Risk-Based Geometric Design for Roads

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Tom Casey – Transport Infrastructure Ireland

9th May 2018
Road Services Training Group
2018 Roads Conference & Exhibition
Context & The Challenge for Road Network Management
“Legacy Roads” were never designed to an engineering standard and will have very variable quality in terms of speed, comfort and most importantly SAFETY.

There is currently no national strategy for generalised improvements to over half the National Road Network, and all of the Regional Road Network.

Upgrade of existing single carriageway roads would cost typically €5m/km.

A full upgrade programme of the legacy National Road Network would cost €15 billion !!
Performance Requirements for National Secondary & Regional Roads?

- Low Traffic Flows:
  - Half of National Secondary Routes > 5,000 AADT
  - Rest of Network < 3,000 AADT typically

- Journey Time Objectives? Limited Economic Value

- Road Safety is the only real concern.

- How can limited financial resources be invested for greatest return for Road Safety?
Road Design Standards
Transport Infrastructure Ireland Publications

DN-GEO-03030  (Former TA 85)  Guidance on Minor Improvements to National Roads

DN-GEO-03031  (Former TD 9)  Rural Road Link Design
Minor Improvement Scheme

1.5 A Minor Improvement Scheme is an upgrade to an existing section of sub-standard road less than 2km in length where a design element or combined set of design elements are improved. Minor Improvement Schemes vary in complexity, ranging from the removal of inappropriate adverse camber to the isolated improvement of sections of an existing road.

Road Safety Improvement Scheme

1.6 A Road Safety Improvement Scheme is a Scheme that specifically targets sections of the network with high collision rates to improve road safety, where a design element or combined set of design elements are improved to reduce the frequency and or the severity of collisions occurring in the future.

Route Consistency

1.8 Route Consistency is achieved by a route improvement appropriate to and consistent with characteristics of the existing road alignment such as the existing route geometric characteristics and traffic demand (in particular the volume of daily traffic and Heavy Commercial Vehicle (HCV) percentage).
Objectives of Minor Improvements Schemes:

Example: Removal of a sub-standard bend. Which Bends?

“Achieve a localised improvement appropriate, and consistent with the characteristics of the adjacent sections of the route ....”

Fine in Theory, but difficult in Practice!

Primary focus is to Manage the Asset:

Maximise Performance & Minimise Collision Risk

“Many roads in Ireland are legacy roads with sub-standard design features... upgrade some, but not all these existing deficiencies within environmental & budget constraints.”
**Road Design Standards**

**Horizontal Alignment:**

Alterations shall be consistent with the existing road network for 2km either side of the proposed scheme.

**Design Speed**

DN-GEO-03031 Method of Design Speed Assessment

**Departures from Standard?**
DN-GEO-03031
Rural Road Link Design

Design Speed
Gives a high result – of limited assistance for the Designer

Departures from Standard?
3 Steps for Type 2 Single
4 Steps for Type 3 Single.
On what Basis to select?
Justification?
Suitable Implementation of TII Standards for Road Geometric Design: A Challenge

DN-GEO-03030 Guidance on Minor Improvements to National Roads
DN-GEO-03031 Rural Road Link Design

Issues:

a) What is Consistent in terms of curvature?

b) How can the Operational Characteristics of a route be best managed?

c) How can Safety Benefits be characterised and evaluated?

d) Is there Risk Transfer if a road is improved at too high a standard locally?

e) How much improvement is “enough” over cumulative schemes?

f) Can a “Big Picture Strategy” be devised for an overall route, or network, that achieves best outcome in the long term with worthwhile incremental improvements?
A New Approach to Appropriate Application of Road Design Standards
Introduction – Main Goal

The project aims to define a risk assessment tool to:

1. Facilitate Risk Based Asset Management – Optimised (Performance, Cost, Risk)
2. Identify the most critical locations of the single carriageway road network based on risk and consistency
3. Examine the causes of risk
4. Assess potential realignments – Risk Based Prioritisation
5. Inform network improvement strategies
6. Inform design standards
Risk-Based Geometric Design

Design consistency
The conformance of a road’s geometric and operational features with driver expectancy.

Driver’s expectancy
Readiness to respond to situations, events, and information in predictable and successful ways

Geometric inconsistencies
Surprise the driver and reduce the safety of the road.
Risk Analysis Model
Geometric - Risk Analysis Model – International Best Practice

Germany
(Lamm, et al., 2007)

USA
American Society of Civil Engineers
(Gibreel, et al., 1999)

USA
National Cooperative Highway Research Program
(NCHRP, 2003)

Australia
(Austroads Ltd., 2015)

USA
Federal Highways
(Messer, et al., 1981)

Speed
Stability
Visibility
Alignment
Workload
Geometric - Risk Analysis Model

- **Risk Analysis Model**

A model has been created to define the overall geometric risk of 7 elements:

1. Speed Variation: Design Speed
2. Speed Variation: Operating Speed
3. Alignment: Horizontal Curvature
4. Vehicle Stability: Side Friction
5. Alignment: Vertical Curvature
6. Sight Distance
7. Driver’s Workload (How alert and Active must they be)

\[
M_i = w_1 \cdot Q_{C_{I_i}} + w_2 \cdot Q_{C_{II_i}} + w_3 \cdot Q_{C_{III_i}} + \\
w_4 \cdot Q_{SSD_i} + w_5 \cdot Q_{CRR_i} + w_6 \cdot Q_{VRR_i} + w_7 \cdot Q_{W_i}
\]
Geometric - Risk Analysis Model

Advantages:

- Not restricted by dimensions (Analysis inconsistencies)
- Quantitative risk metric (always between 0-1)
- All risk and consistency criteria are jointly considered
- Reproducible to any road
- Cross comparison capability (between roads, regions,...)

<table>
<thead>
<tr>
<th>Risk Aspect</th>
<th>Criterion</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed Variation</td>
<td>Design Speed</td>
<td>$C_i = \frac{</td>
</tr>
<tr>
<td></td>
<td>Operating Speed</td>
<td>$C_{II} = \frac{</td>
</tr>
<tr>
<td>Vehicle Stability</td>
<td>Side Friction</td>
<td>$C_{III} = e^{-\Delta f_R}; \quad \Delta f_R = f_{RA} - f_{RD}$</td>
</tr>
<tr>
<td>Sight Distance</td>
<td>Stopping Sight Distance</td>
<td>$C_{SSD} = SSD_i / SSD_{V_d}$</td>
</tr>
<tr>
<td>Alignment Indices</td>
<td>Horizontal</td>
<td>$C_{CRR} = CRR_i = \frac{n_i}{R_{avg}}; \quad R_{avg} = \frac{\sum_i R_i}{n_i}$</td>
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<tr>
<td></td>
<td>Vertical</td>
<td>$C_{VBR} = VBR_i = \frac{l_i}{V_{avg}}; \quad V_{avg} = \frac{\sum_i l_i}{n_i}$</td>
</tr>
<tr>
<td>Driver’s Workload</td>
<td>Workload</td>
<td>$C_{WL} = WL_i = U \cdot E \cdot S \cdot R_f + C \cdot WL_{i-1}$</td>
</tr>
</tbody>
</table>
The main characteristics are:

- **Multicriteria analysis** (7 combined risk criteria)
- **Relative, continuous and dimensionless formula**
- **5 Probabilistic based quality ranges** (previously only 3)
- **Bounded between 1 (Riskiest) – 0 (Safest)**

\[
Q_{j_i}(x) = \text{CDF} = \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{x - \mu}{\sigma \sqrt{2}} \right) \right]
\]
Geometric - Risk Analysis Model

Operating Speed Variation Summarises the Interactions of Geometric Characteristics and Driver Workload and provides a measure of overall Route Performance Quality:

Very Good:  < 5 km/h
Good:        5-10 km/h
Fair:        10-20 km/h
Poor:        20-30 km/h
Very Poor:   > 30 km/h
**Risk Criteria Model**

Hence, this model is based on a **Hierarchical continuous distribution function**, which allow us to:

1. **Analyze any road in both direction.**
2. **Determine the overall risk.** Defining critical, fair or good locations (not only roads)

<table>
<thead>
<tr>
<th>ID</th>
<th>Type</th>
<th>Ini Ch</th>
<th>End Ch</th>
<th>Forward</th>
<th>Reverse</th>
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</table>
Geometric - Risk Analysis Model

➢ Risk Criteria Model

Hence, this model is based on a **Hierarchical continuous distribution function**, which allow us to:

1. Analyze any road in both direction.
2. Determine the overall risk. Defining critical, fair or good locations (not only roads)
3. Risk rank locations. To prioritize correction actions
Roughan & O’ Donovan Innovative Solutions

Geometric - Risk Analysis Model

**Risk Criteria Model**

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1. Analyze any road in both directions.
2. Determine the overall risk. Defining critical, fair or good locations (not only roads)
3. Risk rank locations. To prioritize correction actions
4. Describe risk causes. Define appropriate strategies (Horizontal, vertical...)

<table>
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<tr>
<th>ID</th>
<th>Type</th>
<th>ChIni</th>
<th>ChEnd</th>
<th>QI</th>
<th>QII</th>
<th>QIII</th>
<th>Qssd</th>
<th>Qcrr</th>
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**Criteria**

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<td>Qvrr</td>
<td>Vertical Index</td>
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<tr>
<td>Qwl</td>
<td>Driver Workload</td>
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</table>

**Description**

- Design Speed
- Operating Speed
- Skid Resistance
- Visibility Distance
- Horizontal Index
- Vertical Index
- Driver Workload
Risk Analysis Process
Risk-Based Geometric Design

Risk Analysis process

Consequently, the work process is the following:

1. Define road alignment and Visibility (forward and backward)
Since this project is focused on “legacy” routes that evolved from historical tracks and lack clear and consistent engineering roads.

No alignment data are available, only GPS data (SCRIM Surveys)

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</table>

the model is able to define the **Horizontal Alignment** of any road from its GPS data
Geometric Definition – Horizontal Alignment

A mathematical model has been defined to determine the alignment of any road based on bendiness. Firstly, we define the alignment elements, which are delimited with:

- **Azimuth Angle**
- **Azimuth Variation**
  - Tangent -> 0
  - Bend -> Constant
  - Transition -> Variable

Additionally, we are able to detect consecutive curves.
Geometric Definition – Vertical Alignment

Similarly, the slope and vertical curve can be defined:

**Slope**
- Slope
- Length
- KP and Altitude Ini and End

**Bend**
- Length
- Radius
- A parameter (degree variation)
- Kv of slope and degree variation
- KP and Altitude Ini and End
Since this project is focused on “legacy” routes that evolved from historical tracks and lack clear and consistent engineering roads.

**No alignment data are available, only GPS data from routine SCRIM Surveys**

Hence, a mathematical model was developed to define:

1. **Horizontal Road Alignment**
2. **Vertical Road Alignment**
3. **Stopping Sight Distance**

Necessary data to obtain:

- **Risk Analysis inputs**
- **Alignment information**
- **Critical alignment points**
- **Road alignment analysis**
Risk-Based Geometric Design

- **Risk Analysis process**

Consequently, the work process is the following:

1. Define road alignment and Visibility (forward and backward)
2. Determine Operating and design speed
Consequently, Speed Model was defined to calculate the curve and tangent operating speeds of any road alignment.

Operating Speed Regression (Curves)

\[ V_{85} = -0.0509 \cdot CCR + 92.337 \]  \hspace{1cm} R^2 = 0.8694 \text{ (Lineal Regression)}

\[ V_{85} = 2 \cdot 10^{-6} \cdot CCR^2 - 0.0528 \cdot CCR + 92.577 \]  \hspace{1cm} R^2 = 0.8696 \text{ (Polynomial Regression)}

\[ V_{85} = 94.824 \cdot e^{-8 \cdot 10^{-4} \cdot CCR} \]  \hspace{1cm} R^2 = 0.881 \text{ (Power Regression)}
Pilot Sites for Real Operating Speed Data
Operating Speed—Speed regression

The approximation formula results in:

Operating Speed Comparison

Accuracy level

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<tr>
<th>Order</th>
<th>R²</th>
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<td>0.63</td>
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</table>
Risk-Based Geometric Design

- **Risk Analysis process**

Consequently, the work process is the following:

1. Define road alignment and Visibility (forward and backward)
2. Determine Operating and design speed
3. **Analyze risk for both directions**
4. Determine critical point
Risk Analysis process

Consequently, the work process is the following:

1. Define road alignment and visibility (forward and backward)
2. Determine Operating and Design speed
3. Analyze risk for both directions
4. Determine critical locations
5. Design improvement scheme
6. Re-analyze risk after actions
N66 Case Study
Former N66 Route Details

- 23 km between Loughrea and Gort, County Galway.
- Road Width Varies between 5.5m and 6.5m.
- Typical Verge Width: 2m.

- Recorded Collision History: 67 collisions over 7 Years
  - 3 No. Serious Collisions (2009 – 2013)
Potential cluster of Material Damage Collisions at Curve 94

Potential cluster of Material Damage Collisions at Gortnamacken Bridge
N66 – Derived Horizontal Alignment

- Existing N66 alignment derived from available routine SCRIM Survey GPS data

<table>
<thead>
<tr>
<th>Curve Radius</th>
<th>DN-GE0-03031 Standard for 100km/h Design Speed (Table 1.3)</th>
<th>Number of Curves</th>
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<tr>
<td>&lt;127m</td>
<td>Beyond Standard</td>
<td>8 (6.2%)</td>
</tr>
<tr>
<td>127m - 180m</td>
<td>Beyond Standard</td>
<td>9 (7.0%)</td>
</tr>
<tr>
<td>180m - 255m</td>
<td>Four Steps Below Desirable Minimum</td>
<td>16 (12.4%)</td>
</tr>
<tr>
<td>255m - 360m</td>
<td>Three Steps Below Desirable Minimum</td>
<td>15 (11.6%)</td>
</tr>
<tr>
<td>360m – 510m</td>
<td>Two Steps Below Desirable Minimum</td>
<td>14 (10.9%)</td>
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<td>510m – 720m</td>
<td>One Steps Below Desirable Minimum</td>
<td>21 (16.3%)</td>
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<td>&gt;720m</td>
<td>Desirable Minimum</td>
<td>46 (35.6%)</td>
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</table>

48 of 129 (37.2%) of horizontal curves are more than 2 Steps below Des. Min.

17 bends (13%) are beyond the lowest range of the Design Standards.
Existing N66 alignment Risk Profile determined from Risk Model

2 sites have very high risk ratings and 4 more are high
N66 – Existing Alignment Risk Profile

N66 – Risk Analysis

Quality Rates

<table>
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<tr>
<th>Rate</th>
<th>Value</th>
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<td>Poor</td>
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<td>Good</td>
<td>0.50</td>
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<tr>
<td>Very Good</td>
<td>0.25</td>
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Gortnamacken Bridge

Curve 94
Existing N66 alignment Operating Speed Profile determined from Risk Model

The Speed Variation along N66 Route was calculated at 69 km/h.
Indicative horizontal realignments were developed at the two highest Overall Risk locations.

- A compliant DN-GEO-03031 alignment (Desirable Minimum).
- A reduced standard alignment (3 or 4 Steps Below Desirable Minimum).

These indicative realignments were remodeled to determine the optimal solution to provide an alignment that is consistent with the adjacent sections of road.

The optimal indicative realignments comprised of two realignment sections totaling 1.2km in length.
N66 – Optimal Risk-Based Indicative Realignments

<table>
<thead>
<tr>
<th>Section</th>
<th>Alignment Standard</th>
<th>Realignment Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gortnamacken Bridge</td>
<td>Minimum Desirable</td>
<td>800m</td>
</tr>
<tr>
<td>Curve 94</td>
<td>Three Steps below</td>
<td>400m</td>
</tr>
</tbody>
</table>
N66 – Realignment Risk Profile

N66 realignment Risk Profile determined from Risk Model

Overall Risk at Curve No. 94 reduced from 0.953 to 0.428

Overall Risk at Gortnamacken reduced from a peak of 0.921 to 0.237
13% of the existing N66 horizontal curves are non-compliant with lowest level of the Design Standard.

Highest Risk Rating: 0.953.

2 realignment sections totaling 1.2km in length: 5.2% of 23km.

Highest Risk Rating: Reduced to 0.768.

Speed Variation falls from 69 km/h to 26 km/h: Very Poor to Poor.
N76 at Seskin, Co. Tipperary
Case Study
N76 – Case Study Route

Extents of N76 Study Route

N76_M_2016_019
N76_M_2016_020
N76_M_2016_021
N76 Study Route Details

- 7 km.
- Width: 6.3 m to 7.2m with 0.3m Hard Strips.
- Typical Verge Width of 2m.
- Bendy alignment
  - 3 sharp bends: 163m, 196m and 214m - 4 or 5 Steps below Des. Min. @ 100 km/h
  - Several other bends typically 400m to 900m R.
- Recorded Collision History: 22 no. over 20 years at 3 sites
Existing N76 alignment Risk Profile determined from Risk Model
N76 – Existing Operating Speed Profile

The Speed Variation was calculated at 17 km/h = FAIR.
N76 – Indicative Realignments

- Risk-Based Indicative Realignment for one sample site

<table>
<thead>
<tr>
<th>Section</th>
<th>Alignment Standard</th>
<th>Realignment Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curve 57</td>
<td>255m Radius. 3-Steps below Desirable Minimum</td>
<td>400m</td>
</tr>
</tbody>
</table>
N76 – Realignment Risk Profile

Sample Realignment Risk Profile determined from Risk Model

Overall Risk at Curve No. 57 reduced from 0.688 to 0.372
N71 Innishannon to Bandon, Co. Cork Case Study
N71 – Case Study Route

Bends 24 & 25

Extents of N71 Study Route
N71 Study Route Details

- 6 km between the Inishannon and Bandon.
- Width: 7.6m with 2.5m Hard Shoulders or 0.5m Hard Strips.
- Verge Width: 1 to 2m.
- Bendy:
  - several 200m Radius bends
  - 1 particularly tight curve of <100m.
- Risk Mitigation Measure: High Friction Surfacing
- Collision History: 52 collisions over 7 years
N71 – Existing Alignment Risk Profile

High Overall Risk Rating at Curve No.25 and 26
The Speed Variation was calculated at 27 km/h = POOR.
Risk-Based Indicative Realignment Consistent with General Bendiness

<table>
<thead>
<tr>
<th>Section</th>
<th>Alignment Standard</th>
<th>Realignment Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curves 25 and 26</td>
<td>180m Radius. 4-Steps below Desirable Minimum</td>
<td>500m</td>
</tr>
</tbody>
</table>
Conclusions
Conclusion

The project has obtained:

1. A Risk Analysis Model capable of preforming risk analysis at multiple scales (i.e. National, Regional, Local).

2. Automated procedures & models to provide:
   a. Alignment definition (horizontal & vertical)
   b. Stopping Sight distances
   c. Operating speeds

3. Coupling of these models provides the means to:
   a) perform risk screening exercises and develop roads needs studies at National and Regional levels; and to
   b) Optimise route planning (rolling programmes) and phasing of improvements to optimise (i) Risk, (ii) Performance (consistency) and (iii) Cost.
Risk-Based Geometric Design for Roads

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Tom Casey – Transport Infrastructure Ireland