View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by OAR@UM

Aerotecnica Missili & Spazio, *The Journal of Aerospace Science, Technology and Systems*

A Technique for Improving Conflict Alerting Performance in the context of Runway Incursions *

A. Sammut[a], D. Zammit-Mangion[a] [b]

[a] University of Malta
Department of Electronic Systems Engineeing

[b] Cranfield University
Department of Aerospace Engineering

Abstract

An effective solution to the problem of runway incursions is long overdue. To date, an average of a thousand incursions are registered yearly in the United States alone, with similar figures registed in Europe. Installing a system on-board aircraft capable of providing an alert in the case of a runway incursion has the potential of significantly reducing this. As with any conflict detection and alerting system, the difficulty lies in the fine-tuning of the parameters which define a conflict, in effect resulting in finding the right trade-off between false and missed detections and associated alerts. This is an important consideration in the design of any conflict detection system and is key in the context of runway incursion alerting where aircraft would be travelling at high speed and in close proximity of eachother. This paper addresses this problem by providing an assessement on the effects of false and missed detections in the event of a runway incursion and provides mathematical tools for tuning the conflict detection boundaries.

1. Introduction

Runway incursions have been a major concern in the aviation industry for several years and this has resulted in numerous initiatives to mitigate the risk of incursion, within both Europe and the United States. These range from awareness campaigns and improved signage, to air traffic control alerting tools that are used to advise the air traffic controller of a runway incursion. Whilst these initiatives have undoubtedly provided improved levels of safety and contributed to the reduction in the number of incidents, up to now, they have not provided satisfactory mitigation to the problem. This is evidenced by the fact that, to date, the United States National Transportation Safety Board still keeps the topic of runway incursions on its top ten most wanted safety improvements list [1].

There have been a number of programmes dealing with the design of systems for airfield surveillance with the capability of detecting conflicting situations onboard the aircraft and generating a corresponding alert in the cockpit [2, 3, 4]. One of the biggest challenges, however, is to reliably detect a runway conflict, given the uncertainties inherent to the ownship and traffic data. Although the general technique to runway conflict detection available in the literature has been shown to be valid, this paper addresses a study carried out to determine the impact data uncertainty has on the positioning of the detection threshold.

2. Runway Conflict Detection

When an aircraft is cleared to make use of a runway for take-off or landing, the designated runway is essentially reserved for sole use by that aircraft. Any other aircraft or vehicle entering this reserved area results in a runway incursion. This is similar to the concept of a 'protected zone' or no transgression zone (NTZ) surrounding an aircraft whilst airborne, which defines a region into which no other entity must enter to ensure safety of the flight. In a similar way, the protected zone of an aircraft during runway manoeuvres is, actually, the entirety of the runway, extended in length and width such that it includes traffic approaching the runway for landing and those approaching the runway through taxiways (Figure 1). Whilst this technique functions well with accurate aircraft positional data, it is susceptible to the generation of false alerts when positional errors such as those introduced by positional reporting uncertainties are present. For example, with a detection treshold set just at the taxiway hold-short bars, an aircraft holding short just before the bar could trigger a detection (and alert) if it transmits its posi-

*Based on paper presented at the CEAS/AIDAA Conference, October 2011, Venice, Italy

[1]©AIDAA, Associazione Italiana di Aeronautica e Astronautica

tion as being beyond the bar. This would constitute the generation of a false alert. On the other hand, setting the conflict detection boundary closer towards the runway, such as at the runway shoulder, although reducing false events would have the effect of delaying the issue of an alert in the case where a runway incursion does occur. A carefull trade-off between the two is therefore required.

Figure 1. The protected zone described around the active runway which defines the region reserved for the ownship whilst performing a take-off or landing manoeuvre. (Not to scale).

2.1. Trading-off False for Delayed Detections

The trade-off between the probability of missed or delayed detection $P(\mathrm{MD})$ and that of a false detection $P(\mathrm{FD})$ requires very careful consideration. With the intended role of such a conflict detection system being that of a safety-net function, the trade-off is biased towards maintaining a low false detection rate. The effect of false detections is most serious during take-off. Falsely alerting of a runway conflict can lead to an unnecessary rejected take-off (RTO) that could have major or hazardous consequences. This is particularly so if the RTO is initiated at high speed (close to V_1) where, apart from the risk of brake fire and tyre failure, there is only a 50% chance of bringing the aircraft to a halt within the distance allowed. In field limited runways, therefore, a high speed RTO could lead to an overrun. Consequently the $P(\mathrm{FD})$ during the latter part of the take-off run (typically above 80 or $100kts$) must be maintained below 10^{-7} to be in compliance with the philosophy of AMC-25.1309 in CS-25 [5]. An unnecessary low speed RTO, although not as serious as a high speed RTO, is disruptive and is of nuisance since it requires the aircraft to taxi back to the start of the runway, join the queue of aircraft waiting to depart and allow sufficient time for the brakes to cool. Such an occurrence would invariably affect scheduling and induce delays.

False alerting during landing is also undesirable. However, unlike in take-off, where an unnecessary abort will have a relatively higher impact on safety, the main effect of unnecessary go-arounds is of a nuisance level, as this would usually only result in a delay in the flight and the inconvenience of needing to, where relevant, join an airborne queue to land. Nevertheless, unnecessary alerts would still lead to loss of confidence in the system with the possibility of crews disregarding the alert when a runway conflict really occurs. A further consideration is that, in certain circumstances, an unnecessary go-around may actually compromise safety and even lead to an accident. The presence of obstacles and high terrain in the vicinity of the airfield, bad weather (in particular with the presence of thunderstorm cells), conditions of low fuel and other contributing effects may combine to significantly raise the risk of accident following a missed approach.

To achieve a low false detection rate, the conflict boundaries need to be carefully placed so that they can handle errors in state data without causing false detections at a rate higher than acceptable. However, the positioning of the boundary also affects the missed detection rate. Within the context of runway conflict detection, this results in a degradation in the alerting performance of the system, where, as the aircraft in conflict proceeds within the protected zone, a missed alert is expressed as a delay in detection. This will affect the effectiveness of the system in successfully mitigating conflicts. This however will not mean that the role of the system is not achieved. Indeed, even if, through late detection the system would be able to lead to the successful resolution of the conflict on only 50% of events, this will translate to a 100% improvement in the mitigation of the risk of runway collisions. Therefore, the trade-off between false and missed detections is that of reducing the false detection rate to an acceptably low level at the expense of late detection. This ensures that the improvement in safety introduced by the system is not compromised by false alerts and their associated unnecessary manoeuvres.

As a means to mitigate this problem, two techniques have been developed. The first involves withdrawing the alerting threshold just enough that an acceptable false detection rate due to the residual state uncertainty is achieved, without introducing an excessive delay in detection and alerting. The second technique involves a prediction of whether an aircraft taxiing towards the runway will not stop before crossing it. This, performed through an analysis of the aircraft's speed and acceleration profiles, further improves the early warning of an incursion and aleviates the delay introduced in alerting due to the withdrawal of the alerting treshold for the purpose of controlling false detections. It is relevant to note that in runway conflicts, even a one second difference can differentiate between a collision or a successful avoidance of the conflict, underlining the impact this technique could have on the effectiveness of a runway collision avoidance system.

3. Tuning the Conflict Detection Boundary

The width W of the protected zone affects the sensitivity of the detection algorithm to traffic intruding laterally into the zone (along the Y axis). When the runway is cleared for use by an aircraft in take-off or landing, procedure dictates that no traffic entity is to enter the runway and must therefore hold-short at the runway stop-bars. Choosing $\frac{W}{2}$ to be the distance S_s of the hold-short bars from the centreline of the runway is the theoretically ideal solution as it correctly maps the actual protection zone generated by procedure. This is a conservative approach, since when an aircraft crosses the hold-short bar, there still remains a buffer distance (the distance of the hold-short bar from the runway shoulder) before the aircraft actually enters the runway. However, choosing the zone to extend exactly to the hold-short bars may result in a high false detection rate due to the residual uncertainties in the filtered traffic positional states. False detections are expected to be generated by aircraft correctly holding at the hold-short bar but are erroneously reported as being beyond the bar.

The lateral distance $S_\perp$ between the reported traffic position and the runway centreline, being GPS-derived exhibits noise having a Gaussian distribution.This can be defined by:

$$S_\perp \sim N(s_\perp, \sigma_{p_y}^2) \quad (1)$$

where $s_\perp$ is the mean perpendicular distance and $\sigma_{p_y}^2$ is the variance of the reported traffic position in the Y direction[2].

Therefore, when aircraft stops exactly at the hold short bar, there is a 50% expectancy that the reported position of the aircraft falls beyond the threshold, erroneously triggering a conflict. This is inadequate and in order to reduce this probability, the threshold (width) of the protected zone needs to be displaced away from the hold-short bar as show in Figure 2. With the threshold set to $S_s - 5\sigma_{p_y}$, a false detection rate $P(\text{FD})$ of 2.9×10^{-7} for aircraft positioned exactly at the hold-short bar can be expected, being in compliance with the AMC-25.1309 philosophy previously explained. However in reality, aircraft tend to stop before even reaching the hold-short bar, which means that the shift in the detection boundary of $5\sigma_{p_y}$ is conservative and a lower false detection rate would actually be achieved.

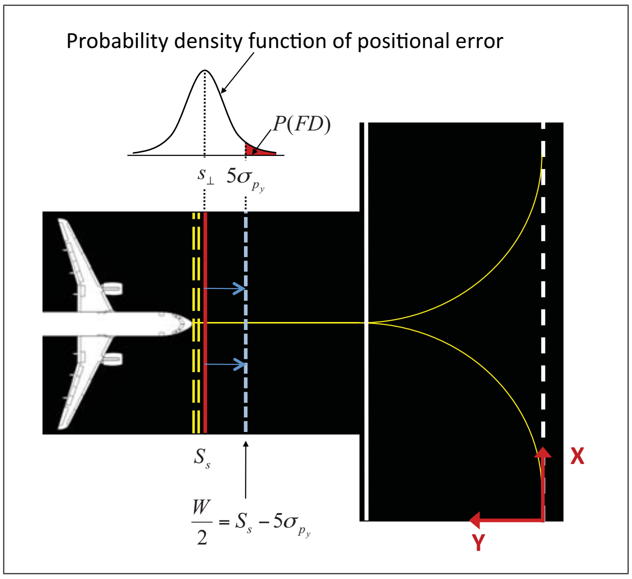


Figure 2. Shifting in the protected zone detection boundary to maintain the level of false detections at 2.9×10^{-7}.

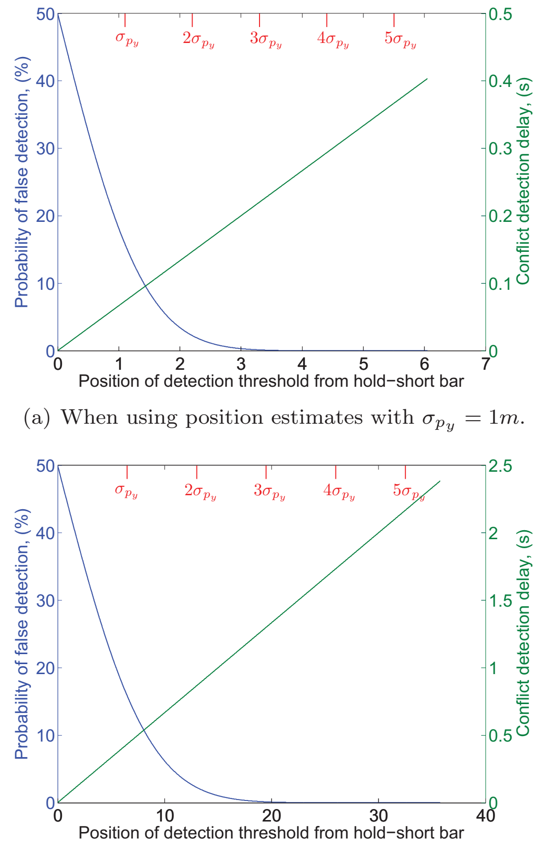
Shifting the detection boundary also impacts the missed detection rate. This has two effects in this application. The first is that aircraft stopping just over the hold-short bar will be outside the detection boundary and will therefore not be detected. This could be considered as an advantage, as in reality, although the aircraft will have violated procedure and entered the protected zone, it will pose no risk to the ownship in take-off or landing. In fact, a rejected take-off or landing, in this case, would be unnecessary and triggering an alert in such circumstances could be more detrimental to safety. In this respect, therefore, shifting of the detection boundary is considered advantageous.

The second effect of shifting the boundary is that of effectively delaying the alert in the classical runway incursion case where an aircraft continues onto the runway. Introducing a delay in the alerting of a runway incursion is detrimental to the effectiveness of mitigating runway conflicts. Indeed, early warning is fundamental in this application where a few seconds could make the critical difference in the outcome of the conflict. The delay introduced by the threshold shift is best expressed as a percentage of the leeway available from when the aircraft crosses the hold-short bar to when it arrives at the runway shoulder, which is effectively a measure of the early warning given before the physical conflict actually occurs. To quantify this numerically, a typical airfield layout can be considered, where the perpendicular distance between the hold-short bar and the runway shoulder is $50m$ [6]. If position reporting accuracy is in the order of 6.5m

[2]The reported traffic position is strictly reported at the aircraft's centre of gravity. However, for this analysis it is assumed to be referenced to the nose of the aircraft.

RMS, as is typical to GPS-derived ADS-B data in an all-satellites-in-view condition, a σ_{p_y} of $6.5m$ can be defined [7, 8]. In this case, the $5\sigma_{p_y}$ margin by which the protected zone boundary would be shifted is $32m$. This gives a 65% decrease in early warning from when an aircraft is detected to have crossed the hold-short bar until it arrives at the runway shoulder. In terms of time delay, if the aircraft is assumed to be taxiing at a speed of $15m/s$ ($30kts$), the delay introduced will be of the order of $2s$. From this analysis, the impact of ADS-B (or similar) traffic reporting accuracy on the performance of conflcit detection and alerting becomes evident. In fact, in the case where traffic reporting accuracy is higher, such as through data fusion and filtering techniques, a significant reduction in this delay is seen. For instance for ADS-B data based on differentially-computed GPS data, a σ_{p_y} in the order of $1m$ can be defined [8]. In this case, the margin by which the protected zone width would need to be reduced to ensure the same false detection rate is approximately 6-fold lower ($5m$). This would delay early warning by approximately 10% (time delay of 2s), rather than the 65% when using standard GPS data.

Using a statistical software package, the effect of shifting the protected zone boundary on false detection was estimated for the range of shifts between $0\sigma_{p_y}$ and $6\sigma_{p_y}$. The delay introduced by the shift was also estimated, assuming the aircraft approaches the hold short bar at $15m/s$. Figure 3 shows the result of this analysis. Figure 3(a) is applicable to the case were the traffic data is reported with an accuracy of $1m$ RMS, whilst Figure 3(b) is for the case where traffic data is reported with an accuracy of $6.5m$ RMS. The critical effect of data accuracy on the performance of conflcit detection and alerting is again made evident by these figures.



(a) When using position estimates with $\sigma_{p_y} = 1m$.

(b) When using position estimates with $\sigma_{p_y} = 6.5m$.

Figure 3. Trade-off between the false detection rate and the delay in conflict detection, introduced by shifting the protected zone (conflict) boundary position from the hold-short bar (closer towards the runway).

3.1. Extending Early Detection

Basing the conflict detection and alerting algorithm on the presence or otherwise of traffic in the protected zone is a straight forward, effective and reliable technique for detecting runway conflicts. However, in critical situations where the conflict dynamics are marginal with little time to react, earlier detection would be beneficial towards successful conflict mitigation. This is more evident in the case where the uncertainity associated with traffic reports is large, shrinking the early detection margin as a trade-off for false alerts. A typical context is one where the ownship will be in the advanced stage of the take-off run and an intruder enters the runway such that there is insufficient distance remaining for the ownship to safely clear the conflict or to stop in time (cannot-go/cannot-stop situation). In these circumstances, early detection could result in the ownship being able to stop or, at the very least, reduce the impact speed in the case of a collision. Early detection can be achieved when the intruder approaching the hold-short bar is travelling at a relatively high taxi speed, as it will be evident that the aircraft will not stop before the hold-short bar, well before it crosses it. Indeed early detection is most useful in these cases, as at high taxi speeds, the time from crossing the hold-short bar to entering the runway will be short (approximately $3s$ for an aircraft travelling at $15m/s$ and a hold short bar positioned at $50m$ from the runway shoulder). In circumstances where the aircraft approaches the hold-short bar at low speeds, or is stationary at the hold-short bar and starts moving towards the runway, it will not be possible to predict the intentions of the aircraft with confidence any significant time before it crosses the bar. Fortunately the long time (in the order of $20s$) until the aircraft enters the runway reduces the need for early (pre-emptive) alerting in these cases.

To take advantage of this concept of pre-emptive alerting, a prediction (or look-ahead) of the states of the aircraft approaching the hold-short bar needs to be performed. The technique is that of monitoring the aircraft speed profile as it approaches the hold-short bar and determining whether it can be expected to stop before the bar or otherwise. The challenge here is how to ascertain with confidence that the aircraft approaching the hold-short bar does not have the intention to stop. This is necessary as to keep the level of false detections at an acceptably low rate.

The aircraft deceleration d could be expressed in terms of partial derivatives:

$$d = \frac{\partial V_g}{\partial t} = \left(\frac{\partial s}{\partial t}\right)\left(\frac{\partial V_g}{\partial s}\right) = V_g\left(\frac{\partial V_g}{\partial s}\right) \quad (2)$$

where V_g is the ground speed and s is the distance travelled. At low speeds, aircraft deceleration can be assumed to be primarily affected by braking force and therefore constant with respect to V_g. The distance S_B an aircraft or vehicle will travel from an initial velocity V_B until it comes to rest will then be:

$$S_B = \left|\int_{V_B}^{0} \frac{V_g}{d}\delta V\right| = \frac{V_B^2}{2d} \quad (3)$$

Since what is of interest is determining whether an aircraft approaching the hold-short bar can be expected to stop in time or otherwise, a speed profile defining the maximum braking that can reasonably be expected of an aircraft with the intention to stop at the hold-short bar is identified. This is shown in Figure 4.

Aircraft beyond this limit can be expected to not have the intention to stop before reaching the bar, allowing early detection of the conflict. Conversely, for aircraft in the region below this limit, it cannot be ascertained whether the aircraft will be stopping or otherwise and therefore no early warning of a conflict can be provided in such cases. The value chosen for the maximum expected deceleration d_{max} controls the sensitivity of the prediction and needs to be set to provide an adequate balance between false and missed detections. Large values of d_{max}, close to the aircraft's maximum braking capability would essentially delay the generation of an early warning. This, in effect, would ensure that aircraft approaching the hold-short bar, realising only at the latest instance that a runway incursion was about to be caused, thereby braking heavily to stop in time, would correctly not generate a false alert. However, in the normal incursion case, where aircraft would be proceeding without the intention to stop, the early warning effect is compromised as shown in Figure 5. In this context, it is reasonable to capture aircraft with a somewhat higher deceleration rate than what would normally be expected when approaching the hold-short bar, whilst it is deemed unnecessary to cater for the event of crews becoming aware of causing a runway incursion so late as to necessitate emergency braking to stop before the hold-short bar. Although the rate of occurrence of such an event cannot be quantified statistically, the authors are of the opinion that the risk of false alarms generated by such events should be acceptable.

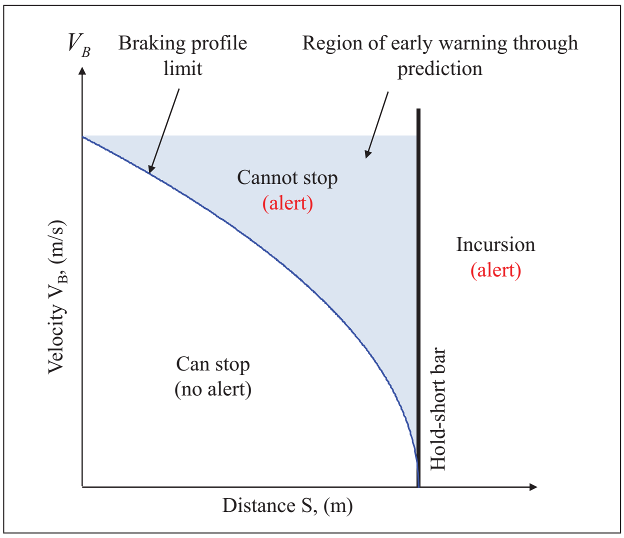


Figure 4. The early detection braking profile limit. Aircraft above the limit cannot stop before reaching the hold-short bar and therefore an alert can be triggered earlier.

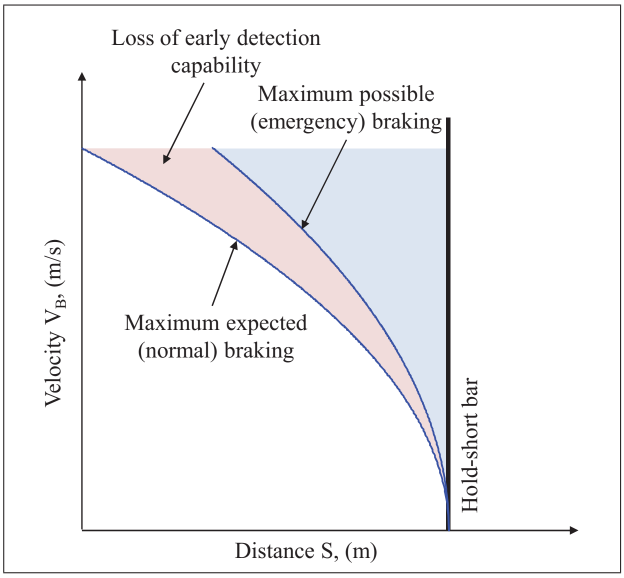


Figure 5. Graph showing the effect of choice of maximum braking profile on early warning.

In this context, therefore, it is appropriate to identify the maximum braking d_{max} that would be expected in normal braking behaviour on approaching a hold-short bar and then add an extra leeway to mitigate the risk of false detections. In an experiment conducted by NASA to model aircraft trajectories on the airport surface [9], the maximum decelerations measured were of the order of $-0.25m/s^2$ when travelling in a straight line. These results were consistent across different types of aircraft, including narrow, wide-bodied and regional aircraft. In fact, the experiments also showed that pilots typically apply hardest braking when decelerating from higher velocities (of the order of $-0.25m/s^2$ when at $15m/s$), rather than when decelerating from low velocities. Therefore, setting d_{max} of $-0.5m/s^2$ should ensure an adequate representation of the typical maximum deceleration expected when approaching a hold-short bar. This value was consequently use for this analysis.

3.1.1. Uncertainties due to Speed and Position Errors

The reliable prediction of whether an aircraft can stop before crossing the hold-short bar requires an analysis of the uncertainties involved in performing the calculation. This is dependent on both the uncertainty in the aircraft speed V_B as it approaches the hold-short bar, as well as on the uncertainty in its position. In fact, due to the dependency of the braking distance on the aircraft velocity, the uncertainty with which the braking distance can be determined is velocity dependent. These two effects can be depicted graphically in Figure 6.

The extent of the effect of this uncertainty can be determined through analyses. Referring to Figure 6, the worst case effect occurs when the reported aircraft position is on the limit of acceptable braking that will allow it to stop at the hold-short bar. Due to uncertainties in actual aircraft position and velocity, a probability density function exists about the reported state, as shown in the figure. Approximately half the combinations of actual speed and position will clearly allow the aircraft to stop in time. However, the remainder of the combinations will result in the aircraft overrunning the hold-short bar. This is graphically expressed by the probability density function C. In order to limit the effect of false warnings, the displacement of the protected zone threshold away from the hold-short bar is advantageous, as can be seen in the figure. What is necessary here is to ensure that the threshold is beyond the 5σ tail of distribution C, in order to reduce the probability of false detections to a level of the order of 10^{-7}. Clearly, the probability of an aircraft actually reporting its state to be on the limit braking profile is also low and this further reduces the overall probability of false detections due to such an event.

The shifting of the threshold away from the hold-short bar also has the effect of displacing the braking profile limit to the right as shown in Figure 7. In this context, it is then necessary to ensure that all but only a few instances in 10^7 occurrences of the density function fall within the displaced profile to ensure the target low false detection rate. The overall effect of this consideration, is once again that, of reducing the effectiveness of the early warning concept. This can be seen in Figure 7 and comparing it with Figure 6.

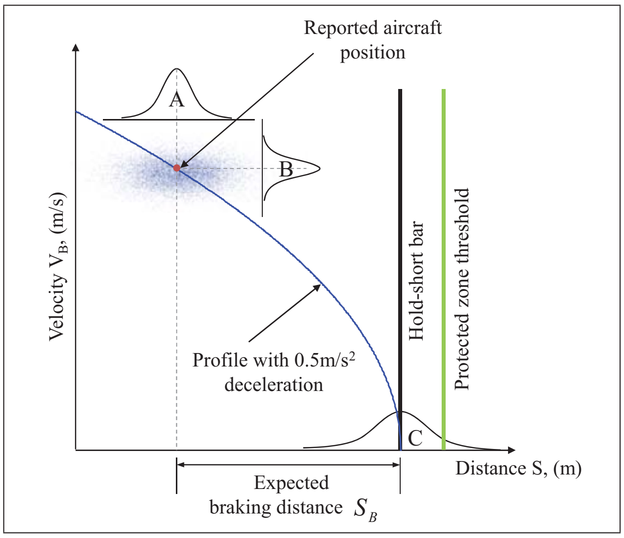


Figure 6. The effect of uncertainties on the estimate of the braking distance. A, B and C are the probability density functions of the velocity error, positional error and stopping point respectively.

Following the above discussion, it is relevant to quantify the extent of the displacement in the braking profile required to ensure satisfactory operation. Referring to Figure 6, the expected braking distance of the aircraft is given by:

$$S_B = \frac{V_B^2}{2|d_{max}|} \quad (4)$$

where V_B is the velocity at which braking starts and d_{max} is the maximum expected braking deceleration of $-0.5m/s^2$.

In the general case, assuming the taxiway is not perpendicular to the runway, V_B needs to be considered as the vector sum of the components in the X and Y directions. Hence,

$$S_B = \frac{V_{B_x}^2 + V_{B_y}^2}{2|d_{max}|} \quad (5)$$

where V_{B_x} and V_{B_y} have Gaussian distributed errors with variances $\sigma_{v_x}^2$ and $\sigma_{v_y}^2$ respectively. However, the actual distance travelled by which the aircraft can be expected to come to rest from the reported position

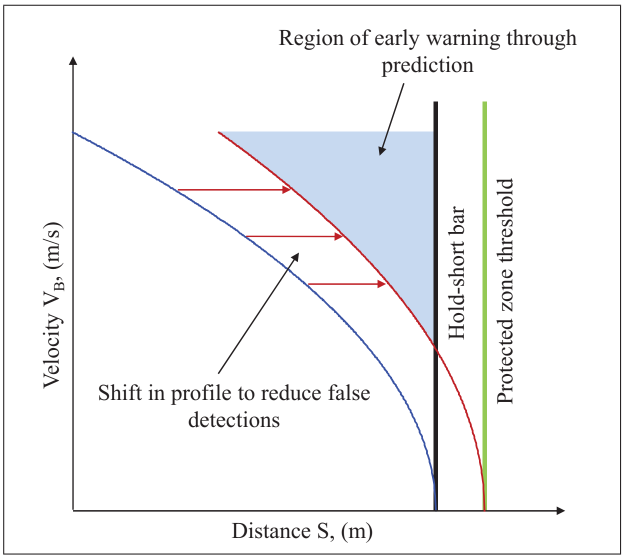


Figure 7. Shifting of the braking limit to reduce false detections. This also has the effect of reducing the effectiveness of the early warning concept.

must also include the error in the reported position:

$$S'_B = \frac{V_{B_x}^2 + V_{B_y}^2}{2|d_{max}|} + \sqrt{\epsilon_{dx}^2 + \epsilon_{dy}^2} \tag{6}$$

where ϵ_{dx} is the error in the X direction, being Gaussian distributed with σ_{p_x} and ϵ_{dy} is the error in the Y direction, being normally distributed with σ_{p_y}.

With these considerations, the variance σ_B^2 of the actual braking distance S'_B (i.e. the variance of distribution C in Figure 6), can be expressed by applying a first-order Taylor series approximation of the statistical moments:

$$\sigma_B^2 = \left(\frac{\partial S'_B}{\partial V_{B_x}}\sigma_{v_x}\right)^2 + \left(\frac{\partial S'_B}{\partial V_{B_y}}\sigma_{v_y}\right)^2 \ldots + \left(\frac{\partial S'_B}{\partial \epsilon_{dx}}\sigma_{p_x}\right)^2 + \left(\frac{\partial S'_B}{\partial \epsilon_{dy}}\sigma_{p_y}\right)^2 \tag{7}$$

Therefore, taking partial derivatives on Eq. (6) gives:

$$\sigma_B^2 = \frac{V_{B_x}^2\sigma_{v_x}^2 + V_{B_y}^2\sigma_{v_y}^2}{d_{max}^2} + \frac{\epsilon_{dx}^2\sigma_{p_x}^2 + \epsilon_{dy}^2\sigma_{p_y}^2}{\epsilon_{dx}^2 + \epsilon_{dy}^2} \tag{8}$$

The first-order approximation to σ_B is only accurate when S'_B is much larger than the measurement noise; that is when the aircraft is travelling at high taxi speeds and is therefore still far away from the hold-short bar. This is due to the fact that the approximation of the complex error distribution of S'_B to a Gaussian function becomes less valid when close to the measurement noise.

In the cases where the taxiways are perpendicular to the runway, the aircraft approaching the hold-short bar only travels in the Y direction, with its velocity also aligned to this direction. Eq. (6) will then be simplified, by setting V_{B_x} and ϵ_{dx} to zero, reducing it to:

$$S'_B = \frac{V_{B_y}^2}{2|d_{max}|} + \epsilon_{dy} \tag{9}$$

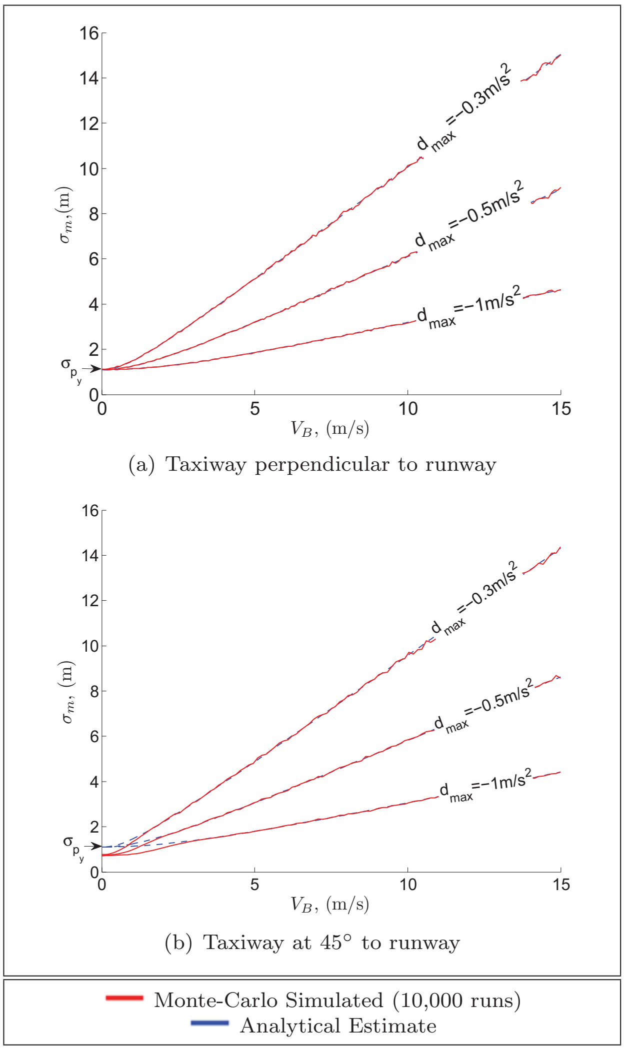
and its variance to:

$$\sigma_B^2 = \left(\frac{V_{B_y}\sigma_{v_y}}{d_{max}}\right)^2 + \sigma_{p_y}^2 \tag{10}$$

In order to gain confidence in the assumptions made in deriving Eqs. (8) and (10), a Monte-Carlo simulation with 10,000 runs was carried out and the results correlated with the analytical derived counterparts. For this purpose two scenarios were simulated, one with the aircraft approaching the hold-short bar along a taxiway perpendicular to the runway and one with the aircraft approaching on a taxiway at 45° to the runway. For each scenario, a range of maximum deceleration profiles were applied and the uncertainties in the position and velocity estimates used are representative of those in differential-GPS-derived ADS-B data. The two sets of results correlated well for both scenarios, as evident in Figures 8(a) and 8(b). The only discrepancy observed is at low speeds in the 45° taxiway scenario. This is due to the first-order Taylor series approximation taken when deriving Eq. (8), where the higher order terms of interaction between the variables are not considered when estimating σ_B, resulting in Eq. (8) giving a slight over-estimate to σ_B. This effect appears only at low speed when the values of V_{B_x} and V_{B_y} are close to the measurement noise σ_{v_x} and σ_{v_y}. Furthermore, this effect is not present in the case where the taxiway is perpendicular to the runway because σ_B calculated using Eq. (10) involves less interaction of variables.

It is also interesting to take further inference from Figure 8. The figures show that the standard deviation in the overall distance covered σ_B (and therefore the uncertainty in the early prediction) increases with velocity. This is as expected because errors in higher velocities will result in a larger effect on braking distance than the same error at lower velocities. The maximum expected deceleration d_{max} also has an impact on this uncertainty, with low decelerations contributing more to the uncertainty. This is again as expected since with low decelerations, the errors in velocity result in a greater effect on the overall distance covered than when the aircraft decelerates quicker.

As previously discussed, maintaining a low false detection rate necessitates displacing the braking profile



(a) Taxiway perpendicular to runway

(b) Taxiway at 45° to runway

Figure 8. Variation of the standard deviation of braking distance σ_B with aircraft velocity V_B for various values of deceleration d_{max} using analytical calculations and Monte-Carlo simulations. Simulated filtered ADS-B data for the aircraft on the ground with $\sigma_{p_x} = \sigma_{p_y} = 1m$, $\sigma_{v_x} = \sigma_{v_y} = 0.30m/s$.

limit towards the right, with a displacement of $5\sigma_B$ giving a false detection rate of the order of 10^{-7}. However, as described by Eq. (8) and shown in Figure 8, σ_B is speed dependent, resulting in the displacement of the braking profile also being speed dependent. Figure 9 shows the results of a simulation performed to demonstrate the shift in the boundary by $5\sigma_B$. From this it is evident that as the speed approaches zero and therefore σ_B approaches σ_{p_y}, the shift in the threshold away from the hold-short bar becomes equivalent to that without the early detection (as defined at the start of Section 3). The figure also shows that early detection with a displaced threshold partially mitigates the disadvantage of late detections (missed warnings) brought about by the shift. Fortunately, it recovers the events involving higher taxi speeds, which, in practice form the major threat in the context. Indeed the undetectable area involving lower speeds will be associated with events where, although delayed, the detection of the runway incursion (at the displaced threshold) will still provide sufficient time for reaction before the aircraft arrives at the runway shoulder.

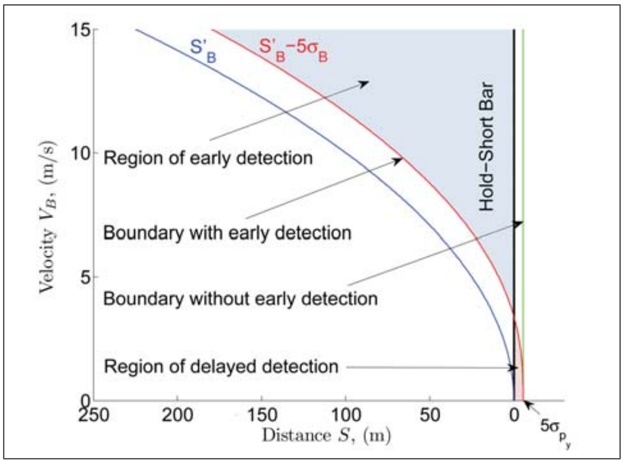


Figure 9. Simulation of the detection boundaries with and without early detection using $\sigma_{p_x} = \sigma_{p_y} = 1m$, $\sigma_{v_x} = \sigma_{v_y} = 0.30m/s$ and $d_{max} = -0.5m/s^2$.

3.1.2. Quantifying the Early Detection Time

What is essentially of interest in early detection is the time from when a conflict is identified to occur to when it actually occurs; that is, how early the conflict is detected. According to the technique described above, a conflict is detected once the aircraft approaching the hold-short bar arrives to a point where it cannot be reasonably expected to stop short of it (that is, it no longer remains within the typical maximum deceleration envelope). In such circumstances the aircraft will be expected to cause a runway incursion and therefore it is reasonable to expect it to be taxiing at a constant speed towards the hold short bar. With this assumption, the early detection time t_B is defined by the distance between the early detection point and the hold-short bar, divided by the aircraft speed. The former can be derived from Figure 10, where the intersection between the braking profile boundary and the aircraft profile is the point where it is identified that a conflict would occur and, therefore, the early detection could be triggered. t_B can, therefore, be defined by Eq. (11), where $S'_B - 5\sigma_m$ defines the distance from the hold-short bar at which the early detection can be triggered.

$$t_B = \frac{S'_B - 5\sigma_B}{V_B} \quad (11)$$

Figure 11 shows the relation between t_B and V_B with and without the $5\sigma_B$ leeway allowed to the braking profile boundary. As expected, the $5\sigma_B$ leeway delays the point at which it can be identified that a conflict would occur and therefore reduces the early detection time. However, even with the leeway in place, aircraft travelling at high velocities, in the order of $15m/s$, are expected to be identified as being in conflict up to approximately $12s$ prior to their crossing of the hold-short bar. As previously mentioned, aircraft travelling slowly in the order of $3.5m/s$, cannot be detected to cross the hold-short bar earlier.

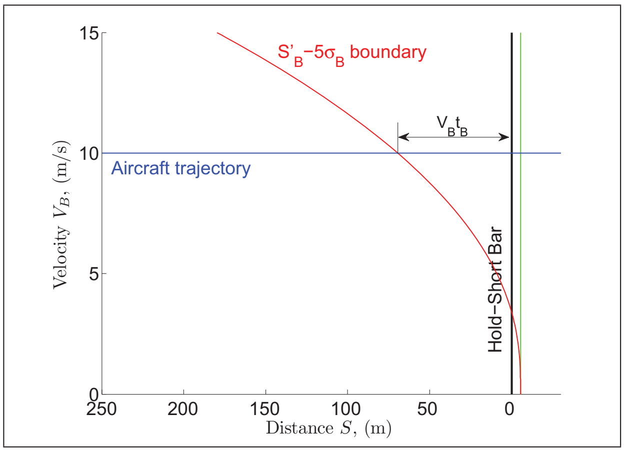


Figure 10. Intersection between the aircraft constant velocity trajectory (in this case at $10m/s$) and the braking profile boundary. The early detection time is given by the time required for the aircraft to travel from the intersection point to the stop-bar.

4. A Case Study: The 2001 Milan-Linate Accident

The Linate accident is an interesting case study in this context, as it may be considered as a critical case scenario where the ownship (MD87) was in rotation when it impacted the conflicting aircraft (Citation). With the continued take-off option clearly not having been viable, the MD87 could only have attempted to stop to avert the collision. The animation of the collision dynamics presented with the accident report [10] shows that the Citation jet reached the runway shoulder $20s$ before impact. At this time, the MD87 was

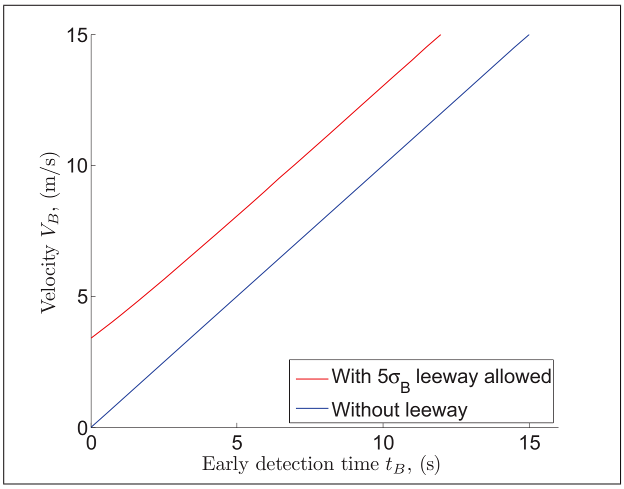


Figure 11. Variation in the early detection time with intruder approach velocity to the hold-short bar, with and without the $5\sigma_B$ leeway allowed to the braking profile boundary with $d_{max} = -0.5m/s^2$.

already at about $65kts$ ($33m/s$) and it would most certainty have managed to stop before the collision point, were the pilots alerted of the incursion at that instant.

In addition, the protected zone width would have extended about $55m$ from the runway shoulder[3], which, due to the airfield geometry, would have resulted in the Citation aircraft taxiing for $80m$ from the moment it would have effectively penetrated the protected zone to the runway shoulder (Figure 12). Unfortunately, the Citation was not required to be equipped with a Flight Data Recorder and, as a result, the precise speed with which the aircraft was taxiing is unknown. In the circumstances, it is reasonable to assume that the Citation must have been travelling at less than $10m/s$ since visibility was so poor. This would have definitely provided a detection time of at least $8s$, as the Citation had a distance of approximately $80m$ to travel before entering the runway. Even without giving credit to the early detection technique described previously, this $8s$ detection time would have resulted in the generation of an alert when the MD87 would have been at around $80kts$ ($41m/s$) and still $1km$ from the conflict point on the runway. This leeway would have been amply sufficient for the collision to be prevented.

In the Linate accident the Citation entered the runway $20s$ before impact and taxied slowly across to proceed onto another taxiway. This would have afforded a minimum of $20s$ of prior warning. It is interesting to consider a more critical condition where the aircraft

[3] Using the published runway width of $60m$, the last hold short bar is positioned at $60m$ from the runway edge. Allowing a withdrawal of $5m$ of the protected zone to suppress false detections positions the protected zone edge at $55m$.

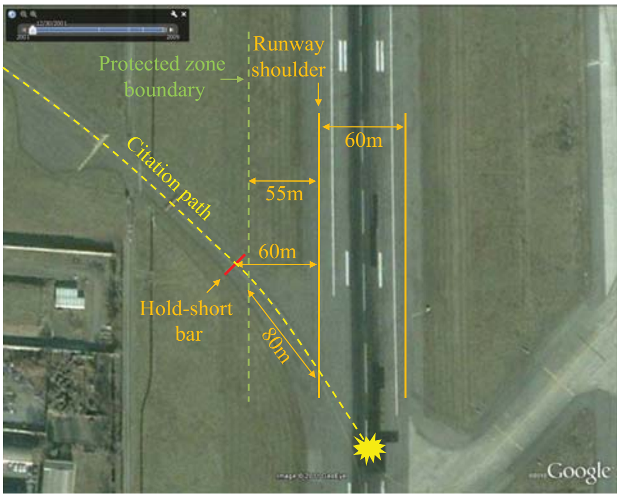


Figure 12. Diagram showing distances associated with the protected zone boundary superimposed on a satelite image of the Milan Linate 18L/36R intersection with taxiway R6 as existent in December 2001. Satellite image sourced from Google Earth.

will have just entered the runway to hit the oncoming aircraft. For this purpose an analysis was made to estimate how early a conflict could be detected before an intruding aircraft reaches the runway shoulder. The total detection time t_t as a function of the conflicting aircraft taxi speed can be caluclated as the sum of:

- The time t_a from the moment the traffic is perceived to penetrate the protected zone until the moment it reaches the runway.
- The additional time t_b afforded by the early detection technique that anticipates that traffic will penetrate the protected zone.

Table 1 tabulates the values for t_a, t_b and t_t for the range of aircraft approach speeds V_y between $1m/s$ and $15m/s$ using a nominal positioning of the edge of the protected zone at $50m$ from the runway shoulder. Two graphs are plotted in Figure 13, one estimating the alerting time for the algorithm without early detection (i.e. alerting only once the traffic will have penetrated the protected zone) and the other showing alerting times with early detection. This shows a minimum alert time of just below $15s$ and highlights the effectiveness of the early detection technique in providing additional early warning.

It is interesting to try to estimate the impact on the outcome of the Linate scenario if an alert time of $14s$ has been afforded. Once again, using the animation of the accident released with the investigation report, one can identify that, with the collision occurring at $147kts$ and a reported distance of $1447m$ from the start of run,

Table 1
Table of detection times for various traffic taxi speeds.

$V_y(m/s)$	$t_a(s)$	$t_b(s)$	$t_t(s)$
1	50.00	1.09	51.09
2	25.00	2.18	27.18
3	16.67	3.27	19.94
4	12.50	4.36	16.86
5	10.00	5.45	15.45
6	8.33	6.54	14.87
7	7.14	7.64	14.78
8	6.25	8.73	14.98
9	5.56	9.82	14.38
10	5.00	10.91	15.91
11	4.54	12.00	16.54
12	4.17	13.09	17.26
13	3.85	14.18	18.03
14	3.57	15.27	17.57
15	3.33	16.36	19.69

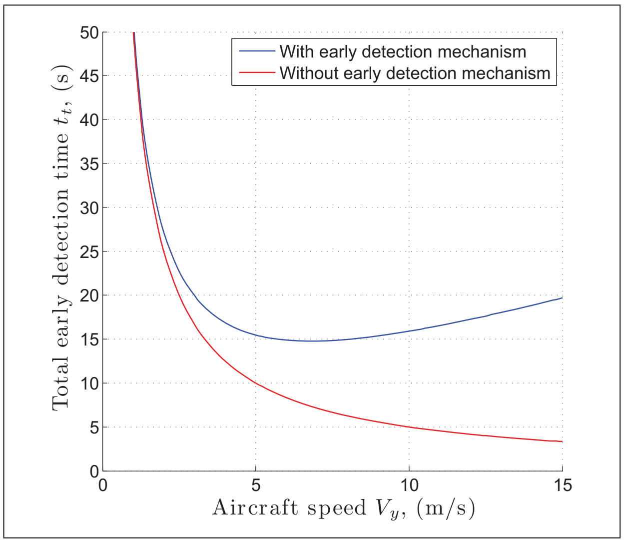


Figure 13. Graph of total alert time t_t as a function of traffic taxi speed.

the MD87 was at about $96kts$ and $560m$ into the run $14s$ before impact. Assuming the alert was generated at this moment and allowing for a crew reaction time of $2s$, the aircraft would have started to decelerate at $106kts$ and $670m$ into the run. This means that the aircraft will have had just over $770m$ in which to stop and a collision would have been averted with an average braking of $2m/s^2$, which should be achievable in the right conditions[4]. Therefore it can be concluded that even in such a critical scenario, early detection

[4] As a comparison, the A320 has three braking rates in automatic braking mode. The deceleration limits in the three rates are: low-$1.7m/s^2$, medium-$3m/s^2$ and high-maximum braking [11].

would have indeed prevented the collision.

5. Conclusions

Whilst conflict detection based on the presence or otherwise of traffic within the ownship's protected zone has shown to be a valid technique, the selection of the conflcit detection threshold has seldomly been addressed in literature. Due to the need for high reliability in the algorithm driving runway conflict alerts, brought about by the safety critical nature of the application, this work has given considerable attention to the design of a technique which allows control of the false and missed detection rates. This has been achieved through a process of state uncertainty propagation, which allows tuning of the conflict detection boundaries such that the false and missed detection rates can be controlled. In fact, by withdrawing the detection threshold by approximately $5m$ from the hold-short bar, a false detection rate below 10^{-7} could be achieved without introducing a significant delay in conflict detection. Additionally, the concept of conflict prediction has been developed, where, through monitoring of the conflicting aircraft's speed profile, it could be determined with confidence whether the aircraft will stop before overrunning the hold-short bar. This is achieved through the definition of a typical maximum braking profile, which, once exceeded, indicates that the aircraft will not stop and will consequently overrun the hold-short bar. These two tools provide the basis for the development of a reliable on-board runway collision avoidance system. Of course, the actual limits allowed on false detections requires futher consideration through consultancy with the stakeholders, including the certification bodies.

References

[1] NTSB. Most Wanted Safety Transportation Safety Improvements. United States National Transportation Safety Board, Washington DC, 2007.

[2] D. Jr. Green. Runway Safety Monitor Algorithm for Runway Incursion Detection and Alerting. Technical Report NASA/CR-2002-211416, Lockheed Martin Corporation, 2002.

[3] R. Cassell, C. Evers, and J. Esche. Safety Benefits of PathProx - A Runway Incursion Alerting System. In *The IEEE 22nd Digital Avionics Systems Conference*, volume 2, pages 9.B.4–91–10, Oct. 2003.

[4] C. Vernaleken, L. Mihalic, M. Güttler, and U. Klingauf. A Fresh Look at Runway Incursions: Onboard Surface Movement Awareness and Alerting System Based on SVS. In *Enhanced and Synthetic Vision*, volume 6226, 2006.

[5] European Aviation Safety Agency. Certification Specification for Large Aeroplanes. Airworthiness Code CS-25 Book 1, 2003.

[6] International Civil Aviation Organization. Air Traffic Management. Technical Report DOC4444, 2001.

[7] United States Department of Defence. Global Positioning System Standard Positioning Service Performance Standard. Technical report, Washington DC, 2001.

[8] B. W. Parkinson and J. J. Spilker, editors. *Global Positioning System: Theory & Applications (Volume One) (Progress in Astronautics and Aeronautics).* AIAA (American Institute of Aeronautics & Astronautics, 1st edition, January 1996.

[9] C. Gong. Kinematic Airport Surface Trajectory Model Development. In *The 9th AIAA Aviation, Integration and Operations Conference*, 2009.

[10] Agenzia Nazionale Per la Sicurezza del Volo (Italy). Accident Involved Aircraft Boeing MD-87 and Cessna 525-a Milano Linate Airport [Online]. `http://www.ansv.it/En/Detail.asp?ID=177`, 2004. [Cited October 2012].

[11] Anon. A320 Braking Limits [Online]. `http://www.kls2.com/cgi-bin/arcfetch?db=sci.aeronautics.airliners&id=%3Cairliners.1993.670@ohare.chicago.com%3E`, 1993. [Cited October 2012].