Risk-Based Geometric Design for Roads

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Context & The Challenge for Road Network Management

Road Network Management

Context & The Challenge for Road Network Management

1.	National Road Network Length	= 5,300 km	
2.	Motorway Network	= 900 km	
3.	High-Quality National Primary Roads	= 1,350 km	
4.	Low-Quality National Primary Roads	= 400 km	
5.	National Secondary Road Network	= 2,650 km	Mostly legacy roads
6.	Legacy National Road Network	= 3,000 km approx.	57% of Total
7.	Regional Road Network	= 13,000 km !	90% legacy roads ?

"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 !!

Road Network Management

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?**

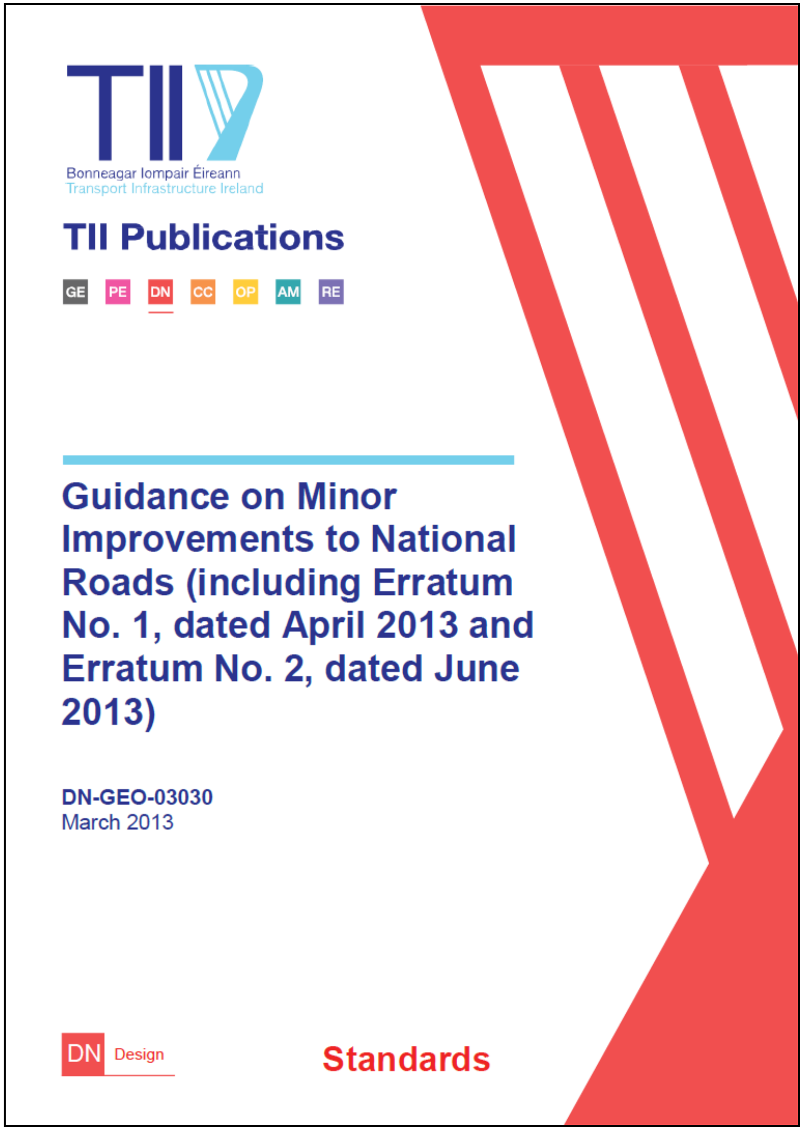
Road Design Standards

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


Bonneagar Iompair Éireann
Transport Infrastructure Ireland

TII Publications

GE PE DN CC OP AM RE

Guidance on Minor Improvements to National Roads (including Erratum No. 1, dated April 2013 and Erratum No. 2, dated June 2013)

DN-GEO-03030
March 2013

DN Design

Standards

Road Design Standards

DN-GEO-03030 Guidance on Minor Improvements to National Roads

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).

Road Design Standards

DN-GEO-03030 Guidance on Minor Improvements to National Roads

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."

DN-GEO-03030 Guidance on Minor Improvements to National Roads

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?

Road Design Standards

DN-GEO-03031
Rural Road Link Design

Design Speed

Gives a high result – of limited assistance for the Designer

Departures from Standard?

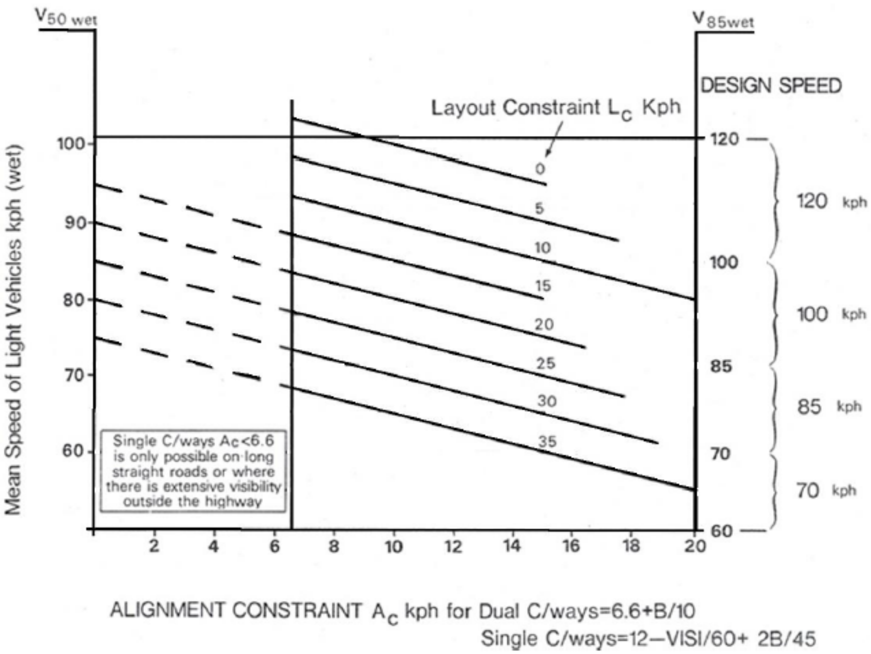
3 Steps for Type 2 Single

4 Steps for Type 3 Single.

On what Basis to select?

Justification?

Figure 1.1: Selection of Design Speed (Rural Roads)



Road Design Standards

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?

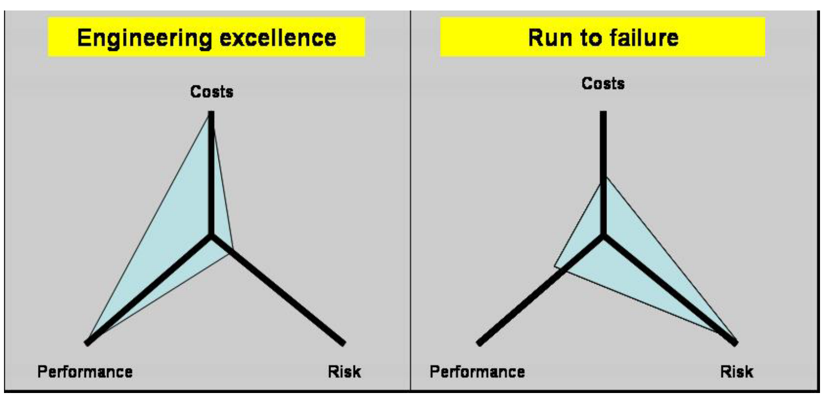
A New Approach to Appropriate Application of Road Design Standards

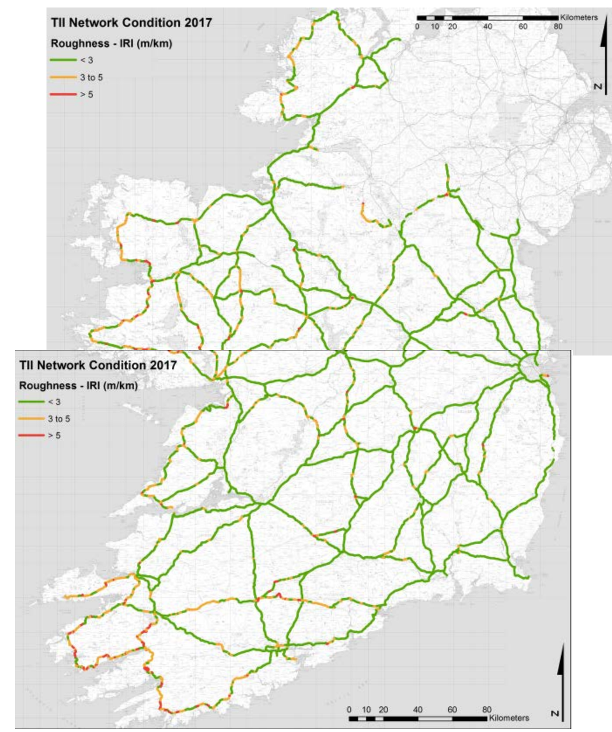
Risk-Based Geometric Design

➢ **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

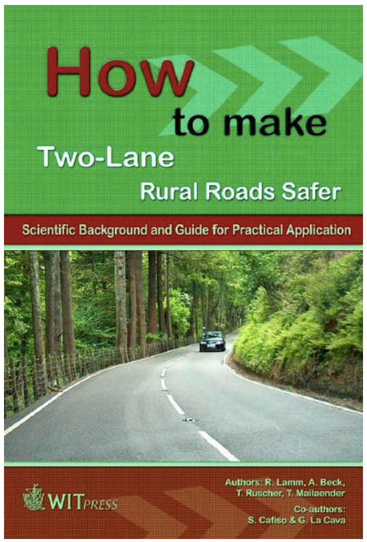
Geometric inconsistencies

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)

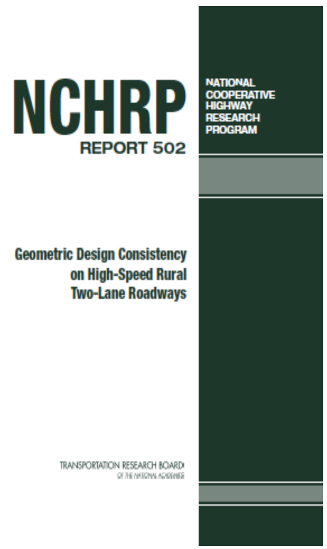


Speed

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

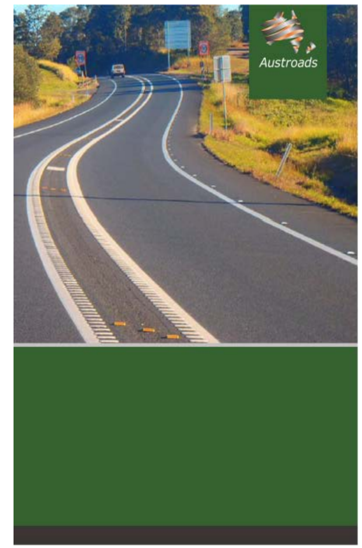
Stability

USA
National Cooperative Highway Research Program
(NCHRP, 2003)



Visibility

Australia
(Austroads Ltd., 2015)



Alignment

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

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)**

$$M_i = w_1 \cdot Q_{C_{I_i}} + w_2 \cdot Q_{C_{II_i}} + w_3 \cdot Q_{C_{III_i}} + w_4 \cdot Q_{SSD_i} + w_5 \cdot Q_{CRR_i} + w_6 \cdot Q_{VRR_i} + w_7 \cdot Q_{Wl}$$

Geometric - Risk Analysis Model

Advantages:

- ✓ **Not restricted by dimensions** (Analysis inconsistiencies)
- ✓ **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,...)

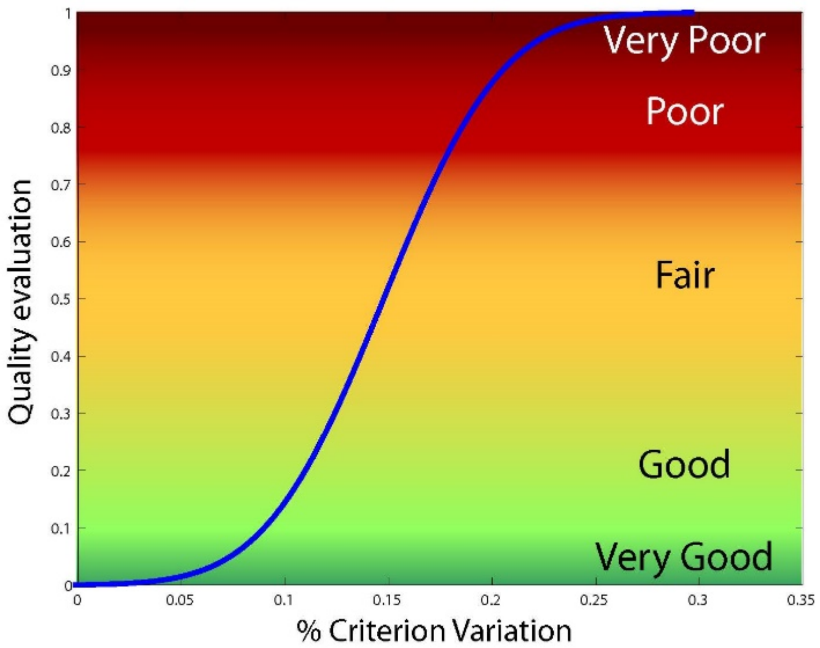
Risk Aspect	Criterion	*Equation*
Speed Variation	Design Speed	$C_I = \lvert V_{85_i} - V_d \rvert / V_d$
	Operating Speed	$C_{II} = \lvert V_{85_i} - V_{85_{i-1}} \rvert / \emptyset V_{85}\rvert$
Vehicle Stability	Side Friction	$C_{III} = e^{-\Delta f_R}; \quad \Delta f_R = f_{R_A} - f_{R_D}$
Sight Distance	Stopping Sight Distance	$C_{SSD} = SSD_i / SSD_{V_d}$
Alignment Indices	Horizontal	$C_{CRR} = CRR_i = \frac{R_i}{R_{avg}}; \quad R_{avg} = \frac{\sum_i R_i}{n_i}$
	Vertical	$C_{VRR} = VRR_i = \frac{\frac{L_i}{\lvert A \rvert}}{VR_{avg}}; \quad VR_{avg} = \frac{\sum_i \frac{L_i}{\lvert A \rvert}}{n_i}$
Driver's Workload	Workload	$C_{WL} = WL_i = U \cdot E \cdot S \cdot R_f + C \cdot WL_{i-1}$

Geometric - Risk Analysis Model

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)

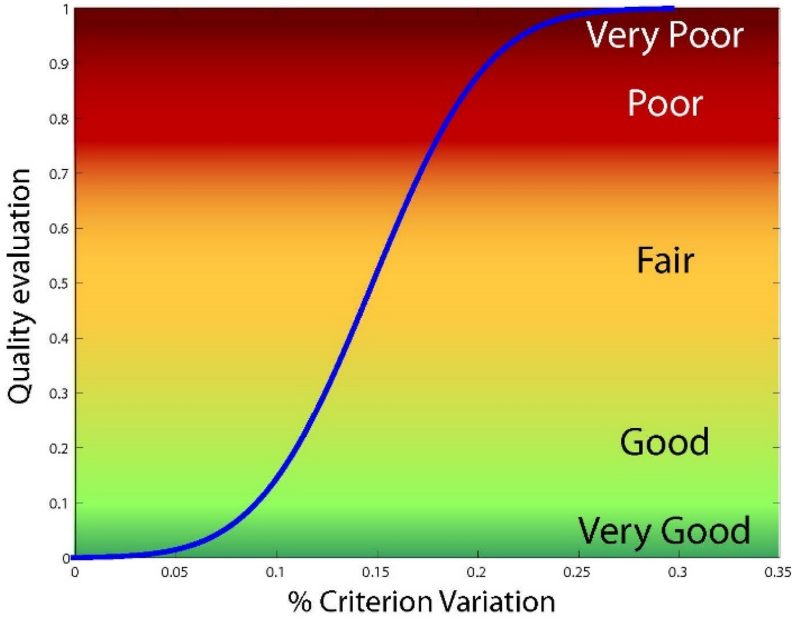
$$Q_{j_i}(x) = \text{CDF} = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right]$$



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



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)

				Risk		
ID	**Type**	**Ini Ch**	**End Ch**	**Forward**	**Reverse**	**Overall**
8	**Tangent**	678	711	0.19	0.29	**0.24**
9	**Bend**	711	857	0.41	0.43	**0.42**
10	**Tangent**	857	930	0.13	0.32	**0.22**
11	**Bend**	930	998	0.15	0.32	**0.23**
17	**Bend**	1325	1511	0.32	0.33	**0.32**
18	**Tangent**	1511	1556	0.13	0.47	**0.30**
19	**Bend**	1556	1643	0.86	0.98	**0.92**
20	**Tangent**	1643	1662	0.38	0.33	**0.35**
21	**Bend**	1662	1764	0.68	0.84	**0.76**
22	**Tangent**	1764	1896	0.30	0.30	**0.30**
28	**Tangent**	2389	2495	0.23	0.49	**0.36**
29	**Bend**	2495	2622	0.75	0.98	**0.86**
30	**Tangent**	2622	2673	0.21	0.33	**0.27**
31	**Bend**	2673	2782	0.46	0.55	**0.50**
32	**Tangent**	2782	2871	0.16	0.33	**0.25**

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

Sorted Risk

Or	ID	Type	Ini Ch	End Ch	Risk
1	19	Bend	1556	1643	0.92
2	29	Bend	2495	2622	0.86
3	21	Bend	1662	1764	0.76
4	37	Bend	4052	4189	0.54
5	31	Bend	2673	2782	0.50
6	33	Bend	2871	3021	0.46
7	9	Bend	711	857	0.42
8	28	Tangent	2389	2495	0.36
9	35	Bend	3769	3860	0.36
10	20	Tangent	1643	1662	0.35
11	13	Bend	1039	1178	0.33
12	17	Bend	1325	1511	0.32
13	34	Tangent	3021	3769	0.32
14	12	Tangent	998	1039	0.31
15	36	Tangent	3860	4052	0.31

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
4. **Describe risk causes**. Define appropriate strategies (Horizontal, vertical…)

Forward Direction

ID	Type	ChIni	ChEnd	QI	QII	QIII	Qssd	Qcrr	Qvrr	Qwl	Risk	Order
19	**Bend**	1556	1643	1	1	1	0	1	1	1	**0.86**	1st
21	**Bend**	1662	1764	0.3	0	1	1	1	1	1	**0.68**	3rd
29	**Bend**	2495	2622	0.99	1	1	0	1	1	0.37	**0.75**	2nd

Backward Direction

ID	Type	ChIni	ChEnd	QI	QII	QIII	Qssd	Qcrr	Qvrr	Qwl	Value	Order
19	**Bend**	1643	1556	1	1	1	0.86	1	1	1	**0.98**	2nd
21	**Bend**	1764	1662	0.31	0.99	1	0.99	1	1	1	**0.84**	3rd
29	**Bend**	2622	2495	0.99	0.99	1	0.89	1	1	0.99	**0.98**	1st

Criteria	Description
Q_I	Design Speed
Q_{II}	Operating Speed
Q_{III}	Skid Resistance
Q_{ssd}	Visibility Distance
Q_{crr}	Horizontal Index
Q_{vrr}	Vertical Index
Q_{wl}	Driver Workload

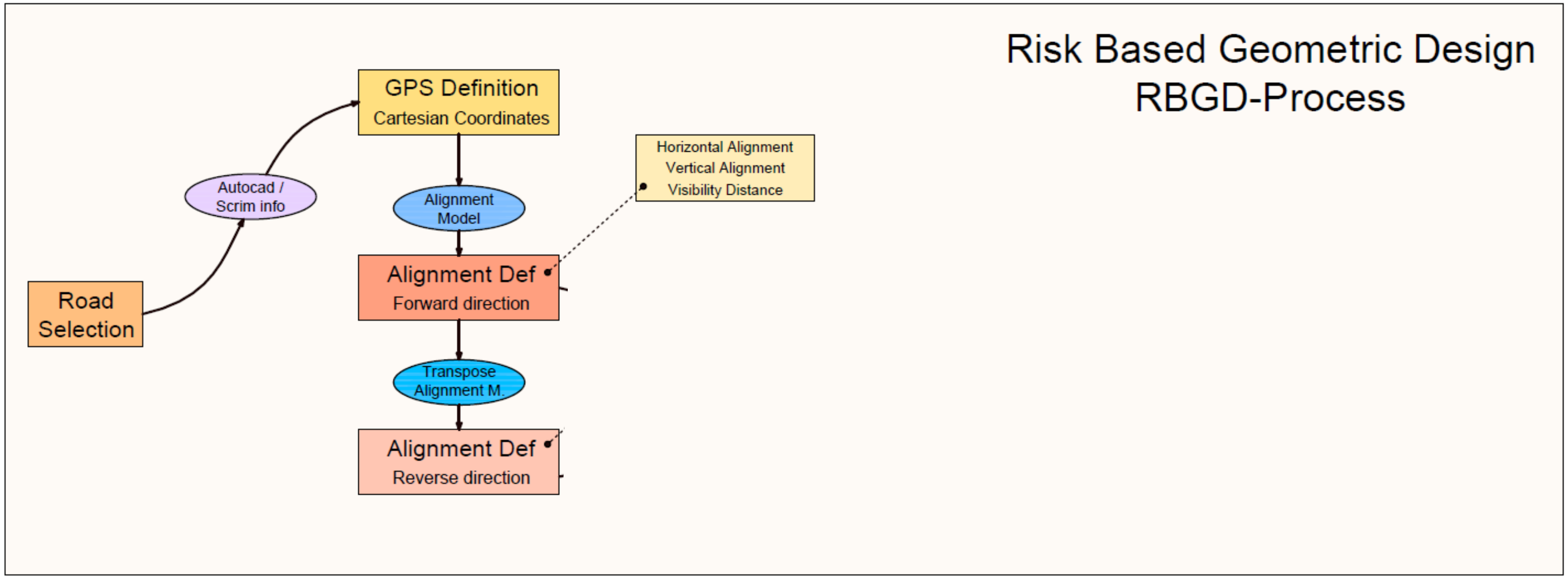
Risk Analysis Process

Risk-Based Geometric Design

➢ Risk Analysis process

Consequently, the work process is the following:

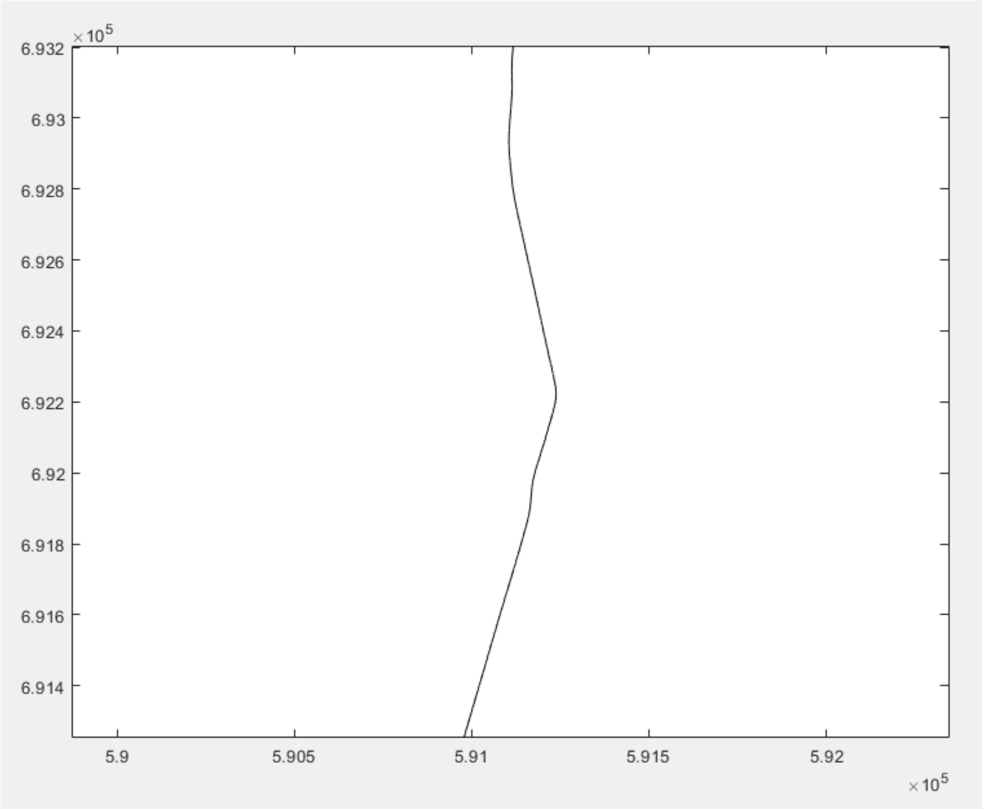
1. **Define road alignment and Visibility (forward and backward)**



Alignment Definition Model

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)



X	Y	Z
590978.1959	691253.5276	432.62
590978.4681	691254.4898	432.62
590978.7404	691255.4520	432.62
590979.0126	691256.4143	432.62
590979.2848	691257.3765	432.62
590979.5570	691258.3387	432.62
590979.8292	691259.3010	432.62
590980.1014	691260.2632	432.62
590980.3740	691261.2253	432.62
590980.6563	691262.1847	432.62
590980.9386	691263.1440	432.62
590981.2208	691264.1033	432.62
590981.5031	691265.0627	432.62
590981.7854	691266.0220	432.62
590982.0677	691266.9813	432.62
590982.3500	691267.9406	432.62
590982.6323	691268.9000	432.62
590982.9146	691269.8593	432.62
590983.1969	691270.8186	432.62
590983.4792	691271.7780	432.62
590983.7615	691272.7373	432.62
590984.0438	691273.6966	432.62
590984.3261	691274.6559	432.62

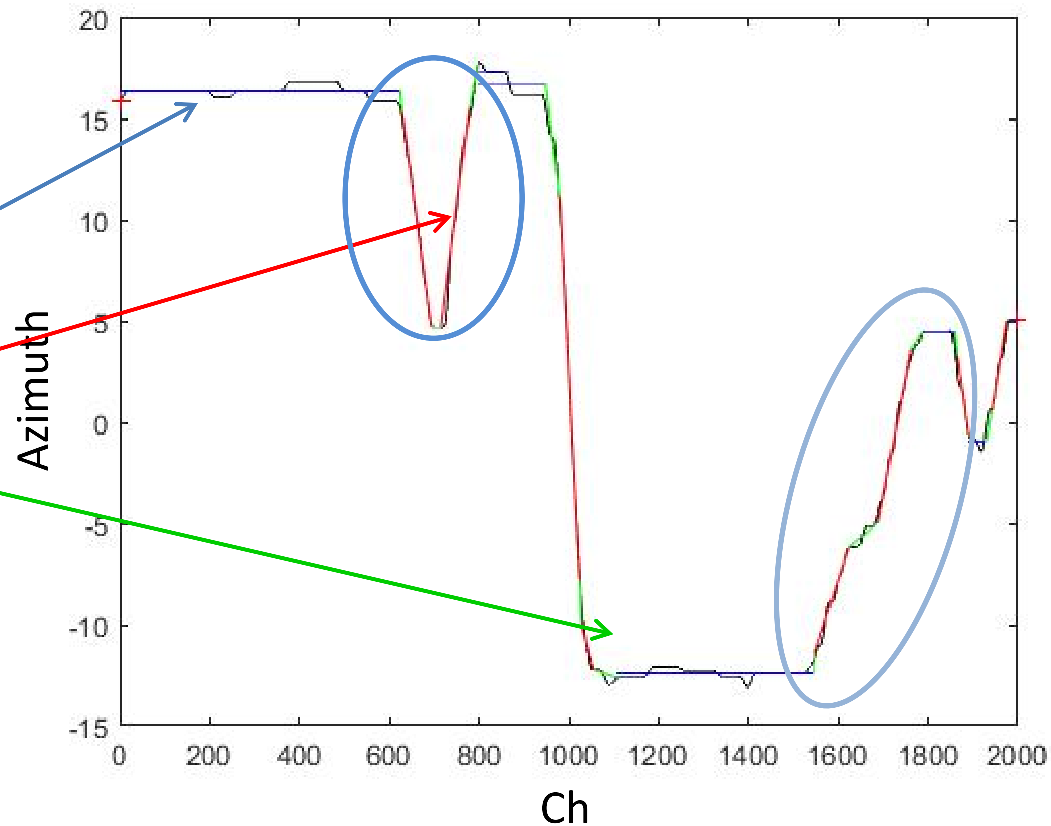
the model is able to define the **Horizontal Alignment** of any road from its GPS data

Alignment Definition Model

➢ **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

Alignment Definition Model

➢ **Geometric Definition –** Vertical Alignment

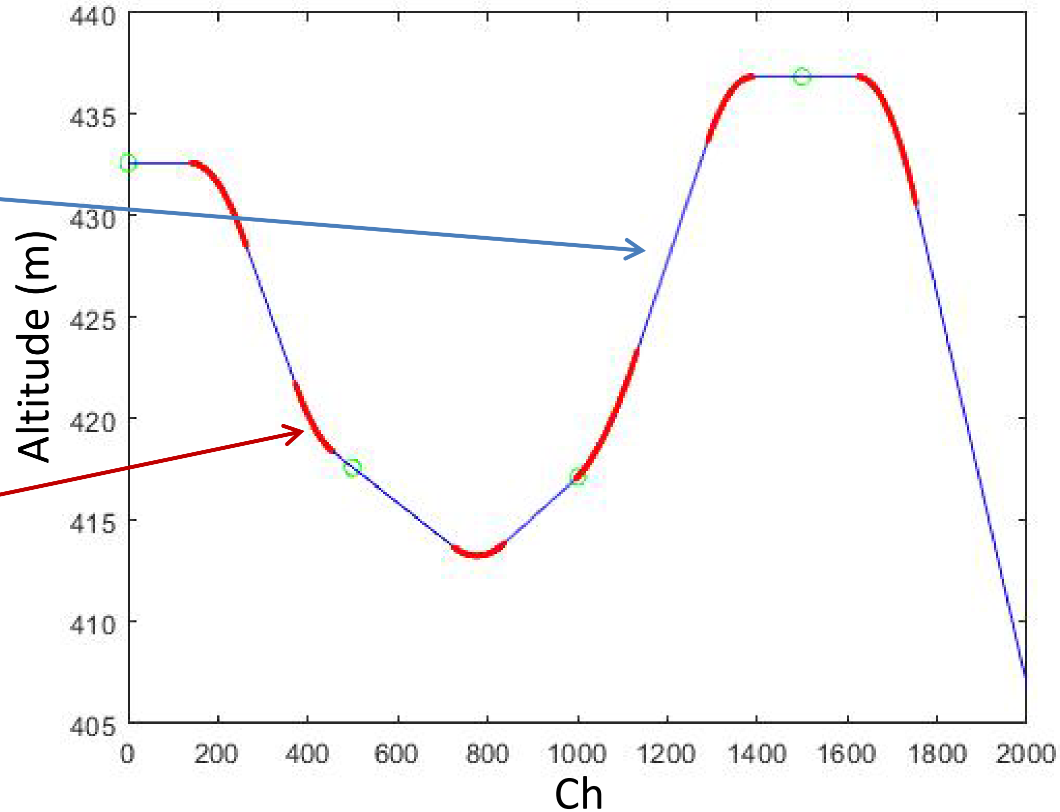
Similarly, the slope and vertical curve can be defined:

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



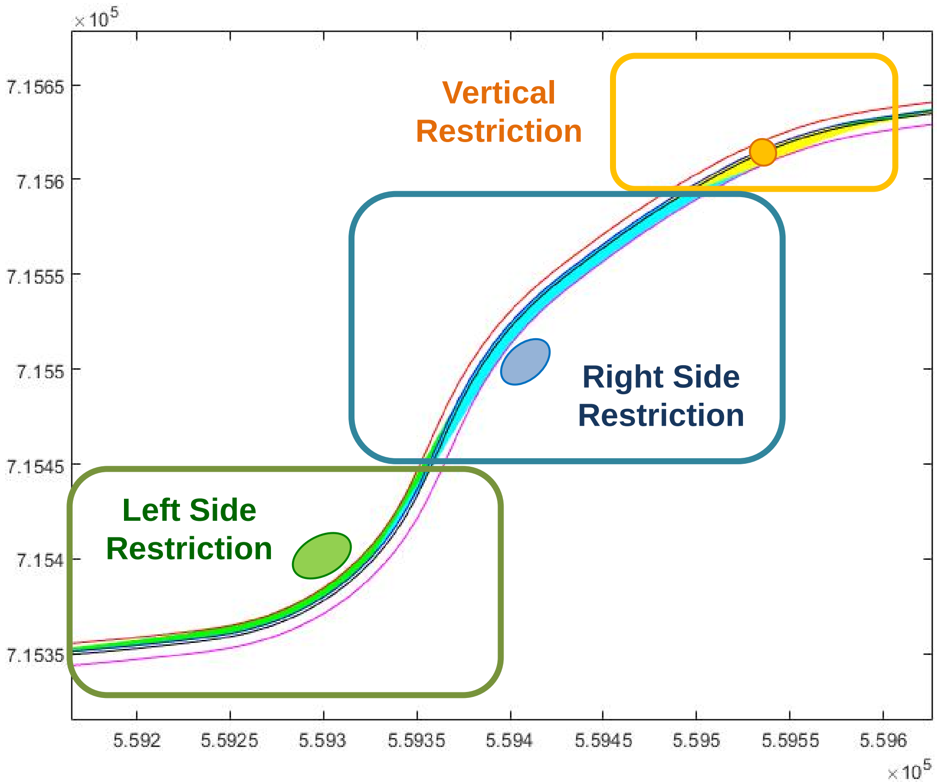
Alignment Definition Model

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:

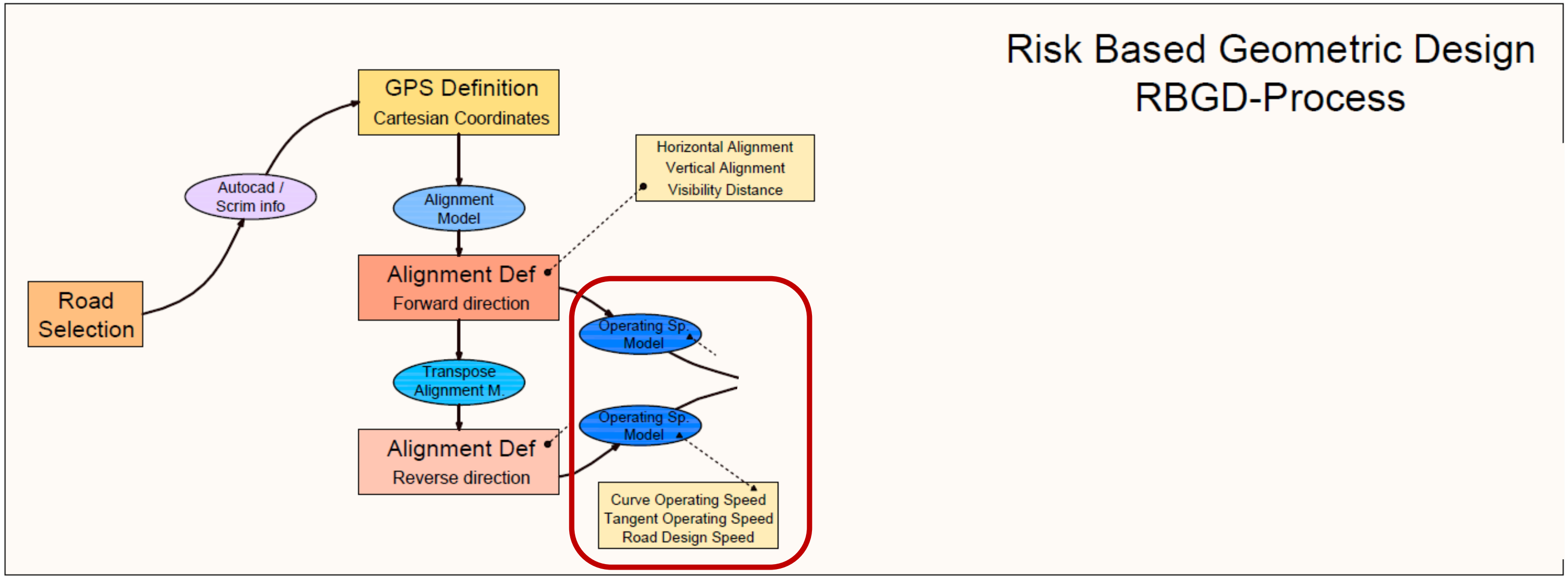
- **Risk Analysis inputs**
- **Alignment information**
- **Critical alignment points**
- **Road alignment analysis**

Risk-Based Geometric Design

➢ Risk Analysis process

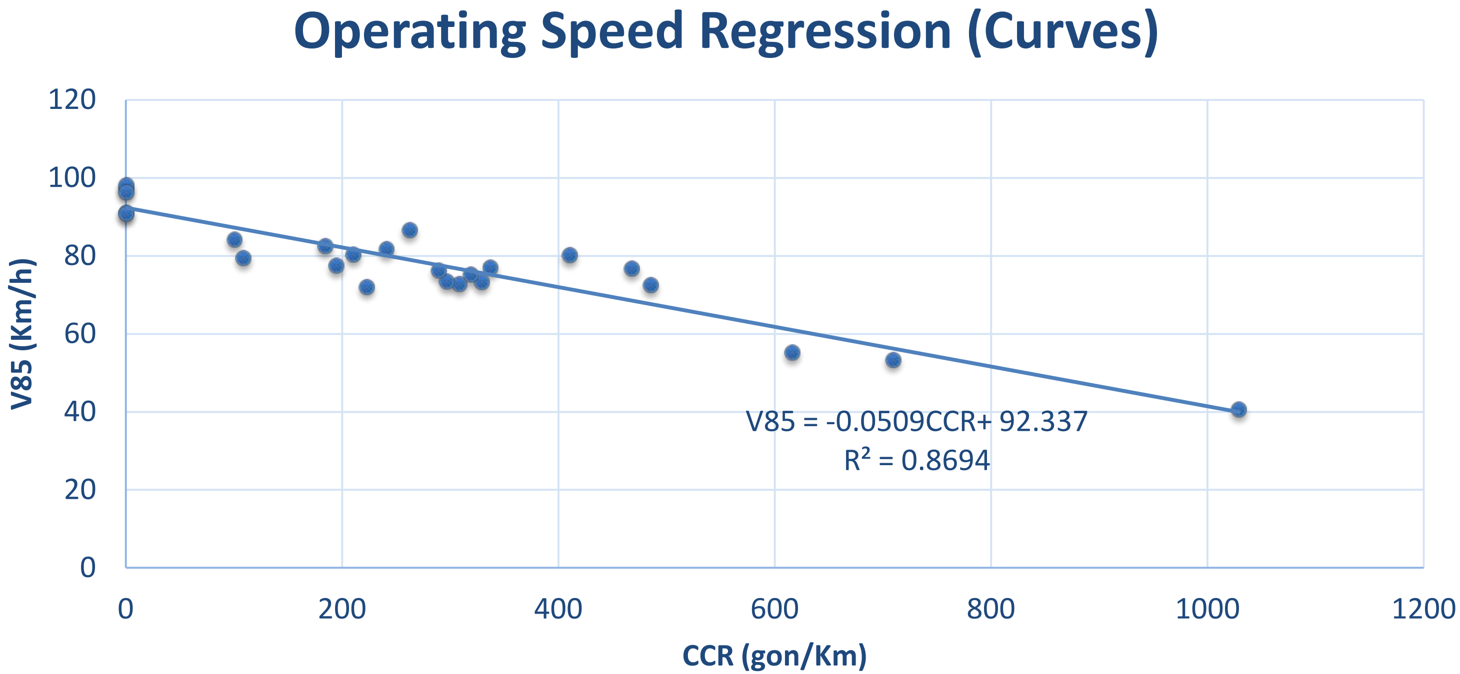
Consequently, the work process is the following:

1. Define road alignment and Visibility (forward and backward)
2. **Determine Operating and design speed**



Operating Speed Model

Consequently, Speed Model was defined to calculate **the curve and tangent operating speeds of any road alignment**

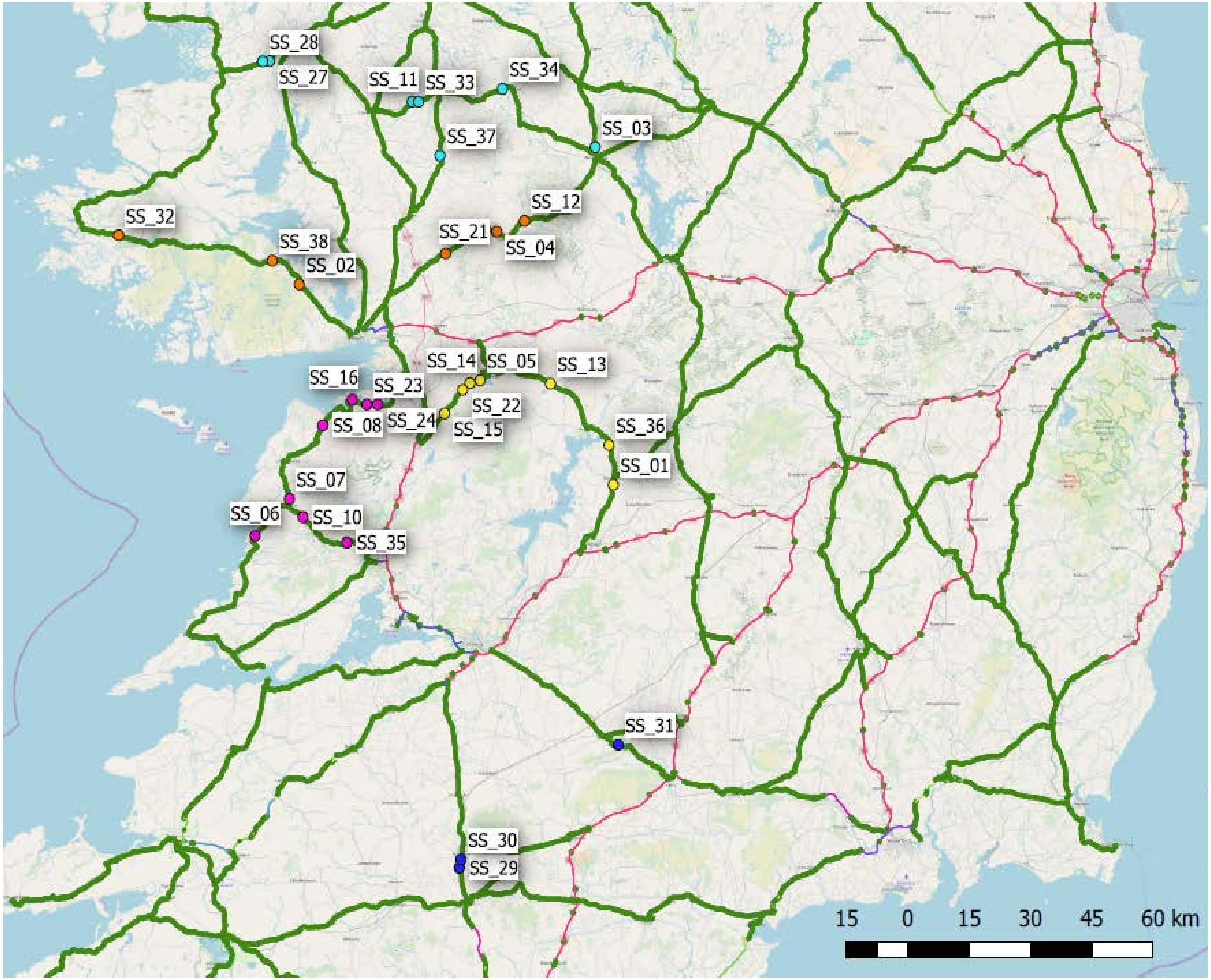


$$\boldsymbol{V_{85} = -0.0509 \cdot CCR + 92.337} \qquad \boldsymbol{R^2 = 0.8694} \textbf{ (Lineal Regression)}$$

$$V_{85} = 2 \cdot 10^{-6} \cdot CCR^2 - 0.0528 \cdot CCR + 92.577 \qquad R^2 = 0.8696 \text{ (Polynomial Regression)}$$

$$V_{85} = 94.824 \cdot e^{-8 \cdot 10^{-4} \cdot CCR} \qquad R^2 = 0.881 \text{ (Power Regression)}$$

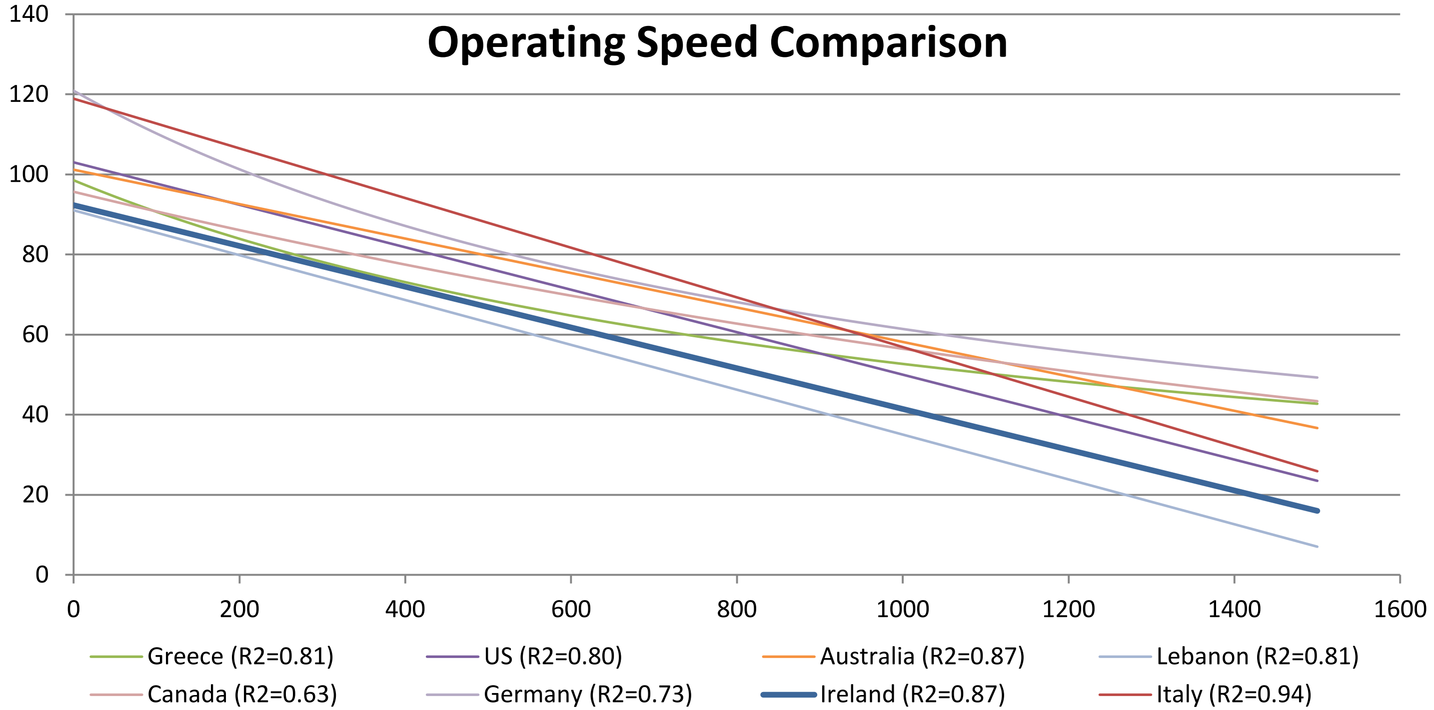
Pilot Sites for Real Operating Speed Data



Operating Speed Model

➢ **Operating Speed–** Speed regression

The approximation formula results in:



Accuracy level

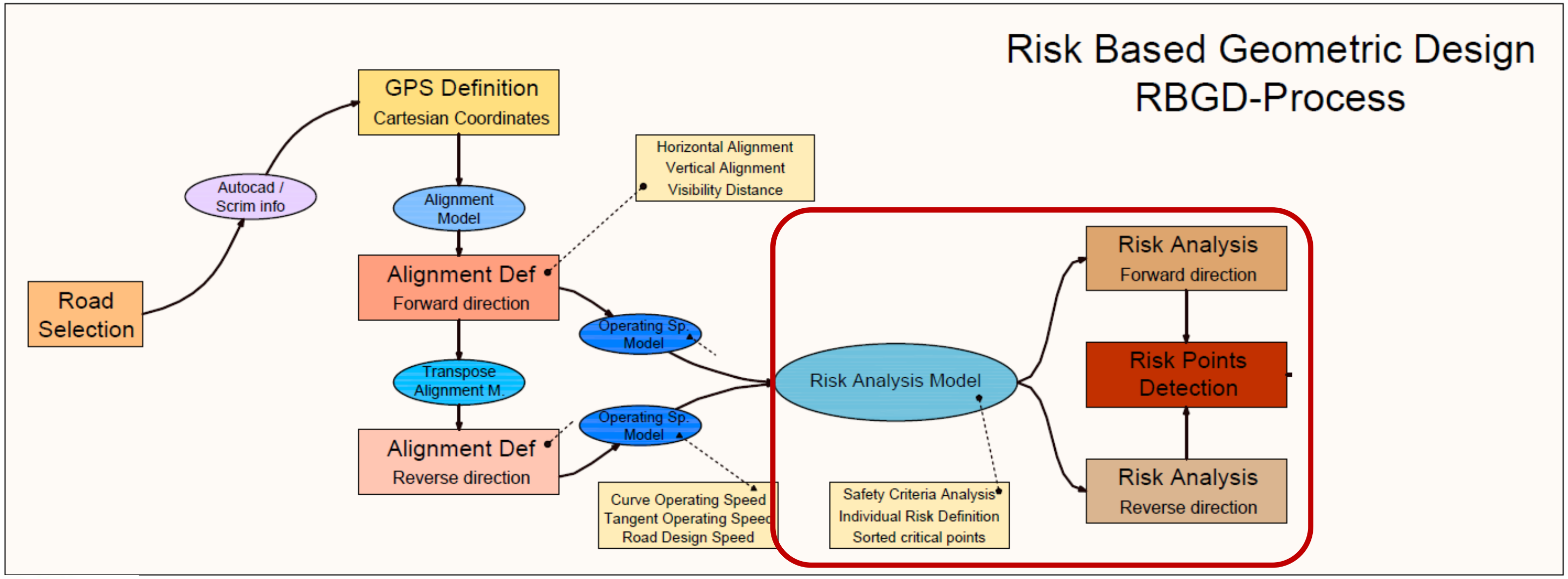
Order	R^2	Country
1	0.94	Italy
2	0.87	**Ireland**
3	0.87	Australia
4	0.81	Greece
5	0.81	Lebanon
6	0.8	US
7	0.73	Germany
8	0.63	Canada

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**

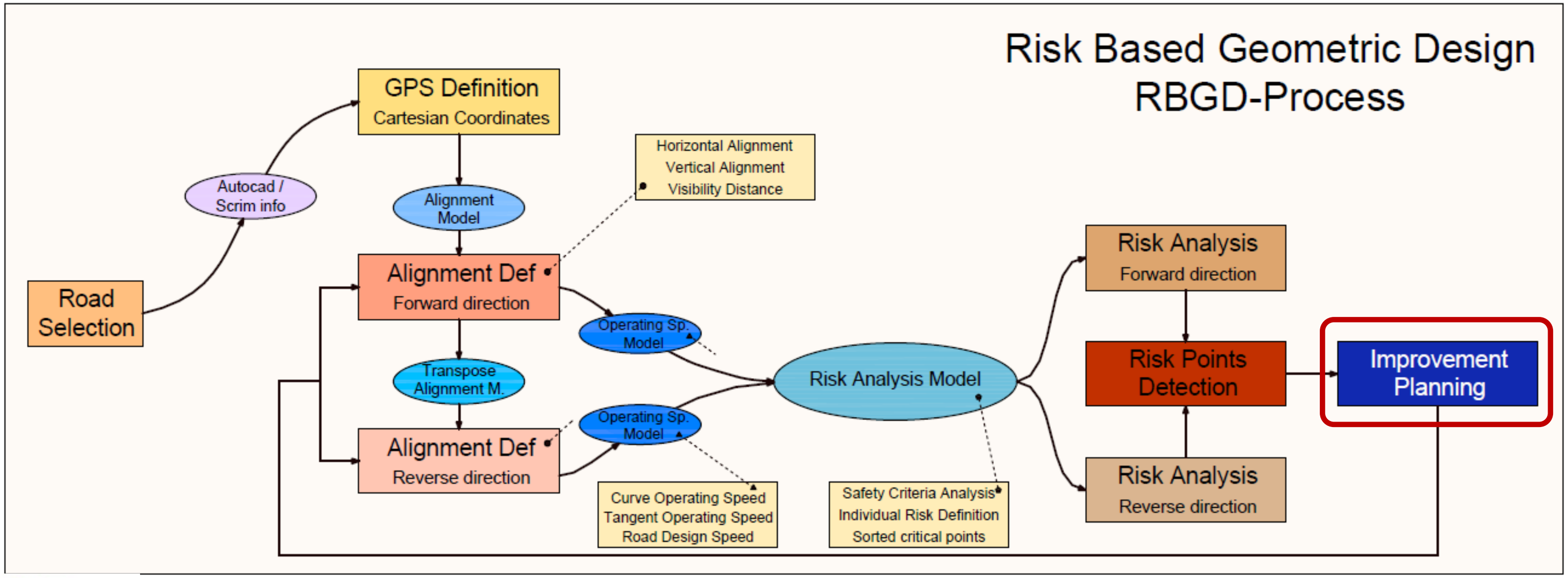


Risk-Based Geometric Design

➢ Risk Analysis process

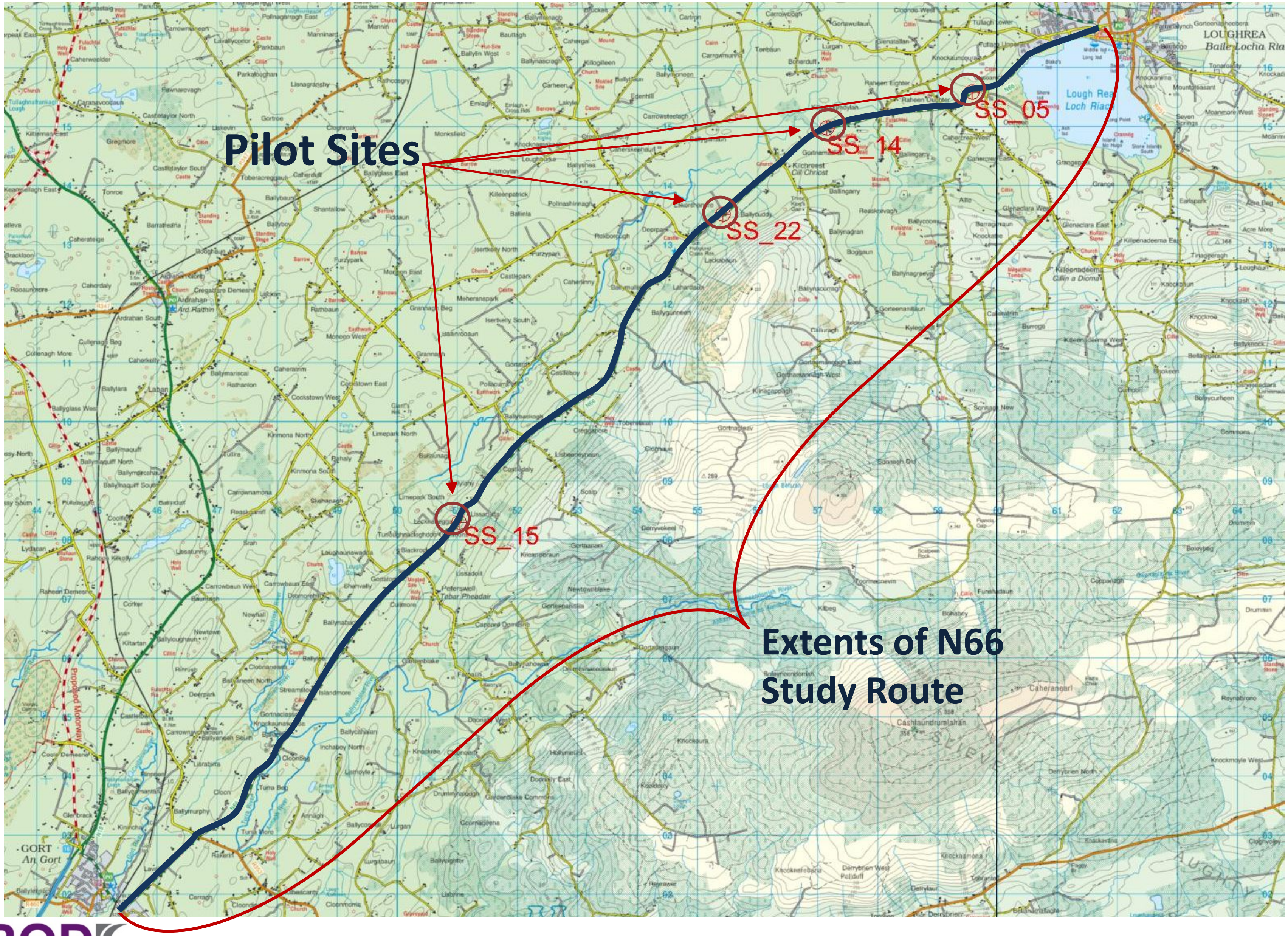
Consequently, the work process is the following:

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



N66 Case Study

N66 – Case Study Route



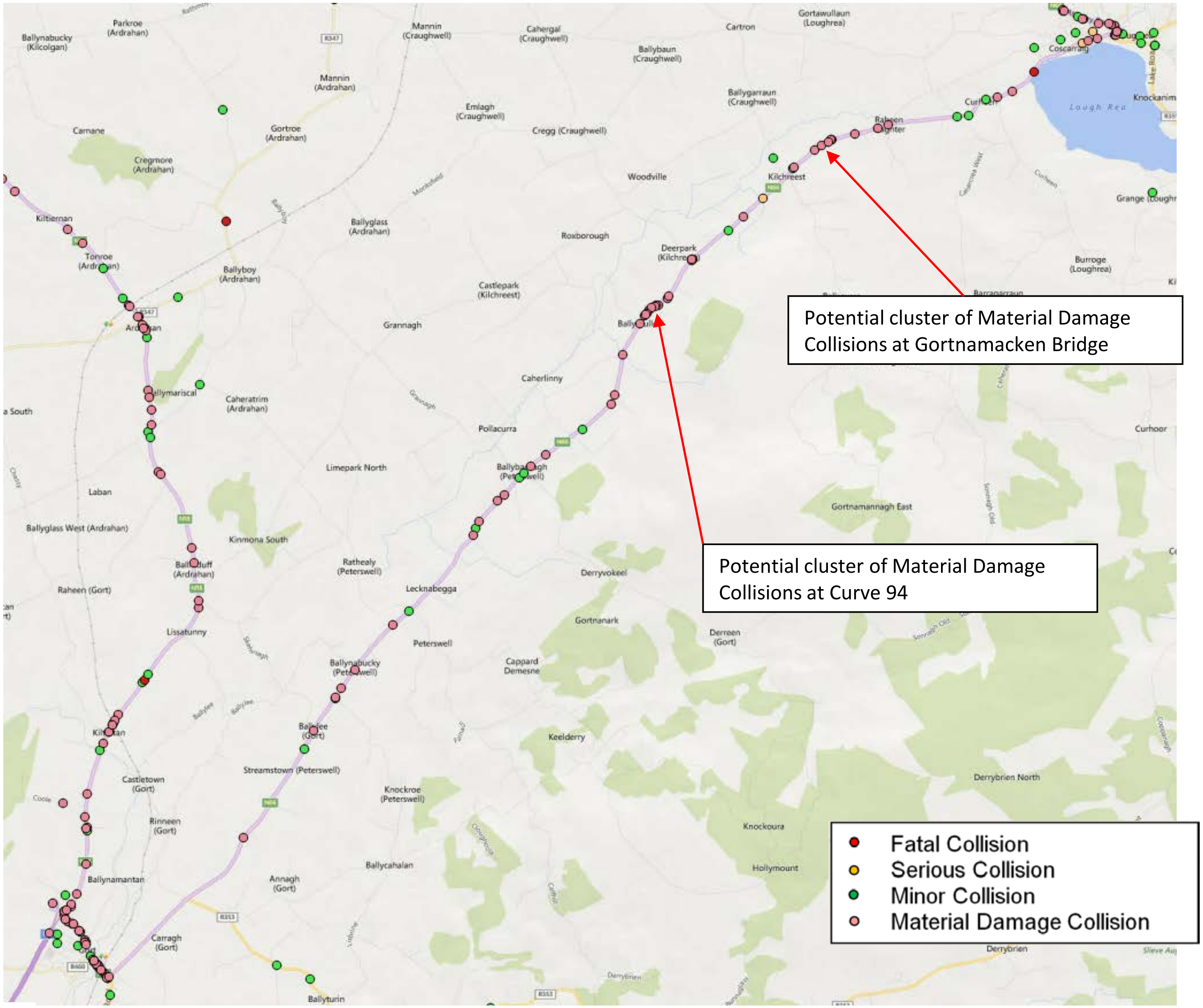
N66 – Case Study Route

➢ 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
  - 1 No. Fatal Collision (2009 – 2013)
  - 3 No. Serious Collisions (2009 – 2013)
  - 12 No. Minor Collisions (2009 – 2013)
  - 51 No. Material Damage Collisions (2014 – 2016)

N66 – Recorded Collision History



N66 – Derived Horizontal Alignment

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

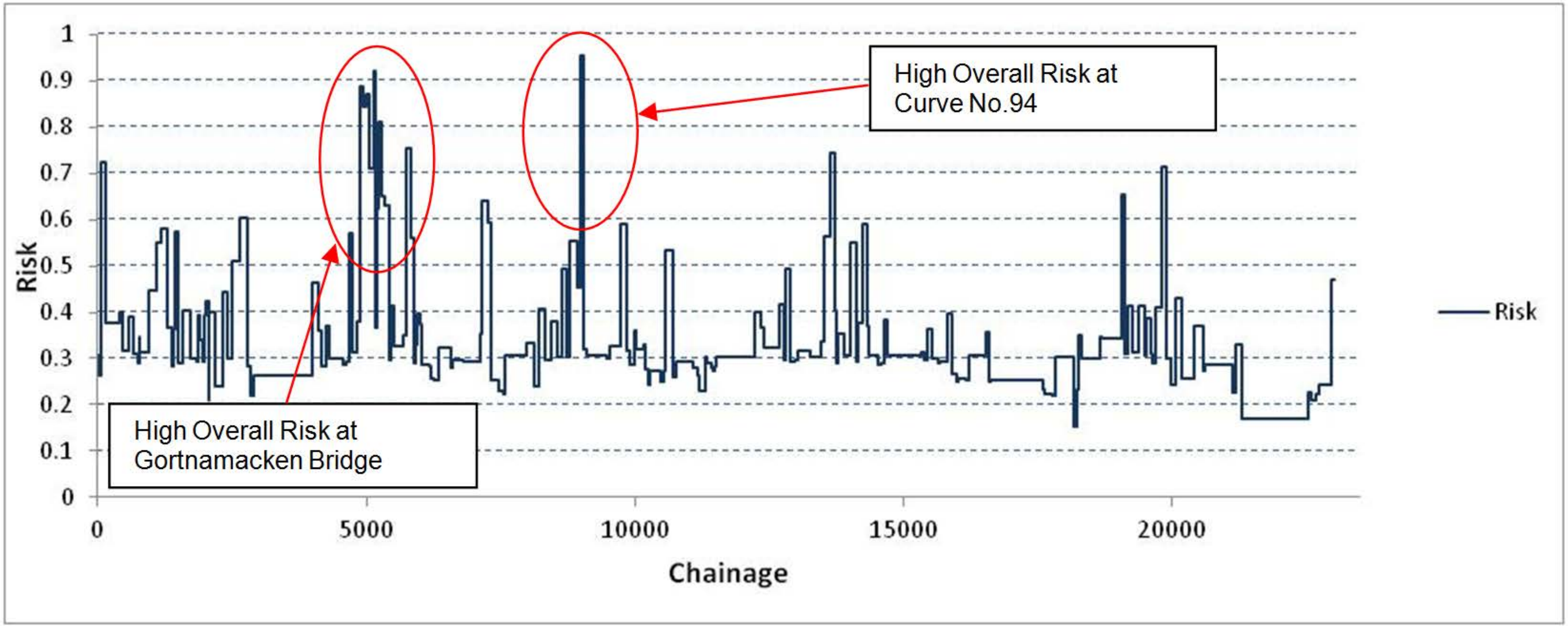
Curve Radius	DN-GE0-03031 Standard for 100km/h Design Speed (Table 1.3)	Number of Curves
<127m	Beyond Standard	8 (6.2%)
127m - 180m	Beyond Standard	9 (7.0%)
180m - 255m	Four Steps Below Desirable Minimum	16 (12.4%)
255m - 360m	Three Steps Below Desirable Minimum	15 (11.6%)
360m – 510m	Two Steps Below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

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.

N66 – Existing Alignment Risk Profile

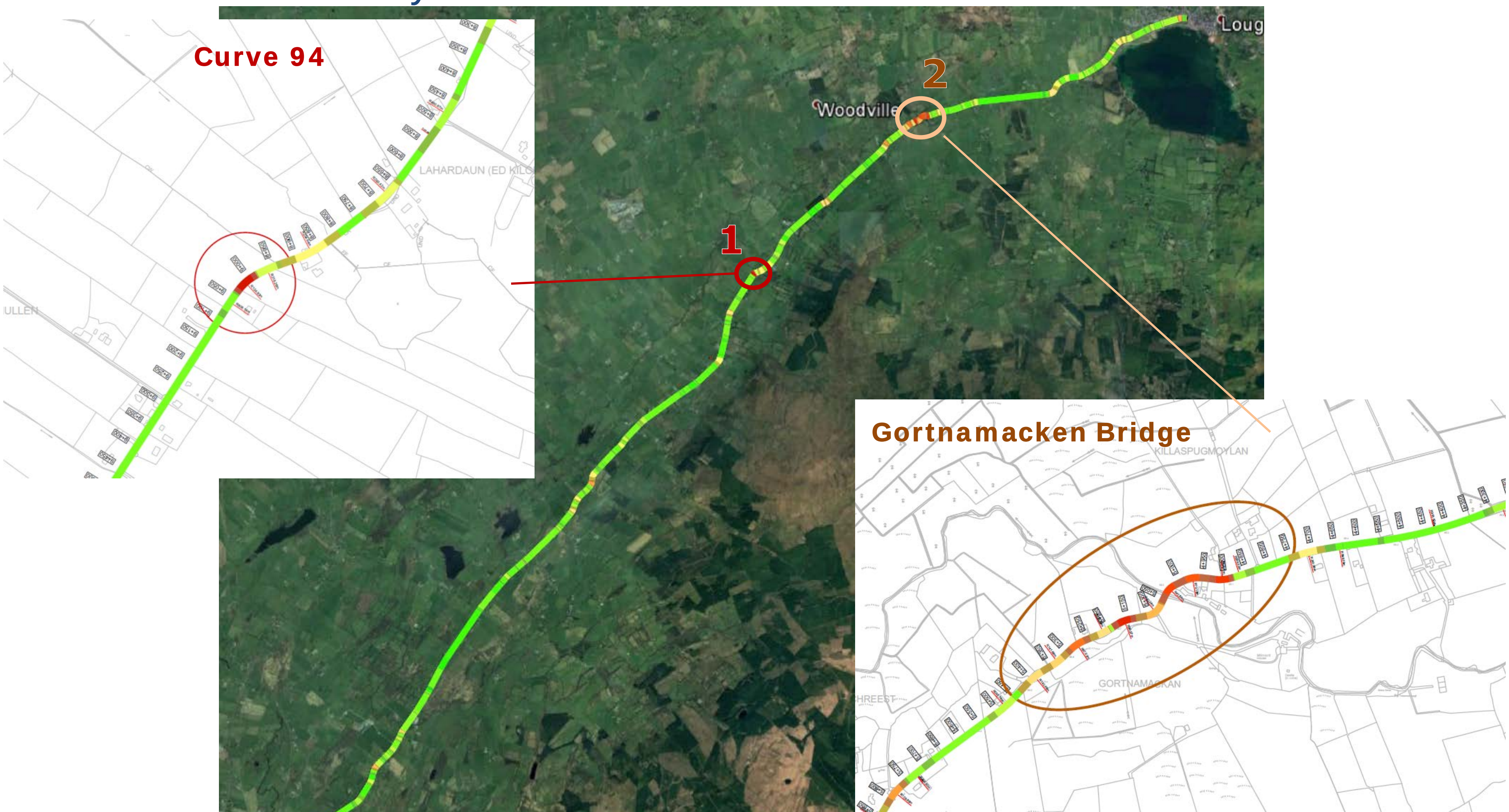
➢ **Existing N66 alignment Risk Profile determined from Risk Model**



2 sites have very high risk ratings and 4 more are high

N66 – Existing Alignment Risk Profile

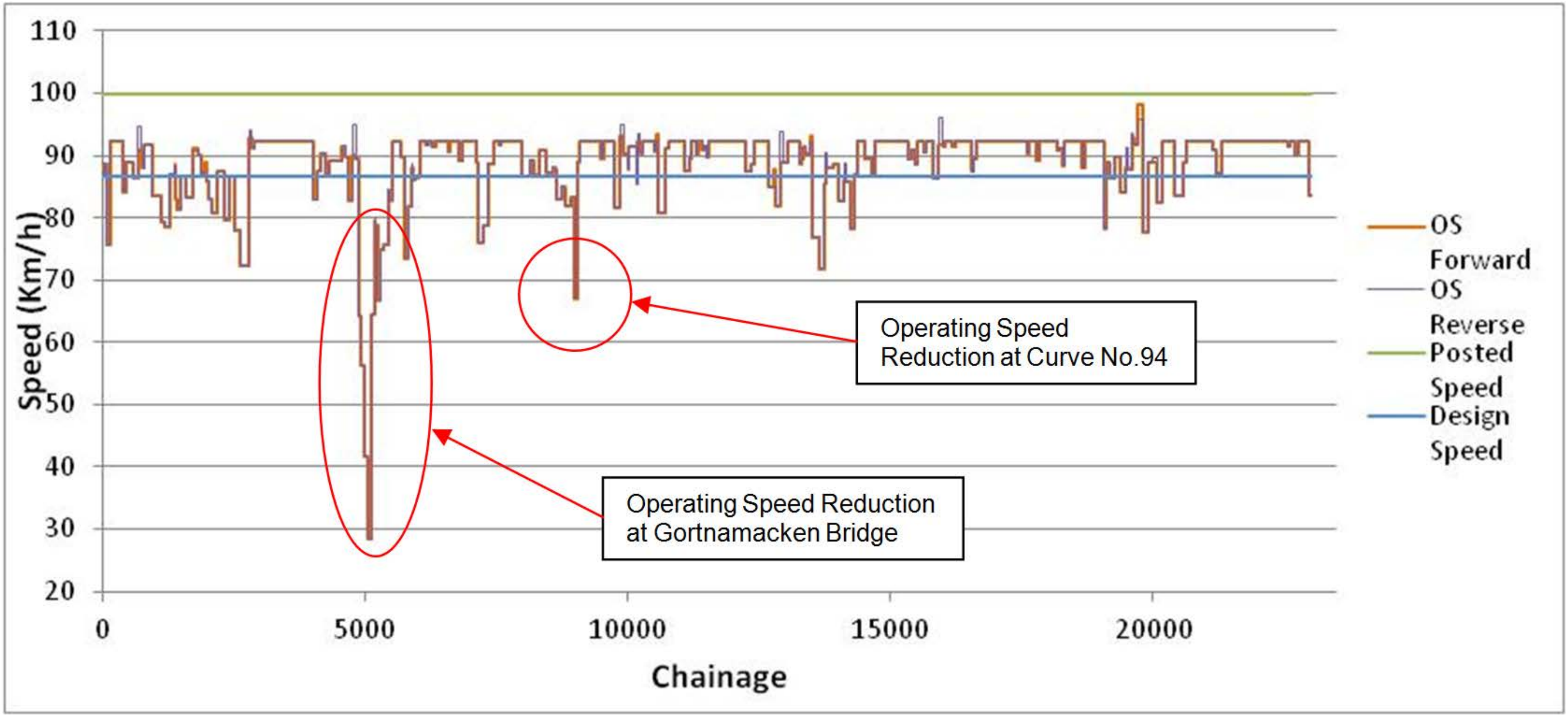
- **N66 –** Risk Analysis



Quality Rates						
Very Poor		Poor	Fair		Good	Very Good
1.00	0.90	0.75	0.50	0.25	0.10	0.00

N66 – Existing Alignment Risk Profile

➢ **Existing N66 alignment Operating Speed Profile determined from Risk Model**



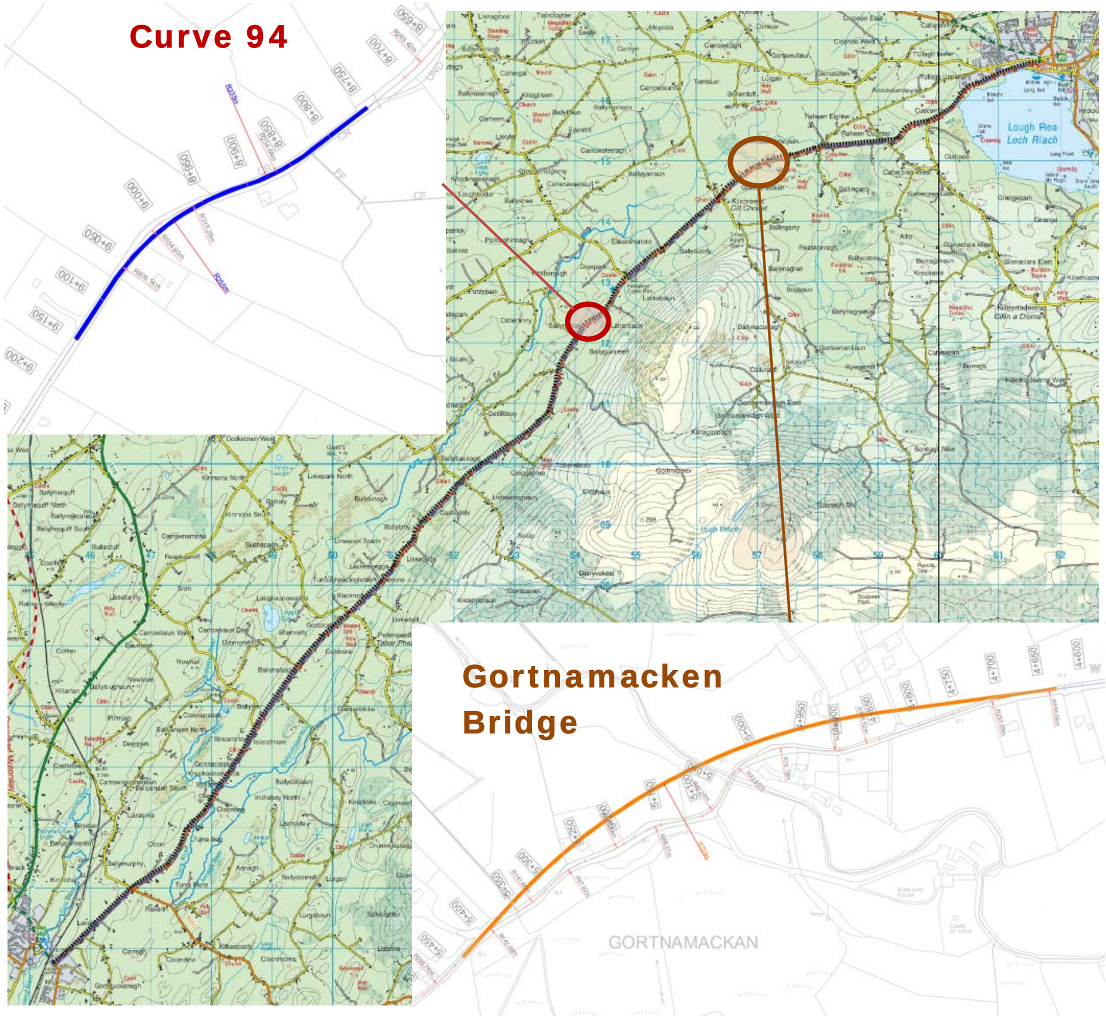
The Speed Variation along N66 Route was calculated at 69 km/h.

N66 – Indicative Realignments

- 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 Indicative Realignments

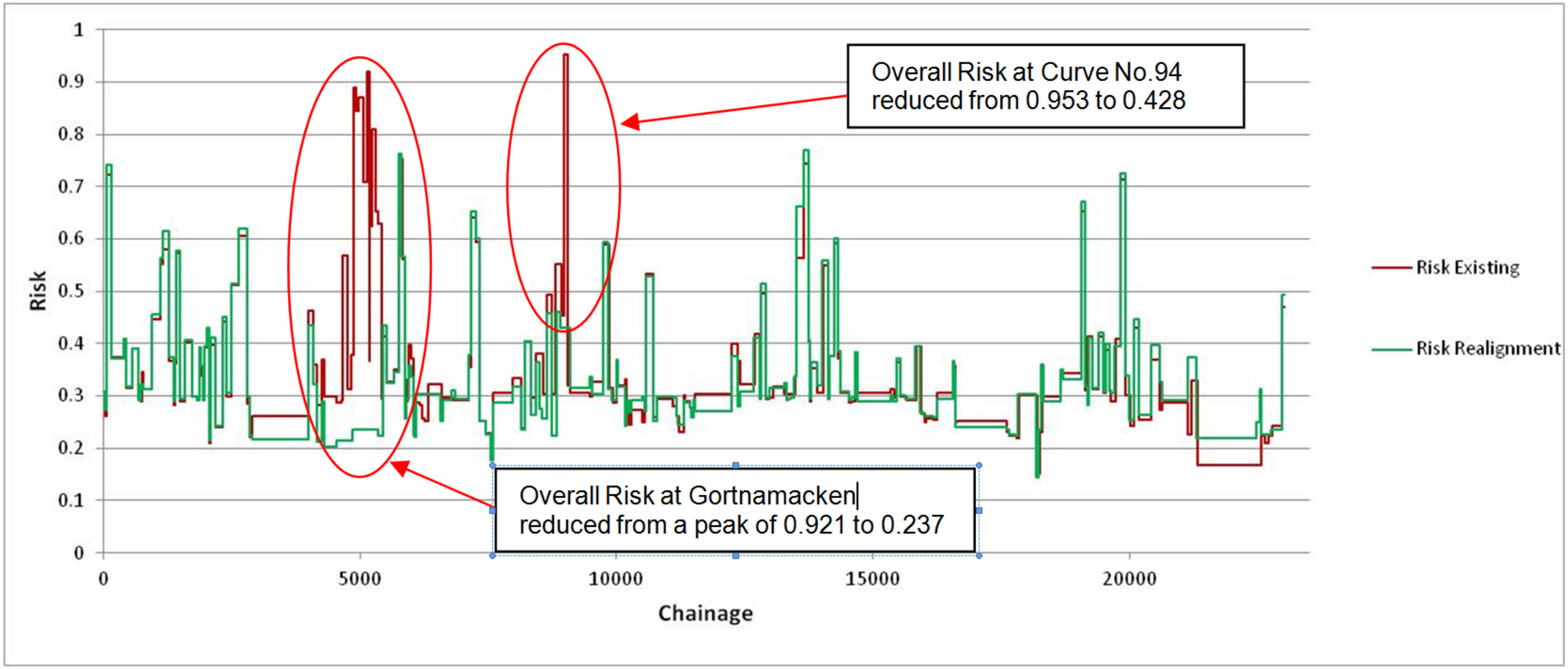
➢ **N66 –** Optimal Risk-Based Indicative Realignments



Section	Alignment Standard	Realignment Length
Gortnamacken Bridge	Minimum Desirable	800m
Curve 94	Three Steps below	400m

N66 – Realignment Risk Profile

- N66 realignment Risk Profile determined from Risk Model



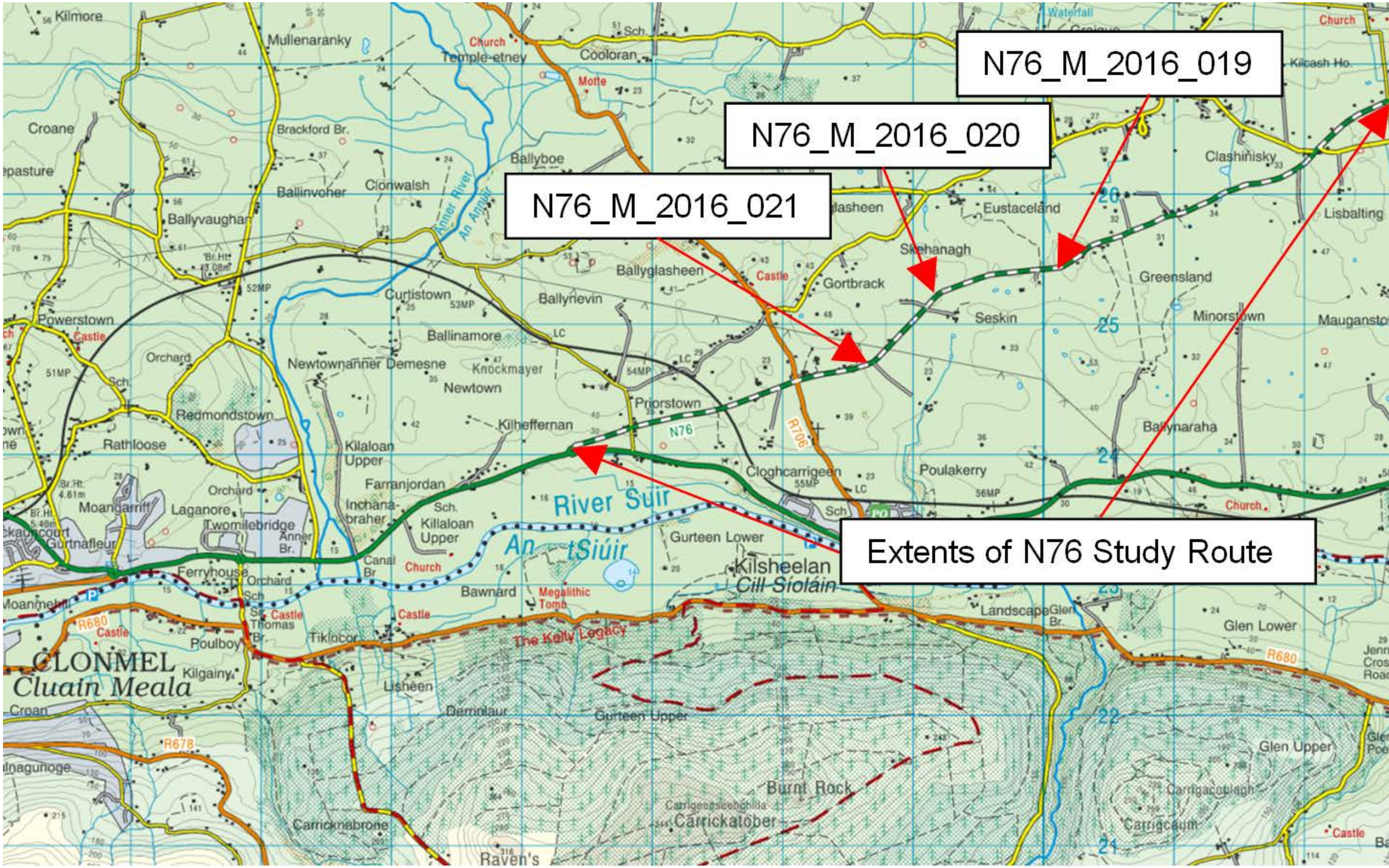
N66 –Summary of Findings

- 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



N76 – Case Study Route

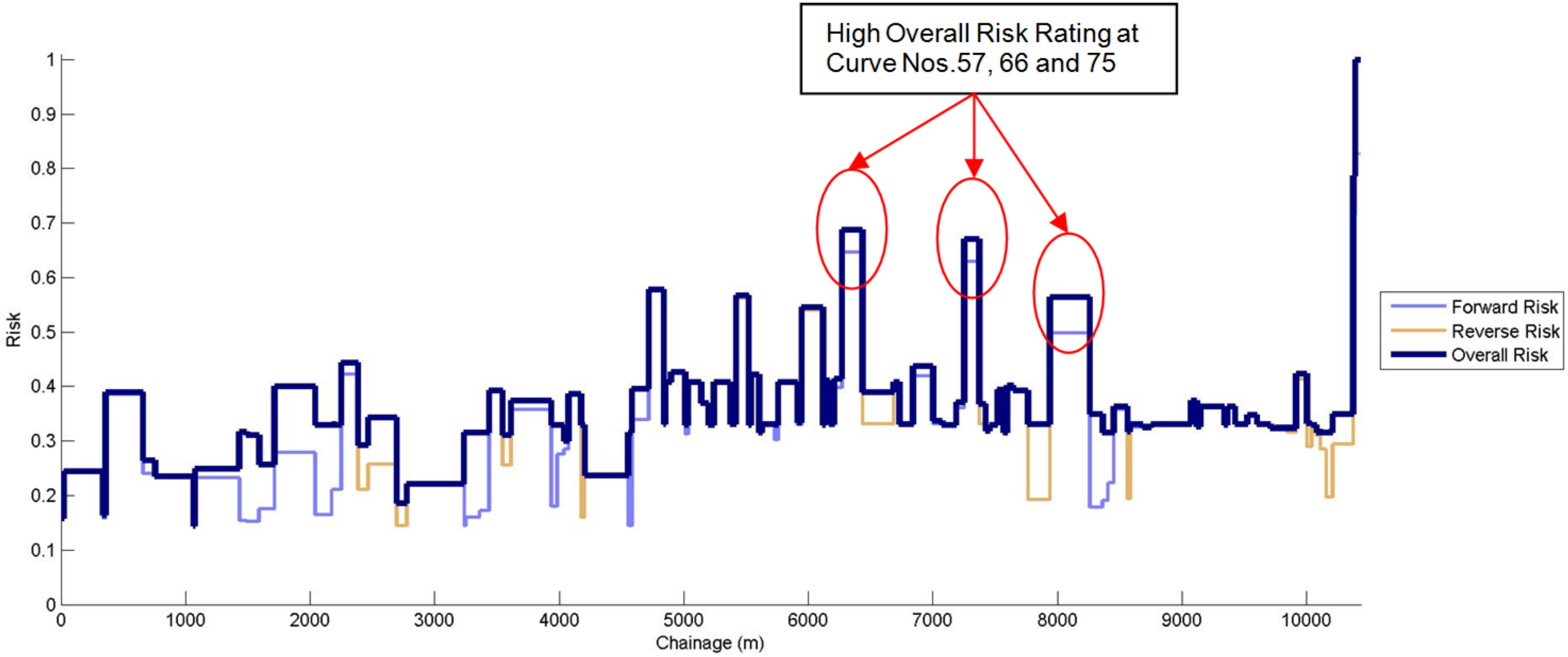
➢ N76 Study Route Details

- 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.

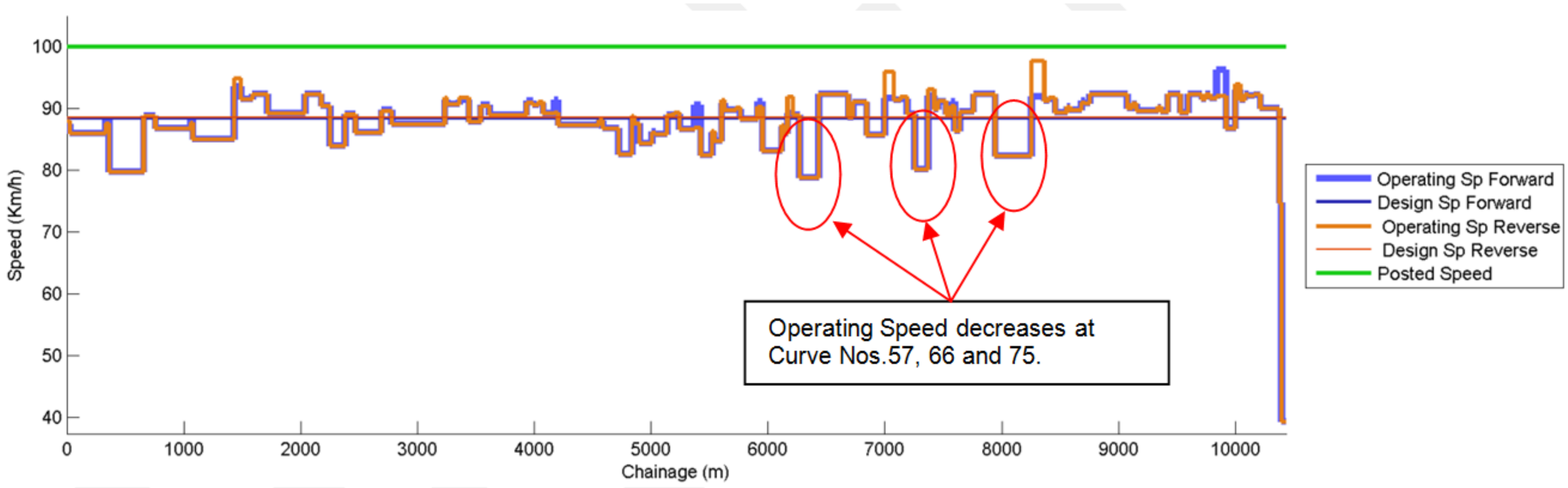
- Recorded Collision History: 22 no. over 20 years at 3 sites

N76 – Existing Alignment Risk Profile

- **Existing N76 alignment Risk Profile determined from Risk Model**



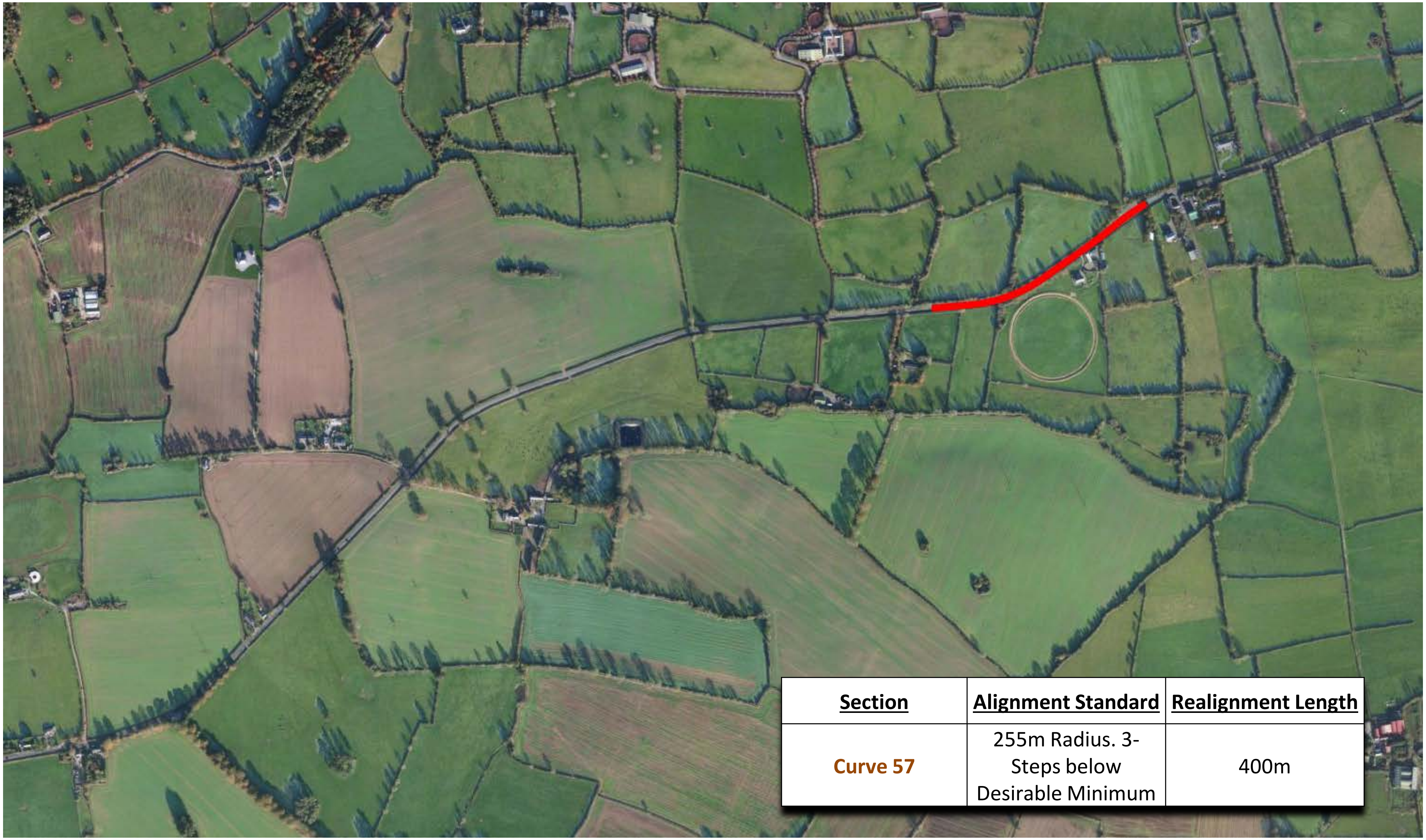
N76 – Existing Operating Speed Profile



The Speed Variation was calculated at 17 km/h = FAIR.

N76 – Indicative Realignments

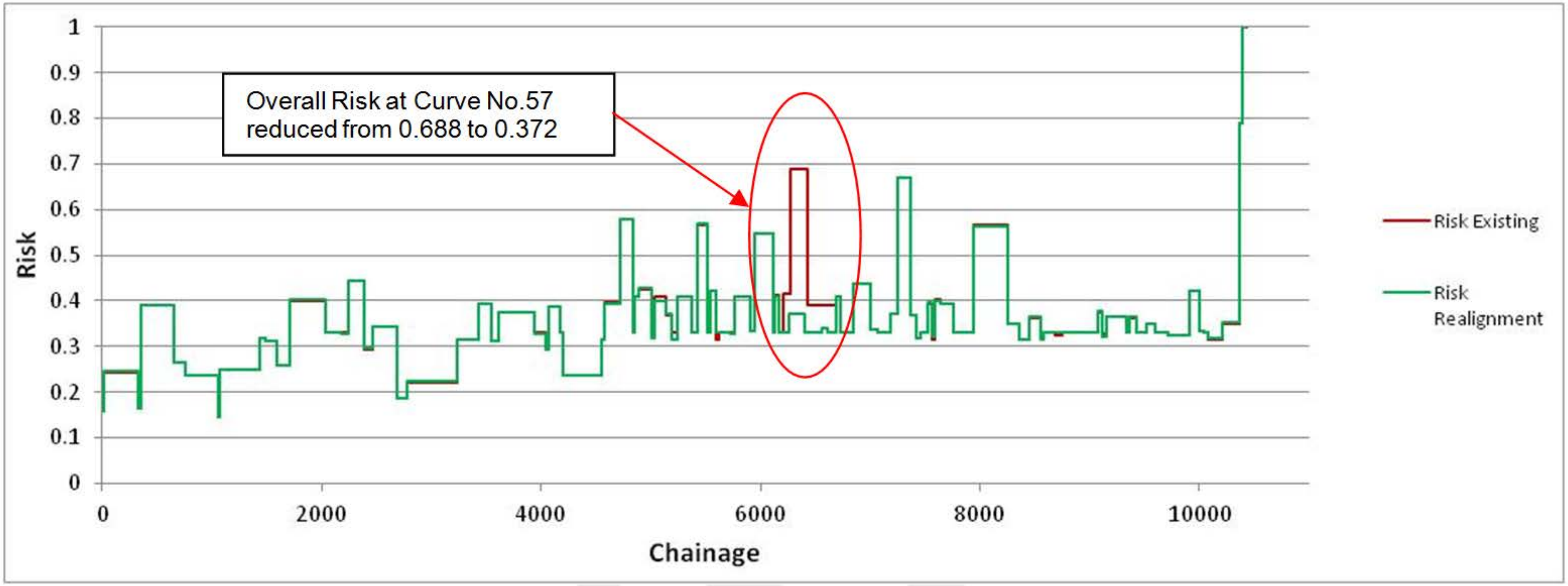
- Risk-Based Indicative Realignment for one sample site



Section	Alignment Standard	Realignment Length
Curve 57	255m Radius. 3-Steps below Desirable Minimum	400m

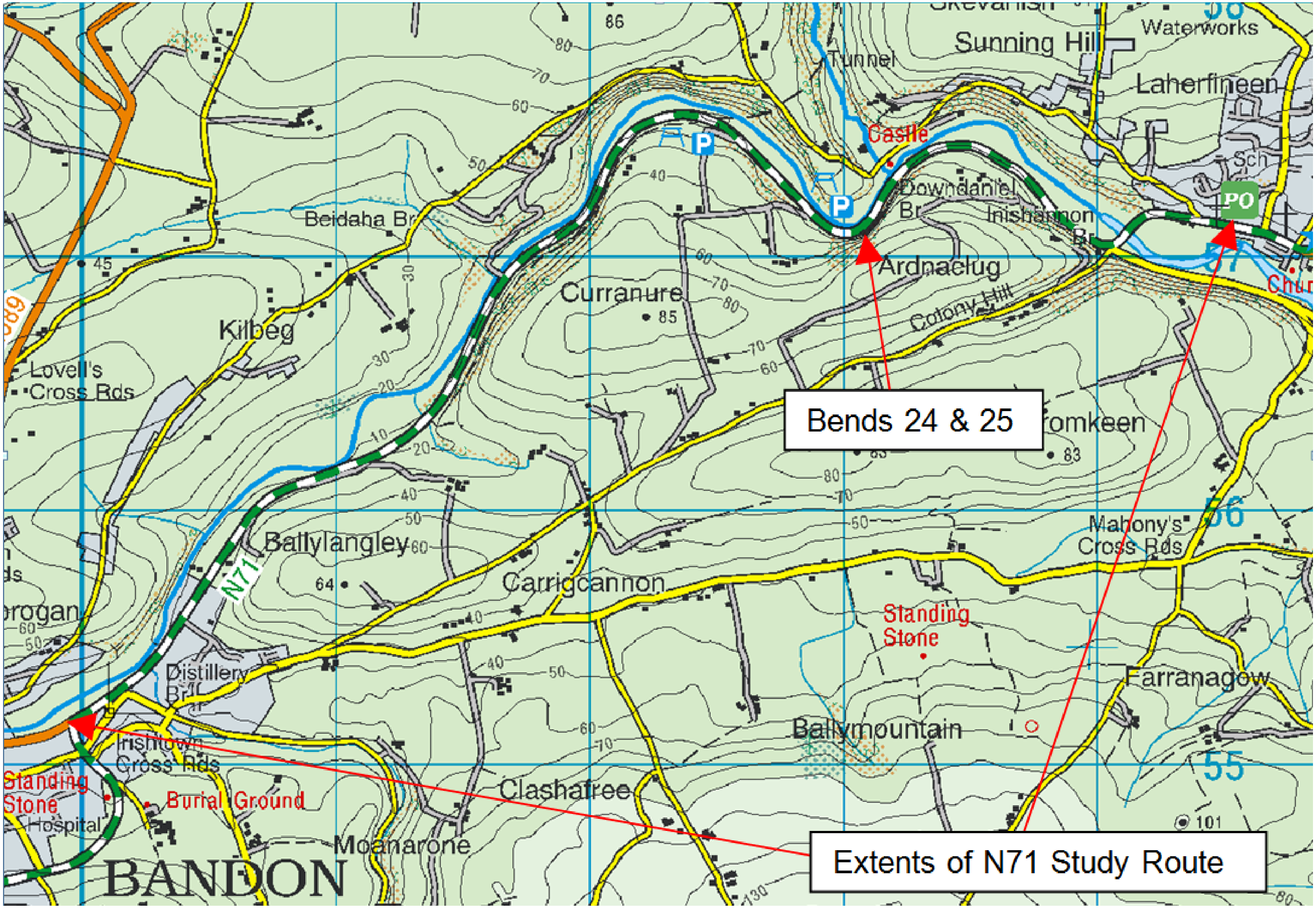
N76 – Realignment Risk Profile

- **Sample Realignment Risk Profile determined from Risk Model**



N71 Innishannon to Bandon, Co. Cork Case Study

N71 – Case Study Route



N71 – Case Study Route

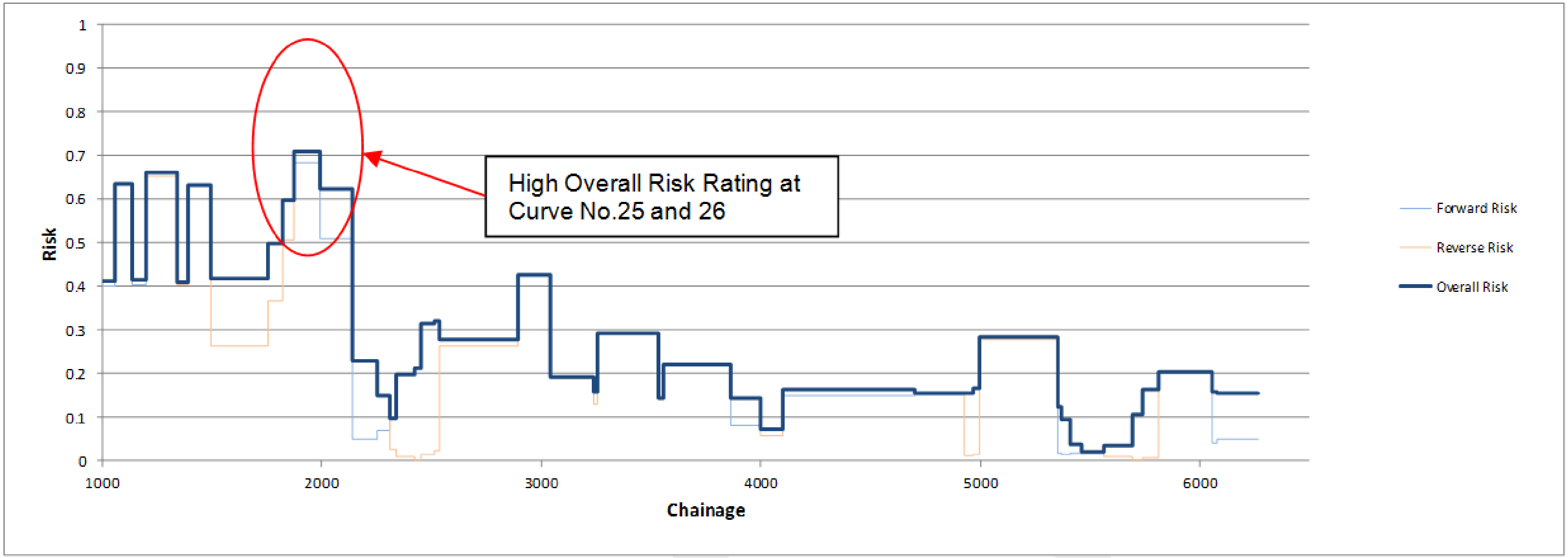
➢ N71 Study Route Details

- 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.

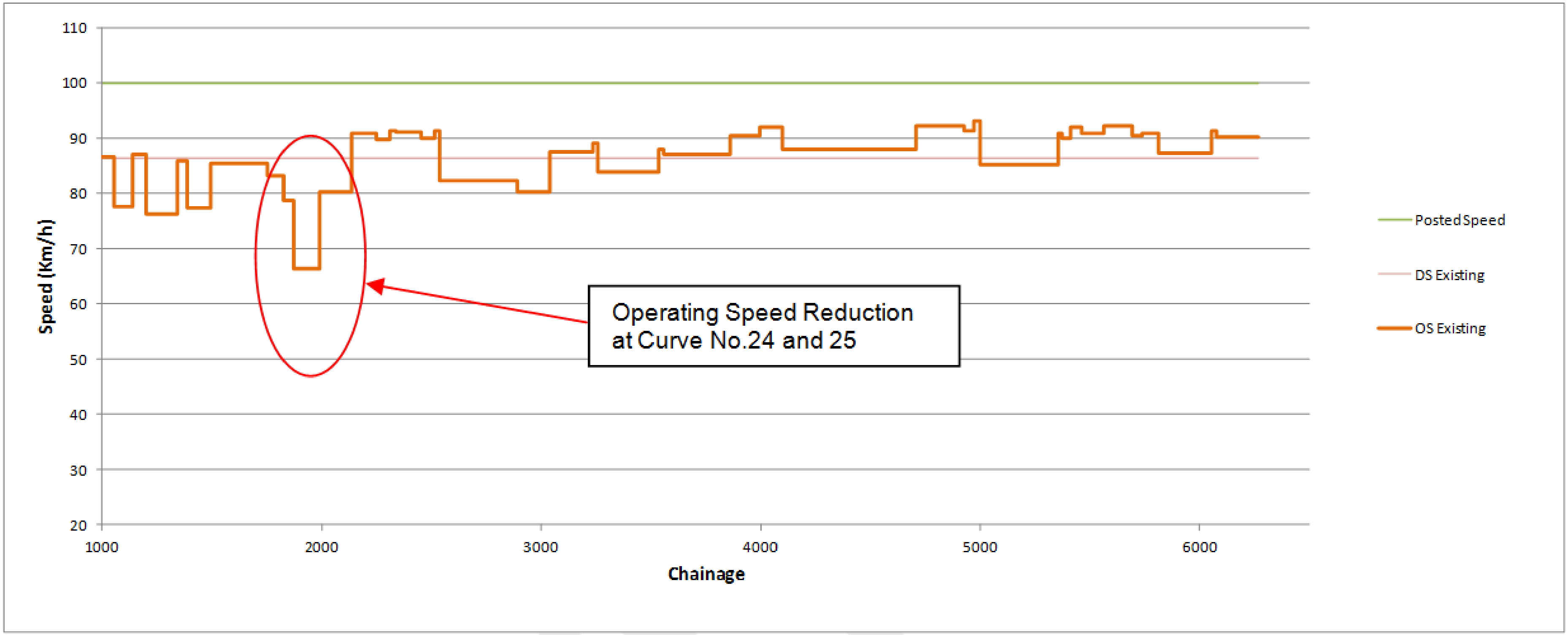
- Risk Mitigation Measure: High Friction Surfacing

- Collision History: 52 collisions over 7 years

N71 – Existing Alignment Risk Profile



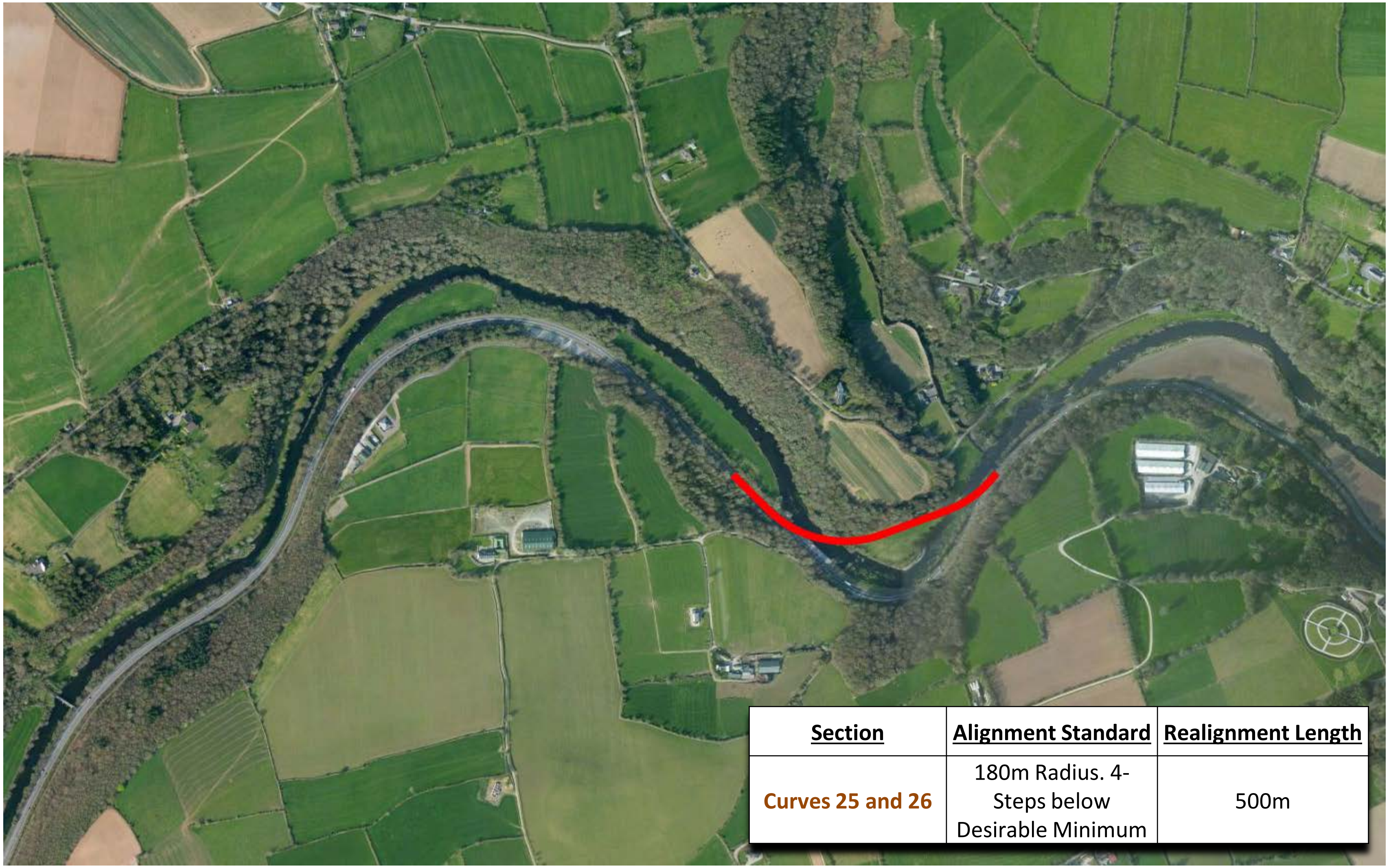
N71 – Existing Operating Speed Profile



The Speed Variation was calculated at 27 km/h = POOR.

N71– Indicative Realignments

Risk-Based Indicative Realignment Consistent with General Bendiness



Section	Alignment Standard	Realignment Length
Curves 25 and 26	180m Radius. 4-Steps below Desirable Minimum	500m

Conclusions

Risk-Based Geometric Design

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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Road Services Training Group

2018 Roads Conference & Exhibition