Safety risk analysis of runway incursion alert systems in the tower and cockpit by multi-agent systemic accident modelling

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7th USA/Europe Air Traffic Management R&D Seminar
Barcelona, Spain, 2-5 July 2007
Contents

Runway incursion alerting
- Context
- Problem
- Operation

Types of accident models

Multi-agent situation awareness accident model

Monte Carlo simulation risk results

Conclusions
Runway incursion: Recognised as important safety issue

FAA Runway Safety Report
August 2005

EVERYTHING MOVES AT AN AIRPORT. BE ALERT!

RUNWAY INCURSIONS ARE REAL!

European Action Plan for the Prevention of Runway Incursions
Release 1.2

7th USA/Europe Air Traffic Management R&D Seminar, Barcelona, Spain, 2-5 July 2007
Strategies to reduce runway incursion risk

Procedures, training, systems, infrastructure

- Enhance situation awareness
- Improved aerodrome guidance
- Improved communication
- Taxiway layout

Runway incursion alert systems

- ATC runway incursion alert systems
  - Commercially available
- Cockpit runway incursion alert systems
  - Research & development (NASA Runway Incursion Prevention System)
Leading question

What is the effectiveness of runway incursion alert systems?
- In the ATC tower?
- In the cockpit?
- In various contextual conditions?
Active runway crossing operation

**Human operators**
- Pilots aircraft taking-off
- Pilots aircraft taxiing
- Runway controller
- Ground controller

**Visibility conditions**
- Visibility condition 1
  - Unrestricted range
- Visibility condition 2
  - Range of 400 – 1500 m

**Technical systems**
- VHF R/T communication
- Ground radar
- Active stopbar
- ATC runway incursion alert
  - Ground radar data
  - Alerts runway controller
- Cockpit runway incursion alert
  - GPS ownship data
  - ADS-B linked othership data
  - Alerts pilots
Contents

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  ● Problem
  ● Operation

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Conclusions
Complexity of aerodrome operations
Complexity of accident risk assessment

Complexity of operations
- Many agents (humans/systems)
- Many interactions
- Highly dynamic
- Performance deviations

Complexity of risk assessment
- Multiple agents
- Dependencies between agents
- Dynamics of agents
- Nominal/non-nominal conditions
Accident models (Hollnagel 2004)

1. Sequential accident models

Accident = Sequence of ordered events, such as failures or malfunctions of humans or machines

Examples: fault trees, event trees, domino theory

Predominantly used in reliability engineering and risk assessment
Accident models (Hollnagel 2004)

2. Epidemiological accident models

Accident = Like spreading of disease: combination of failures combined with latent conditions and environmental conditions, leading to degradation of barriers an defences

Examples: Swiss cheese model, Bayesian belief networks

Used for more complex interdependencies in risk studies
Accident models (Hollnagel 2004)

3. Systemic accident models

Accident = Emergent from the performance variability of a joint cognitive system, as a result of complex interactions and unexpected combinations of actions

Key issues
- Normal human behaviour is variable
- Socio-technical interactions may lead to functional resonance: enlarged performance deviations
- Accident prevention is based on finding critical interdependencies

![Diagram showing interactions between humans and systems, indicating functional resonance.](image-url)
Comparison of systemic versus sequential / epidemiological models

- No fixed event cause-effect relations
- Account for dynamic, non-linear behaviour
- Performance beyond event probability
- Complex multi-agent interactions
- Emergent behaviour

Risk assessment of complex socio-technical organizations in air traffic requires systemic accident modelling
Contents

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Types of accident models

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Conclusions
Safety risk assessment cycle

1. Determine operation
2. Identify hazards
3. Construct scenarios
4. Assess severity
5. Assess frequency
6. Assess risk tolerability
7. Identify safety bottlenecks

Operational development
Decision making
Iterate (option)
Agents in runway incursion scenario

- FMS taking-off aircraft
  - PF taking-off aircraft
  - Taking-off aircraft
  - Runway controller
  - ASMGCS
- FMS taxiing aircraft
  - PF taxiing aircraft
  - Taxiing aircraft
- R/T System
Multi-agent situation awareness

Situation awareness of agent $k$ at time $t$ about agent $j$

$$\sigma_{t,k}^j = \begin{pmatrix} \text{identity} \\ \text{state} \\ \text{mode} \\ \text{intent} \end{pmatrix}$$

- Examples
  - Call-sign
  - Active stopbar ID
  - Alert type
  - Aircraft position
  - Aircraft speed
  - Aerodrome geometry data
  - Alert status
  - Stopbar status
  - Flight mode
  - Taxiing route
  - Take-off time
  - Crossing time
Multi-agent situation awareness updating processes

**Observation**
- State: agent 1 → SA: agent 2

**Communication**
- SA: agent 1 ↔ SA: agent 2

**Reasoning**
- SA: agent → decision rules
Dynamics of multi-agent SA updating processes

\[ \sigma_{t' + \tau} = f_{\text{update}}^{\text{SA}}(\sigma_{t'}, \varepsilon) \]

<table>
<thead>
<tr>
<th>Process duration</th>
<th>Trigger time</th>
<th>Noise</th>
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</thead>
<tbody>
<tr>
<td>Alert interpretation</td>
<td>Alert active</td>
<td>Alert misinterpretation</td>
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<tr>
<td>Clearance interpretation by pilot</td>
<td>Clearance specification by controller</td>
<td>Misinterpretation of clearance</td>
</tr>
<tr>
<td>Visual observation of traffic situation</td>
<td>Internal trigger</td>
<td>Observation error</td>
</tr>
<tr>
<td>ADS-B data processing</td>
<td>Fixed sampling time</td>
<td>Data corruption</td>
</tr>
</tbody>
</table>

**Examples**
Mode dependent SA updating processes

### Examples

<table>
<thead>
<tr>
<th>Component</th>
<th>Mode</th>
<th>Impact on SA updating process</th>
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</thead>
<tbody>
<tr>
<td>ADS-B Receiver</td>
<td>Nominal</td>
<td>Receipt with normal sampling rate</td>
</tr>
<tr>
<td></td>
<td>Interrupt</td>
<td>Receipt after prolonged time</td>
</tr>
<tr>
<td></td>
<td>Down</td>
<td>No receipt</td>
</tr>
<tr>
<td>SA Pilot Flying</td>
<td>Cross runway</td>
<td>Frequent visual monitoring</td>
</tr>
<tr>
<td></td>
<td>Proceed taxiway</td>
<td>Less frequent visual monitoring</td>
</tr>
<tr>
<td>Visibility</td>
<td>Visibility 1</td>
<td>Unrestricted direct visual monitoring for pilots and controllers</td>
</tr>
<tr>
<td></td>
<td>Visibility 2</td>
<td>Controllers use ground radar</td>
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<tr>
<td></td>
<td></td>
<td>Pilots have restricted visibility range</td>
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</tbody>
</table>
Parameter values of the accident model

Types
- Technical systems, e.g. accuracy, availability, update rate, aircraft thrust
- Human performance, e.g. task duration, decision parameter, likelihood of misunderstanding
- Context, e.g. taxiway layout, visibility

Sources
- Technical system specifications
- Human factors literature
- Incident databases
- Interviews with operational experts
- Measurement data of real operations
- Measurement data of real-time simulations
- Simulation results from other relevant models
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Monte Carlo simulation risk results

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Monte Carlo simulation

Model implementation in dedicated Delphi software

Monte Carlo speed-up by risk decomposition

Evaluate probability of collision for various conditions

- Visibility condition
  - 1 (unrestricted)
  - 2 (400 – 1500 m)

- Runway incursion alerts
  - None
  - ATC
  - Both aircraft
  - ATC and both aircraft

- Situation awareness of pilot flying taxiing aircraft
  - Proceed taxiway
  - Cross runway
Monte Carlo simulation results for visibility condition 1

Alerts: None ATC A/C ATC+A/C None ATC A/C ATC+A/C

SA PF: Proceed taxiway Cross runway
Monte Carlo simulation results for visibility condition 2

Conditional collision risk (per take-off)

Alerts: None ATC A/C ATC+A/C None ATC A/C ATC+A/C
SA PF: Proceed taxiway Cross runway
Monte Carlo simulation results for visibility conditions 1 & 2

Conditional collision risk (per take-off)

Alerts: None ATC A/C ATC+A/C None ATC A/C ATC+A/C
SA PF: Proceed taxiway Cross runway
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Conclusions
Conclusions (methods)

A wide scope safety assessment (including performance of all relevant human operators) is needed to evaluate the effectiveness of a runway incursion alert system.

Multi-agent organizations with complex interactions are difficult to analyse effectively by sequential or epidemiological accident models.

Multi-agent situation awareness modelling is a systemic accident modelling approach that addresses performance variability due to dynamic interactions between agents.
Conclusions (MC simulation results)

The risk results depend on the specific setting of the Monte Carlo simulation model. Evaluation of specific aspects of operations at a particular airport may require fine-tuning and can be supported by a bias and uncertainty assessment.

The risk increases largely when visibility is reduced, most notably if the crew of the taxiing aircraft knows of the runway crossing.

The effectiveness of ATC runway incursion alerting is considerable in reduced visibility, but small in good visibility.

The effectiveness of cockpit runway incursion alerting is very large in reduced visibility.

The effectiveness of cockpit runway incursion alerting is still significant in good visibility to warn lost pilots.
Discussion
Risk assessment by two models: MC Simulation + Bias & Uncertainty

Monte Carlo Simulation Model → MC simulation results → Estimated risk

Model-Reality Differences → Bias & Uncertainty Model → Estimated bias & uncertainty

Reality → True risk
Types of differences between simulation model & reality

Numerical approximations
Parameter values
Formal model structure
Non-covered hazards
Operational concept differences
Evaluation of parameter values

Determine for each parameter
- Bias
- 95% Credibility interval
- Risk sensitivity
- Risk uncertainty / bias

Determine joint effect

Methods
- Evaluation by safety/model experts
- Interviews with operational experts
- Other technical/statistical data
- Monte Carlo simulations with adapted parameter values
- Bias & uncertainty meta model

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<tr>
<th>Risk uncertainty</th>
<th>Parameter value uncertainty</th>
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Evaluation of other differences

Determine for each difference
- Probability of difference
- Risk bias given difference
- Risk bias due to difference

Determine joint effect

Methods
- Ordered evaluation by safety/model experts (using sensitivity data)
- Interviews with operational experts
- Other technical/statistical data
- Bias & uncertainty meta model

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<thead>
<tr>
<th>Risk bias</th>
<th>Typical</th>
<th>Regular</th>
<th>Frequent</th>
<th>Less frequent</th>
<th>Infrequent</th>
<th>Unlikely</th>
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Effects of model-reality differences (examples)

**Significant effects (>30%)**
- Type of manoeuvre of taking-off aircraft to avoid collision
- Conflict decision process by pilots of taking-off aircraft
- Speed of taxiing aircraft
- Monitoring frequency by pilots of taxiing aircraft
- Deceleration of taking-off and taxiing aircraft
- Time before braking is initiated by pilots of taking-off aircraft

**Small effects (<13%)**
- Acceleration profile during the take-off run
- Performance of R/T communication systems
- Performance of surveillance systems
- Performance of runway incursion alert system
- Task scheduling of runway controller
MC simulation + bias & uncertainty (visibility 1)