2019. https://doi.org/10.1177/0954407019878540

8. Li X, Chen W, Chan C. A reliable multisensor fusion strategy for land vehicle positioning using low-cost sensors. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* 2014;228(12):1375-97.

9. Walter T, Enge P, Blanch J, et al. Worldwide vertical guidance of aircraft based on modernized GPS and new integrity augmentations. *Proceedings of the IEEE* 2008; 96: 1918-1935.

10. Meng Q, Liu J, Zeng Q, et al. Improved ARAIM fault modes determination scheme based on feedback structure with probability accumulation. *GPS Solutions* 2019; 23: 16.

11. Joerger M, Spenko M. Towards navigation safety for autonomous cars. *Inside GNSS*. December 2017, p. 40-48.

12. Changalvala R, Hafiz M. LiDAR Data Integrity Verification for Autonomous Vehicle. *IEEE Access* 2019; 7: 138018-138031.

13. Chen L, Yu CL, Luo YG, Hu MJ, Li KQ. Safety benefit evaluation of intelligent driving systems based on multisource data mining. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of automobile engineering* 2019;233(9):2362-70.

14. Reid TG, Houts SE, Cammarata R, et al. Localization Requirements for Autonomous Vehicles. SAE *International Journal of Connected and Automated Vehicles* 2019; 2:173-190.

15 .US Department of Transportation. Federal Radionavigation Plan. 2017. https://www.transportation.gov/pnt/radionavigation-systems-planning

16. Zhu N, Marais J, Bétaille D, et al. GNSS position integrity in urban environments: A review of literature. *IEEE Transactions on Intelligent Transportation Systems* 2018; 19: 2762-2778.

17. Yang Y. 2017. Practical Method for 4-Dimentional Strategic Air Traffic Management Problem With Convective Weather Uncertainty. *IEEE Transactions on Intelligent Transportation Systems* 2017; 19: 1697-1708.

18. Abou-zeid H, Pervez F, Adinoyi A, et al. Cellular V2X Transmission for Connected and Autonomous Vehicles Standardization, Applications, and Enabling Technologies. *IEEE Consumer Electronics Magazine* 2019; 8: 91-98.

19. Takefuji Y. Connected vehicle security vulnerabilities. *IEEE Technology and Society Magazine* 2018; 37(1): 15-18.

20. Rosique F, Navarro PJ, Fernández C, et al. A systematic review of perception system and simulators for autonomous vehicles research. *Sensors* 2019; 19(3): 648.

21. Meng Q, Liu J, Zeng Q, et al. An Efficient BeiDou DBZP-based Weak Signal Acquisition Scheme for Software-Defined Receiver. *IET Radar, Sonar and Navigation* 2018; 12(6): 654-662.

22. Kuutti S, Fallah S, Katsaros K, et al. A survey of the state-of-the-art localization techniques and their potentials for autonomous vehicle applications. *IEEE Internet of Things Journal* 2018; 5: 829-846.

23. Hobert L, Festag A, Llatser I, et al. Enhancements of V2X communication in support of cooperative autonomous driving. *IEEE communications magazine* 2015; 53: 64-70.

24. Loureiro R, Benmoussa S, Touati Y, et al. Integration of fault diagnosis and fault-tolerant control for health monitoring of a class of MIMO intelligent autonomous vehicles. *IEEE Transactions on Vehicular Technology* 2014; 63: 30-39.

25. Al Hage J, El Najjar ME and Pomorski D. Multi-sensor fusion approach with fault detection and exclusion based on the Kullback–Leibler Divergence: Application on collaborative multi-robot system. *Information Fusion* 2017; 37:61-76.

26. Washington State Department of Transportation. Design Manual. 2017.

27.Ministry of Transport of the People’s Republic of China. Design Specification for Highway Alignment (JTG D20-2017). 2018.