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Analytical Estimation of Impact Forces Due to Abrupt and Rapid Changes in Track Profile at Rail Ends and Turnout Crossings

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Why do the dynamic impact forces occur?

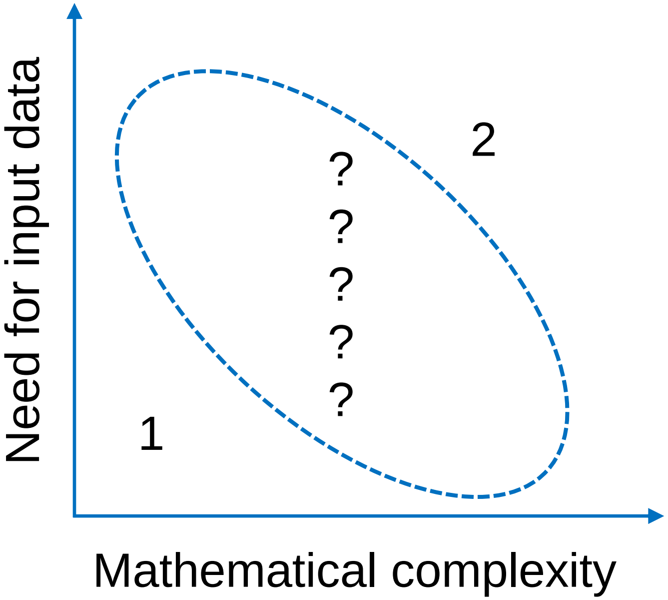
- DIF occurs mainly due to:

  1. Variation in track profile
  2. Variation in track stiffness
  3. Variation in wheel circularity

- Such variations, increase the vertical wheel forces exerted onto the railway tracks to values higher than their static values.

Estimation of highly indeterminate values

- Estimation of dynamic impact forces on railway tracks:
  1. Empirical methods
  2. Numerical methods
  3. Analytical methods ?????



Application of the proposed new analytical method to rail-ends and turnouts

- Bezgin Method was developed to give the railway engineering community:

  I. A practical tool to estimate DIF on railway tracks.

  II. That is practically applicable.

  III. Rests on an explicit set of principles.

- How can we benefit from the proposed method to evaluate the effects of **abrupt** elevation changes at **rail-ends** and **rapid** elevation changes over **turnouts**?

Presentation outline

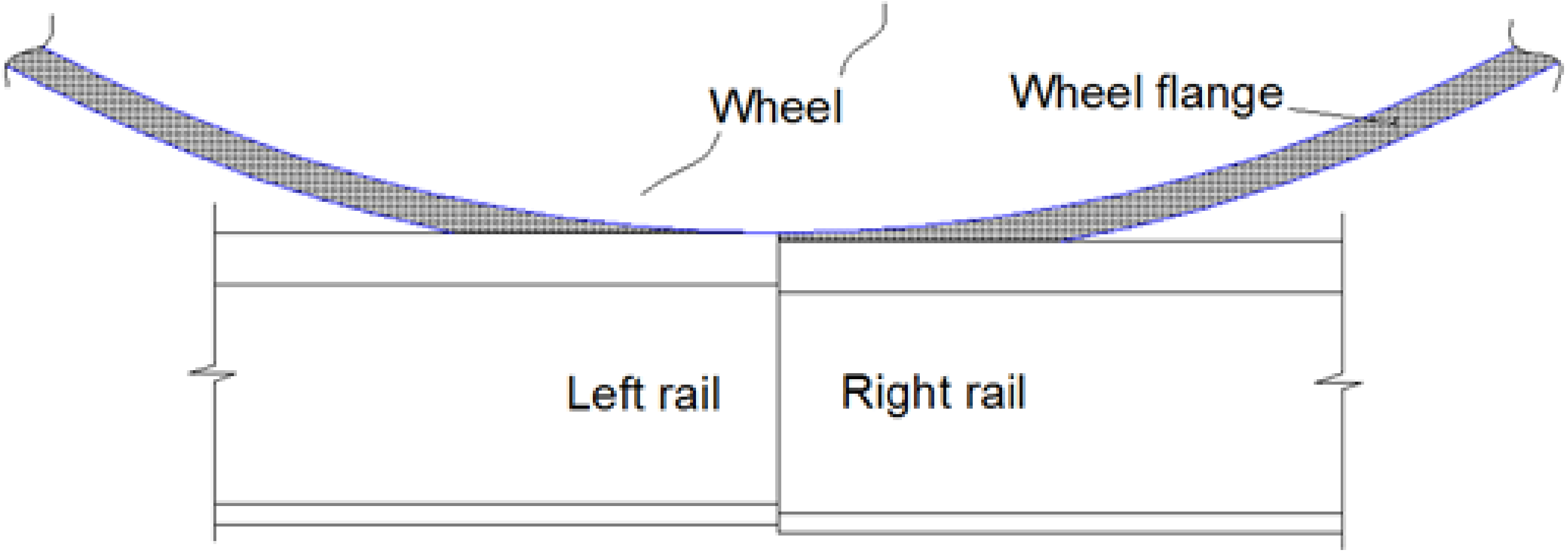
1. Progress
    i. Analytical studies
    ii. Observational results from railway turnouts
2. Conclusions
3. Planned work

Application of the Bezgin Method to rail-ends and turnouts

- Can we estimate the wheel forces that lead to **bearing stresses** under ties which can lead to ballast pulverization and excessive deflections within the subgrade?
- Can we estimate the wheel forces that lead to excessive wheel-rail **contact stresses,** which can cause plastic damage of rail?

Scaled drawing of a wheel rolling over a rail-end with profile variation

- Wheel diameter = **920 mm** *(36.2 in)*
- Rail depth = **170 mm** *(6.7 in)*
- Profile variation = **10 mm** *(0.4 in)* high

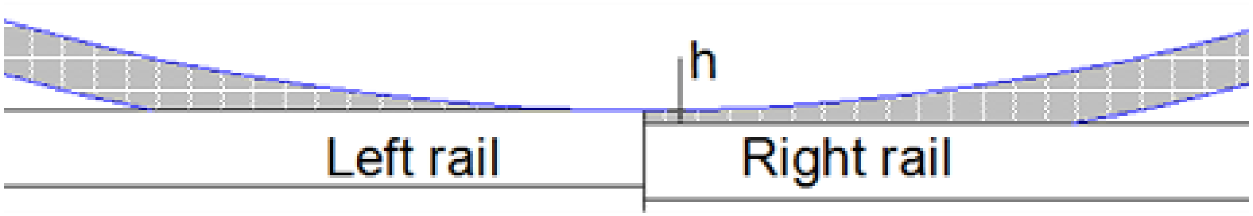


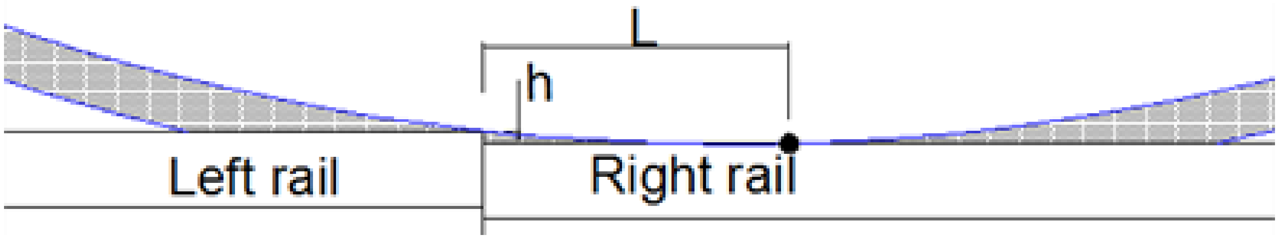
Close-up view showing the impact distance «L» for a given wheel diameter «D» and gap height «h»

- Expectations:

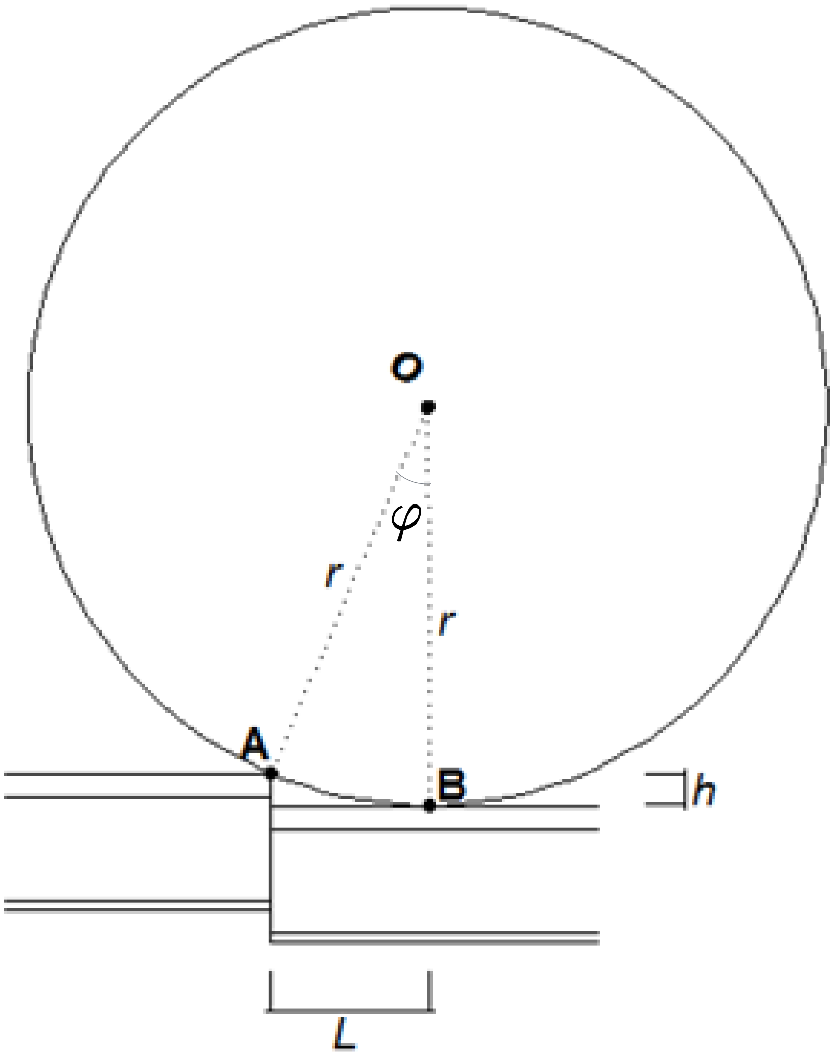
  1. Effects of «h», increase with decreasing wheel diameter and therefore dynamic impact forces vary inversely with wheel diameter.

- We must geometrically **relate «L» to «h»** and **«D»**





Un-scaled conceptual drawing for developing mathematical relations between «D», «h» and «L» through analytical geometry



1. For a given «D» and «h» **find «φ»**
2. Knowing «D» and «φ» **find «L»**

$$\mathbf{h = r(1 - \cos\varphi)}$$

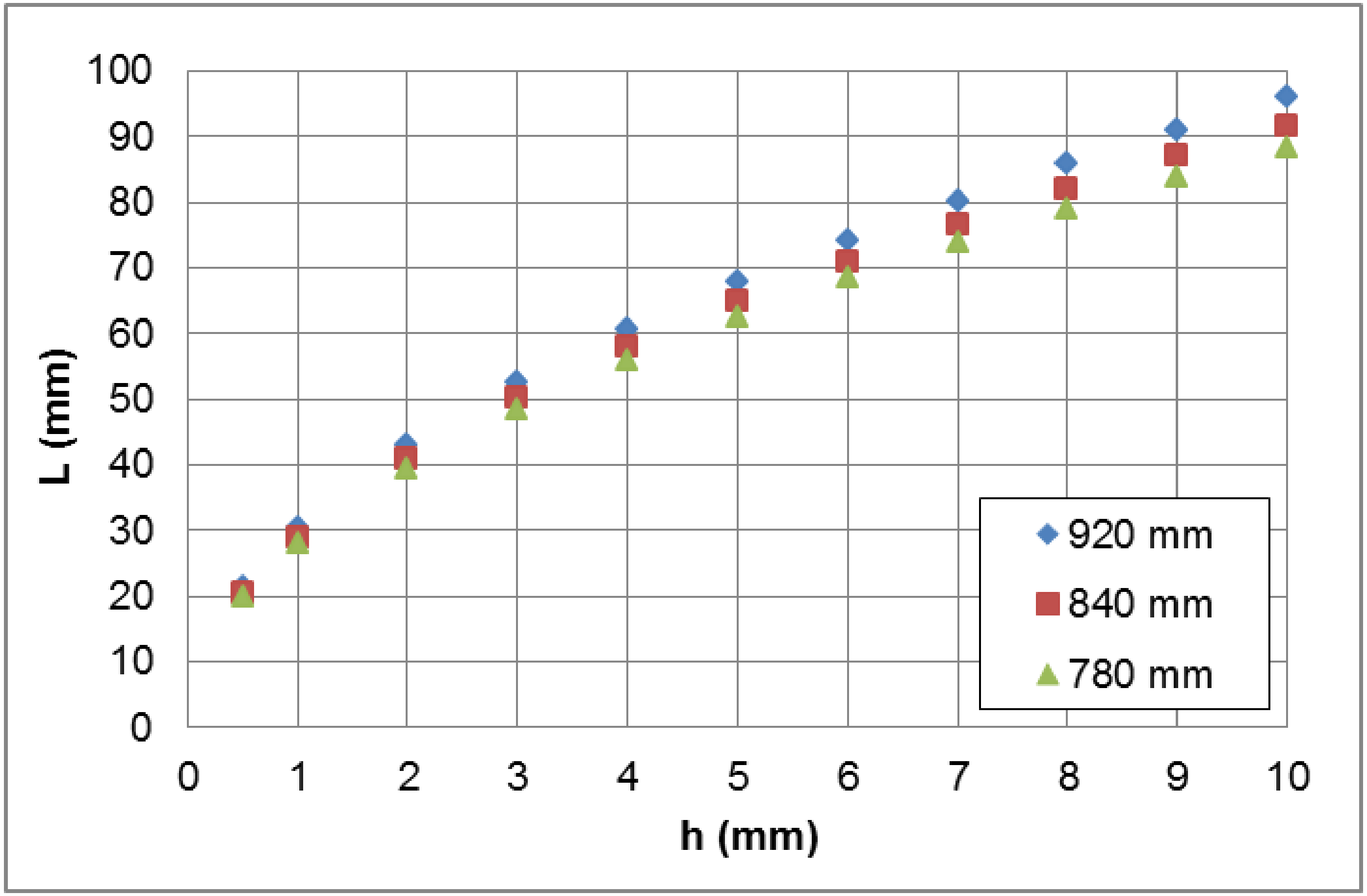
$$L = 2r.\sin\frac{\varphi}{2}.\cos\frac{\varphi}{2}$$

Tabulation of «L» values for varying «h» and wheel diameter «D»

- The impact distance «L» reduces with reduced wheel diameter.
- Thus, for a given translational speed «v», the train with the lower wheel diameter will hit the rail in a shorter amount of time (time = L / v).
- **A larger part of the tributary potential energy of the wheel will be imparted on to the track causing greater impact.**

h		**f (^{o})**			**L for D=920 mm**		**L for D=840 mm**		**L for D=780 mm**	
(mm)	(in)	**D=920 mm**	**D=840 mm**	**D=780 mm**	(mm)	*(in)*	(mm)	*(in)*	(mm)	*(in)*
0.5	0.02	2.67	2.80	2.90	**21.4**	*0.84*	**20.5**	*0.81*	**19.7**	*0.78*
1	0.04	3.78	3.95	4.10	**30.3**	*1.19*	**29.0**	*1.14*	**27.9**	*1.10*
2	0.08	5.34	5.59	5.81	**42.9**	*1.69*	**41.0**	*1.61*	**39.5**	*1.55*
3	0.12	6.55	6.85	7.11	**52.5**	*2.07*	**50.2**	*1.98*	**48.4**	*1.90*
4	0.16	7.56	7.91	8.21	**60.7**	*2.39*	**58.0**	*2.28*	**55.9**	*2.20*
5	0.20	8.46	8.85	9.18	**67.8**	*2.67*	**64.8**	*2.55*	**62.4**	*2.46*
7	0.28	10.01	10.48	10.87	**80.2**	*3.16*	**76.7**	*3.02*	**73.9**	*2.91*
8	0.31	10.70	11.20	11.63	**85.8**	*3.38*	**82.0**	*3.23*	**79.0**	*3.11*
9	0.35	11.35	11.88	12.33	**91.0**	*3.58*	**86.9**	*3.42*	**83.8**	*3.30*
10	0.39	11.97	12.53	13.00	**95.9**	*3.78*	**91.7**	*3.61*	**88.3**	*3.48*

Increasing «L» for a given «h» and «D»



Dynamic impact force factor estimation with the Bezgin Method

- Determine the **«**impact reduction factor, **f»** with the known «h», «L» and «v»

$$f = 1 - \frac{t_{fall}}{t_{pass}} = 1 - \frac{\sqrt{2.h/g}}{L/v} = 1 - \frac{V}{L} . \sqrt{\frac{2h}{g}}$$

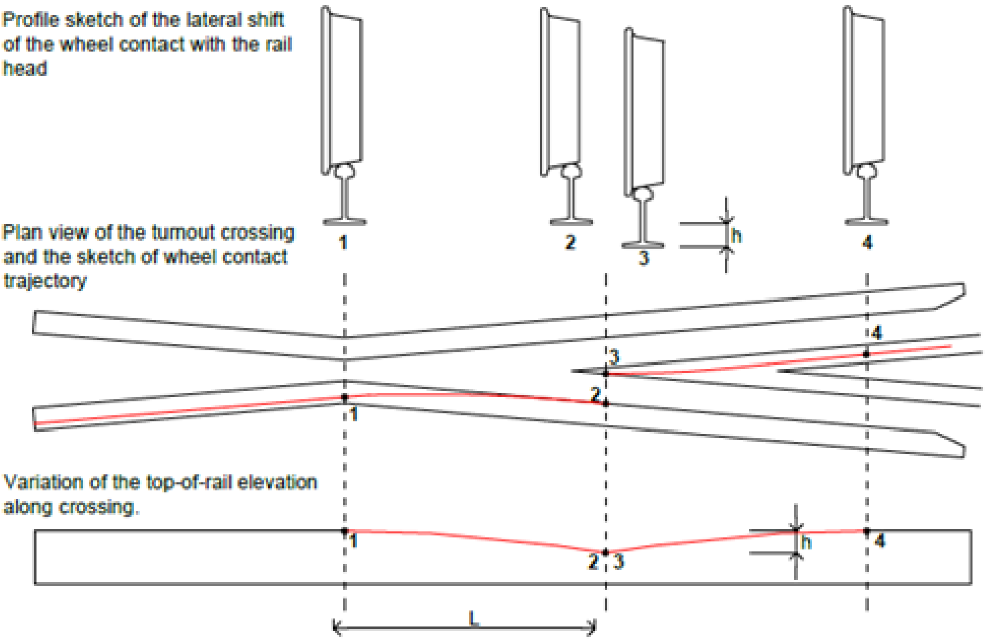
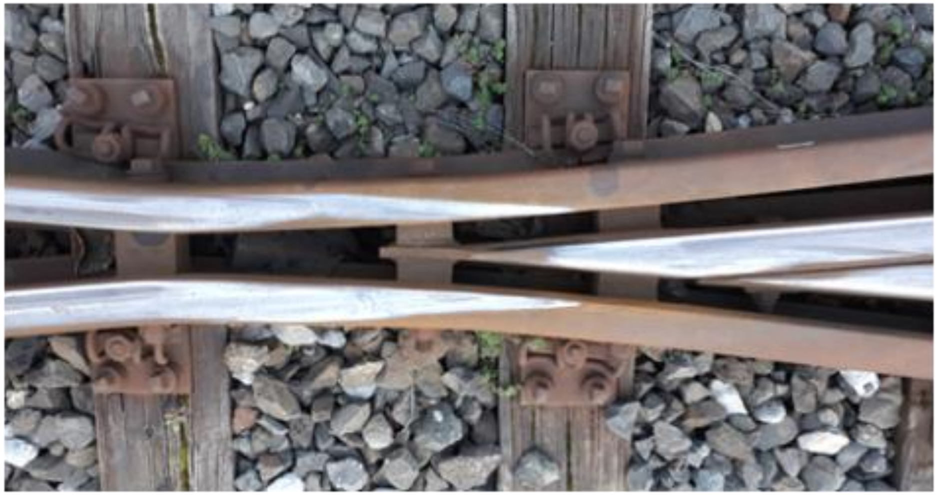
- Knowing static axle force **«F_s»** and equivalent system stiffness **«k_{eq}»** estimate the static system deflection **F_s/k_{eq} = a'**

$$\boldsymbol{K'_{B,d} = 1 + \sqrt{\frac{2h}{a'}(1 - f - s)}}$$

For a given speed:

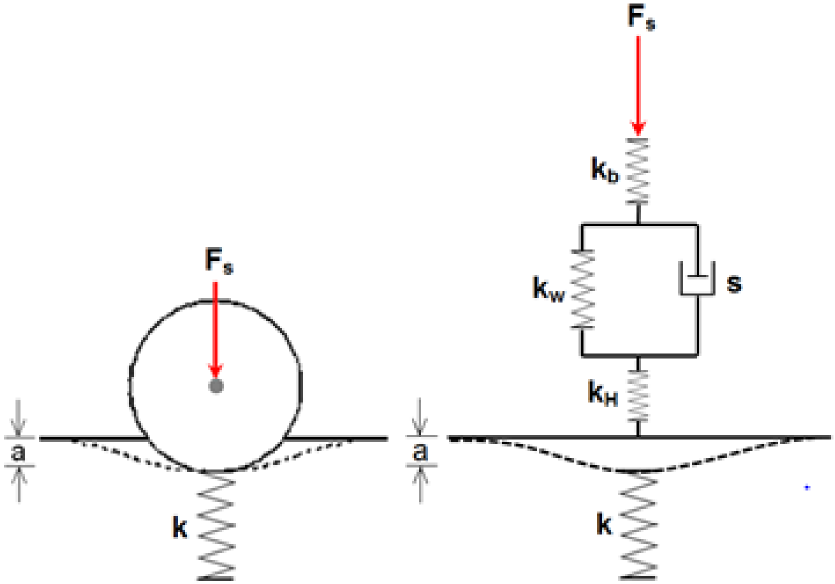
- **The stiffer is the system, the harder is the impact.**
- **For a given stiffness, the higher is the static axle force, the lower is the dynamic impact force factor.**

Rapid changes in track elevation over turnouts



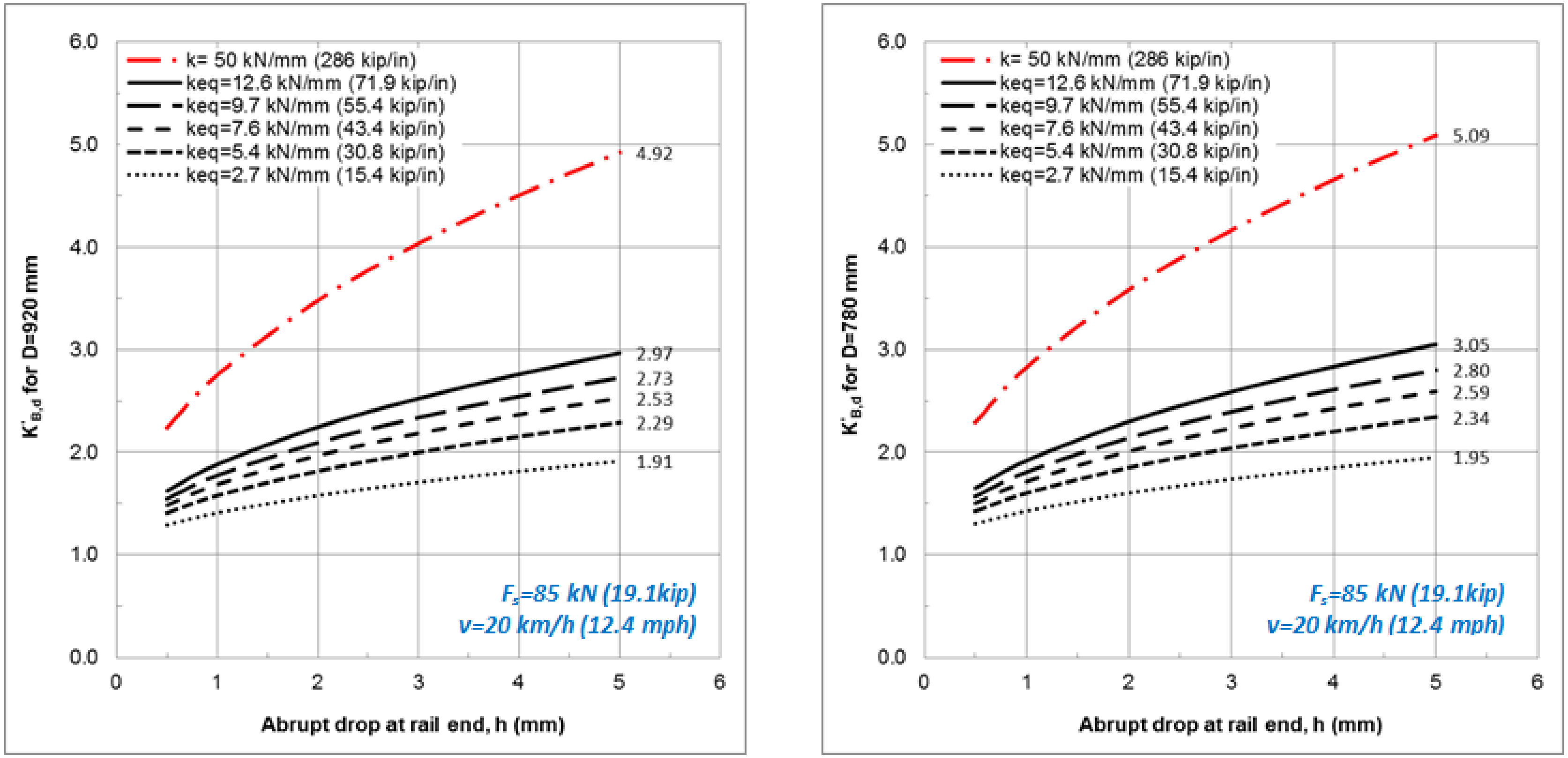
Analytical estimations of dynamic impact force factors for abrupt and rapid changes in track elevations

Consideration of a set of track stiffness and primary stiffness values to evaluate the effect of equivalent stiffness on dynamic impact forces



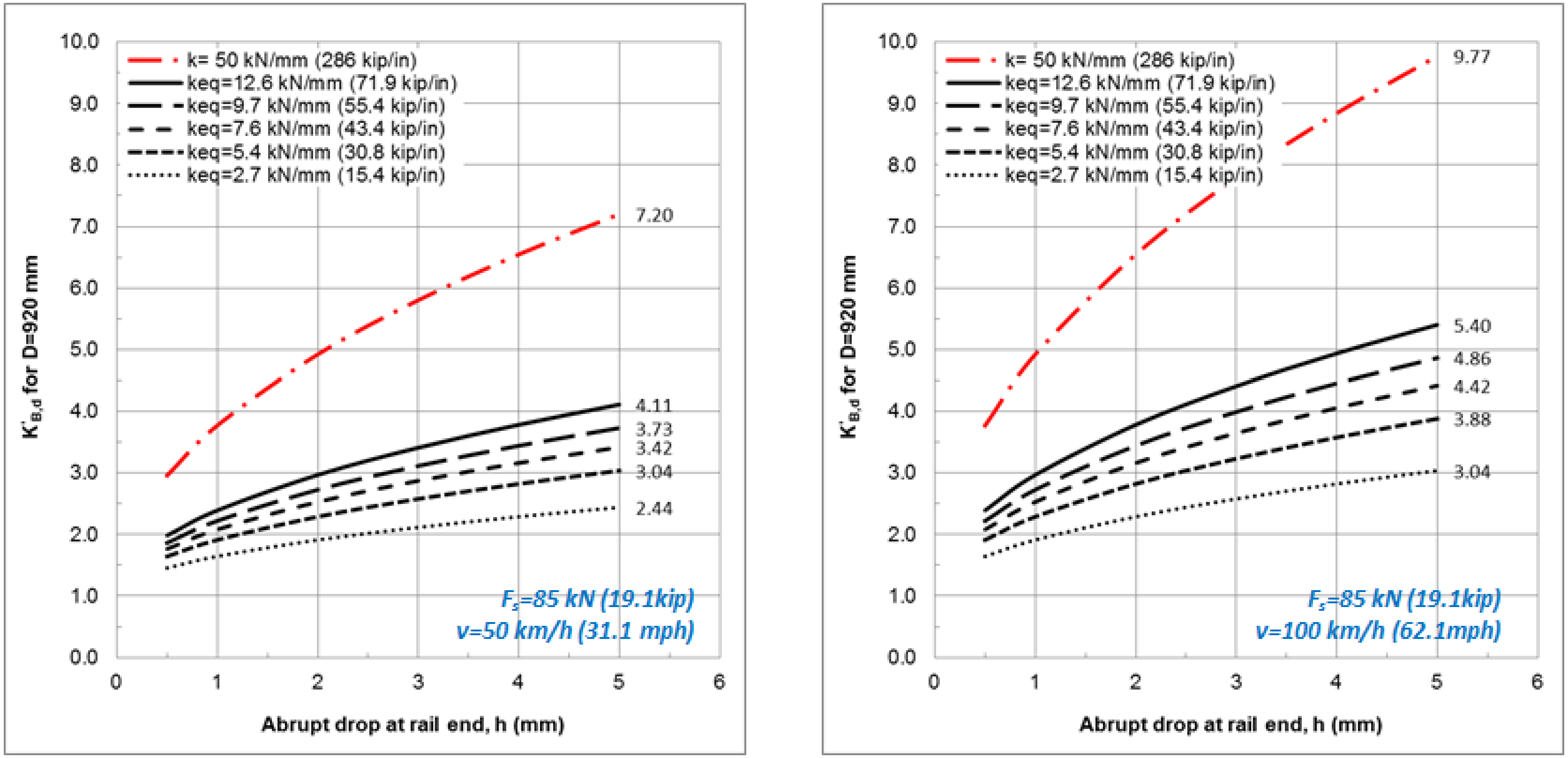
	k_w (kN/mm) (kip/in)				
	3 (17)	6 (34)	9 (51)	12 (69)	15 (86)
k (kN/mm)	**System stiffness: k_{eq} (kN/mm) (kip/in)**				
30 (171)	2.7 (15.6)	5.0 (28.6)	6.9 (39.5)	8.6 (48.9)	10.0 (57.1)
50 (286)	2.8 (16.2)	5.4 (30.6)	7.6 (43.6)	9.7 (55.3)	11.5 (65.9)
80 (457)	2.9 (16.5)	5.6 (31.9)	8.1 (46.2)	10.4 (59.6)	12.6 (72.1)

Abrupt rail-end drop for constant static wheel force and speed: Varying wheel diameters from 920 mm *(36.2 in)* to 780 mm *(30.7 in)*



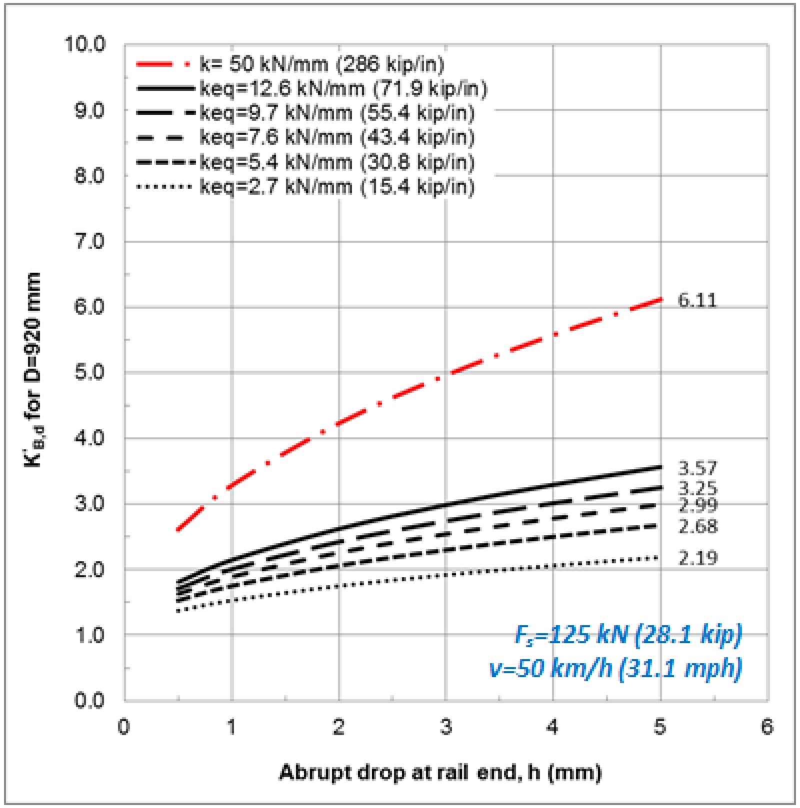
- Lower wheel diameter, magnifies the effect of drop, results in higher impact.
- DIF varies from 1.9 to 3.

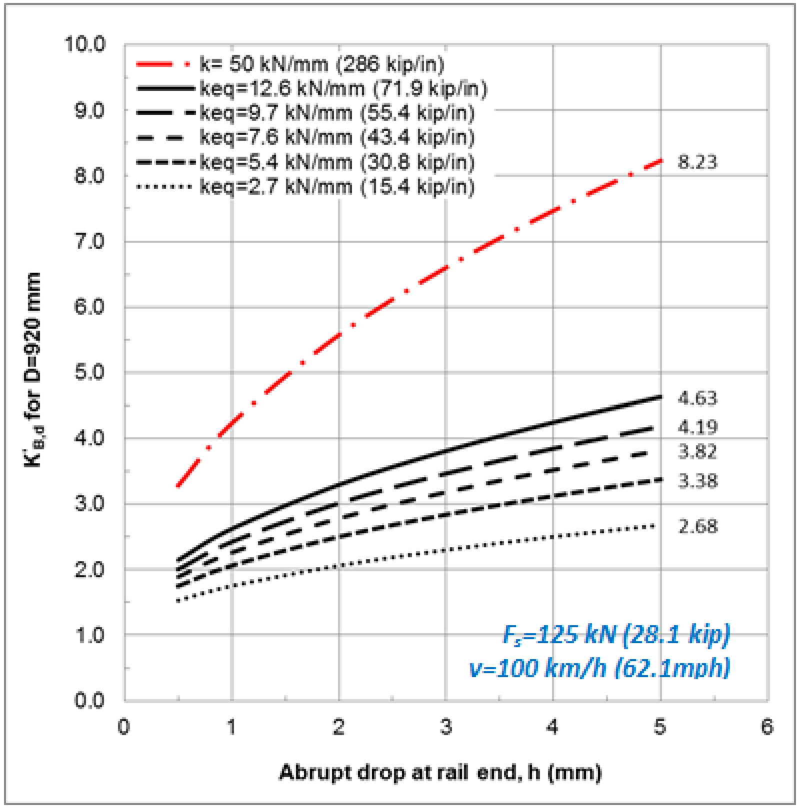
Abrupt rail-end drop for constant static wheel force and diameter: Varying speed compared to previous slide



- Increased speed results in a shorter time to traverse the «L» and imparts a higher part of the tributary potential energy of the wheel.
- DIF varies from 2.4 to 5.4

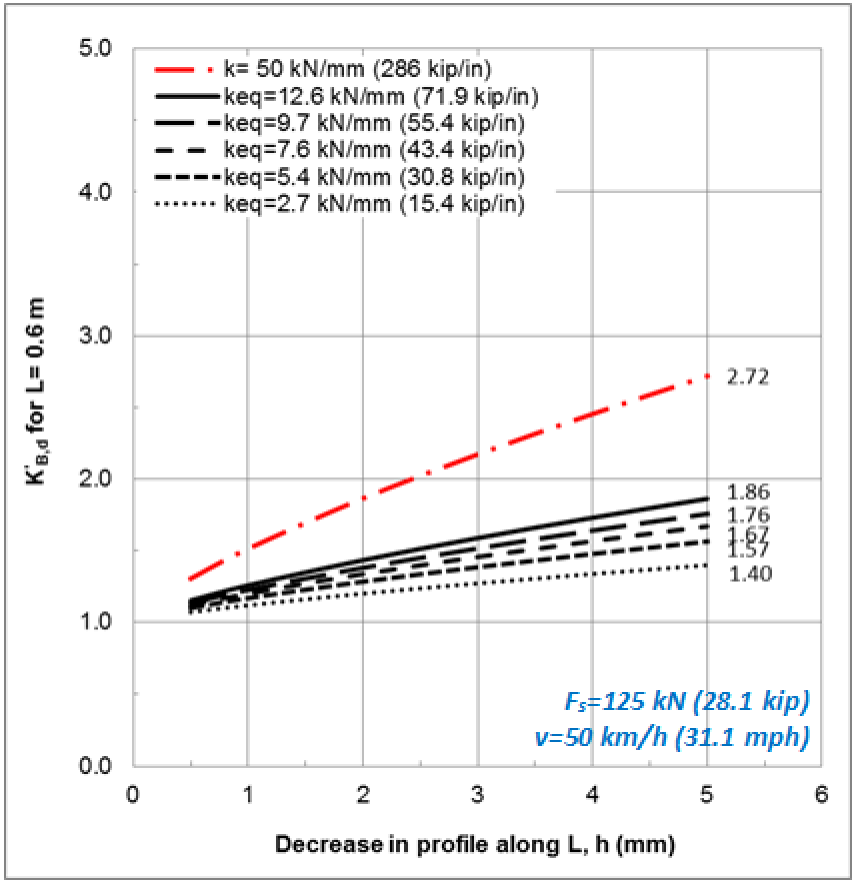
Abrupt rail-end drop for constant static wheel diameter and speed: Varying wheel force compared to previous slide

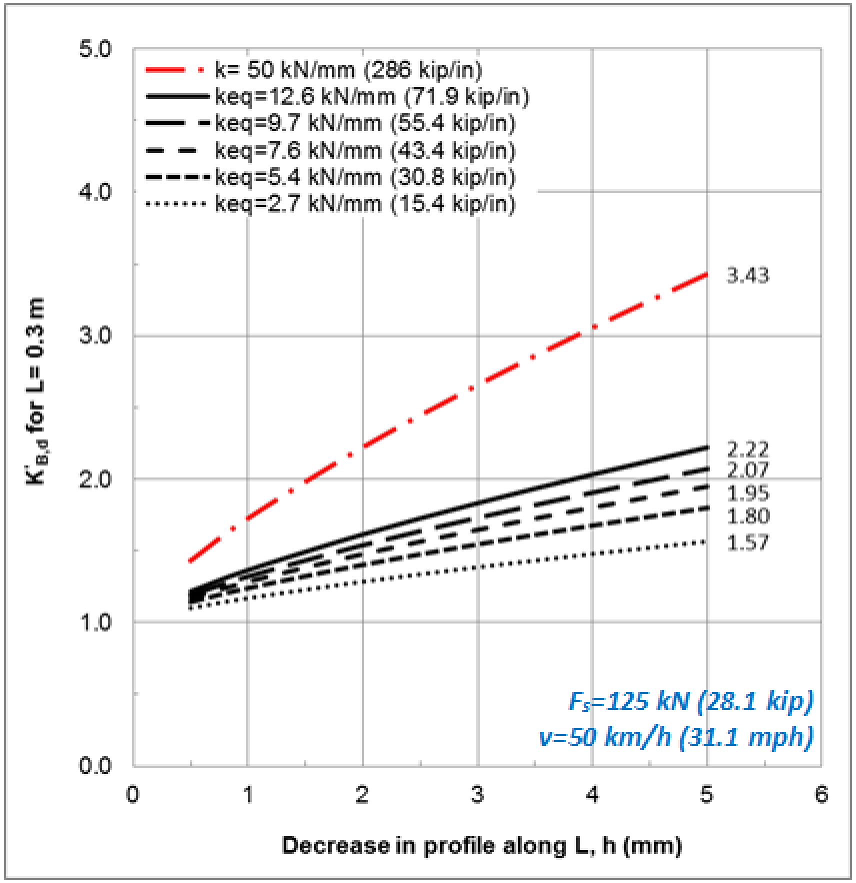




- Increased static wheel force, depresses the track more and reduces the effect of a drop at the rail end with respect to a lower static wheel force and thus results in lower impact factor.

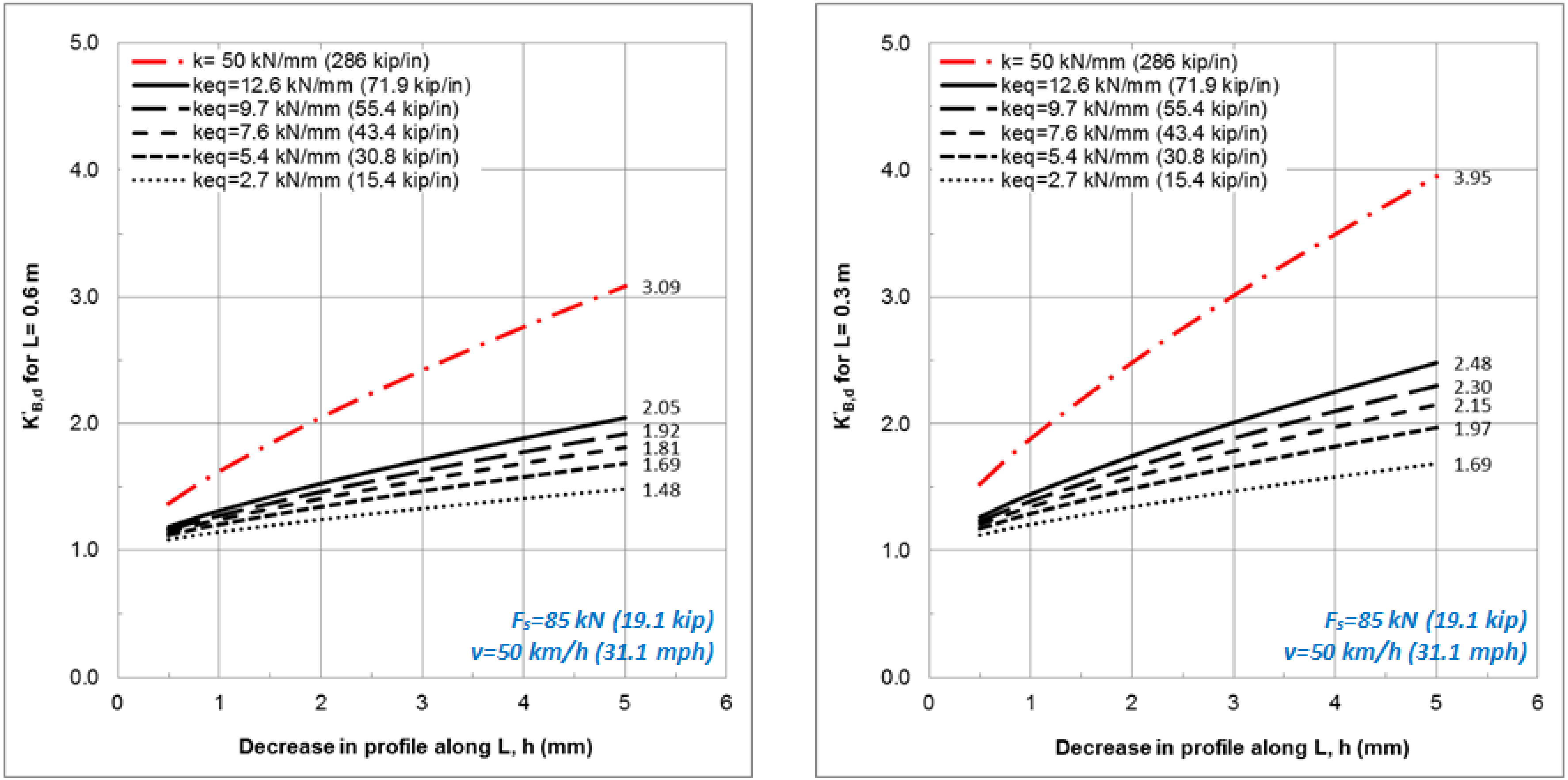
Rapid change over turnout for constant speed: Varying length of elevation change from 60 cm *(2ft)* to 30 cm *(1 ft)*





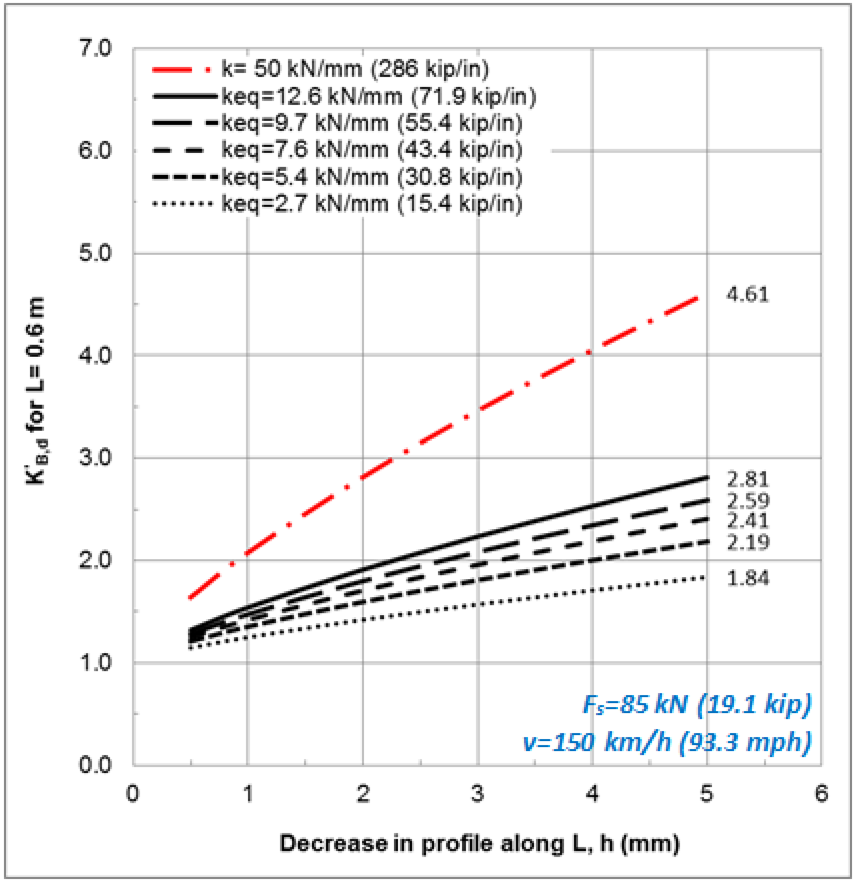
- Reduced length of elevation change over a turnout results in higher impact.

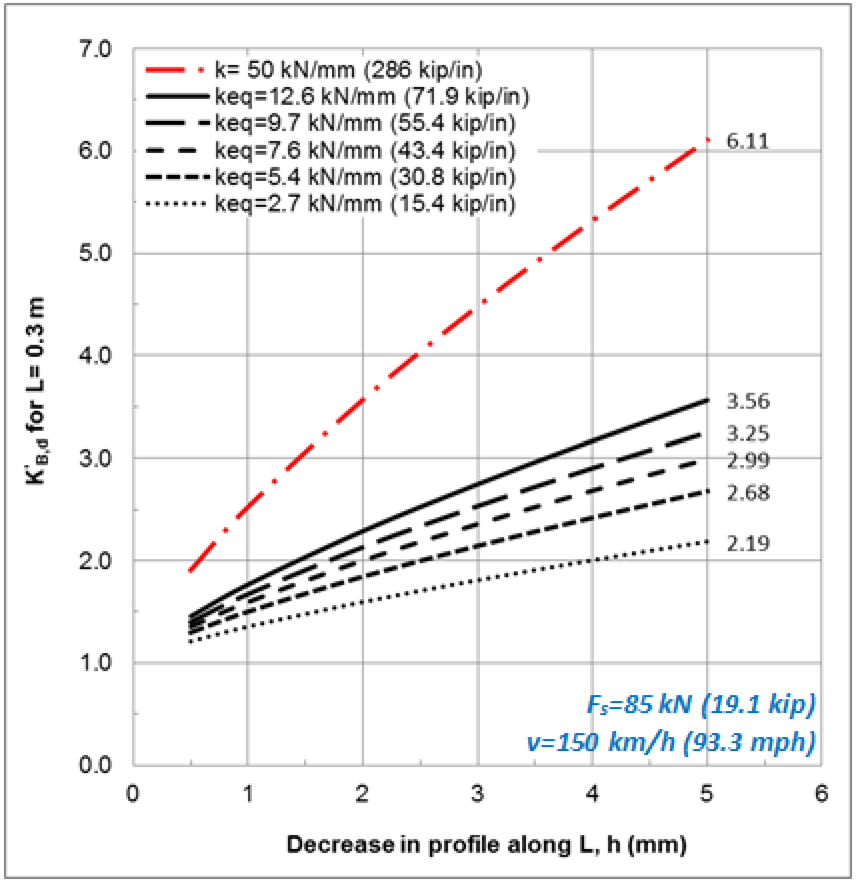
Rapid change over turnout for constant speed: Varying static axle force compared to previous slide



- Reduced static axle force, amplifies the effect of an elevation change.

Rapid change over turnout for constant axle force: Varying speed compared to previous slide

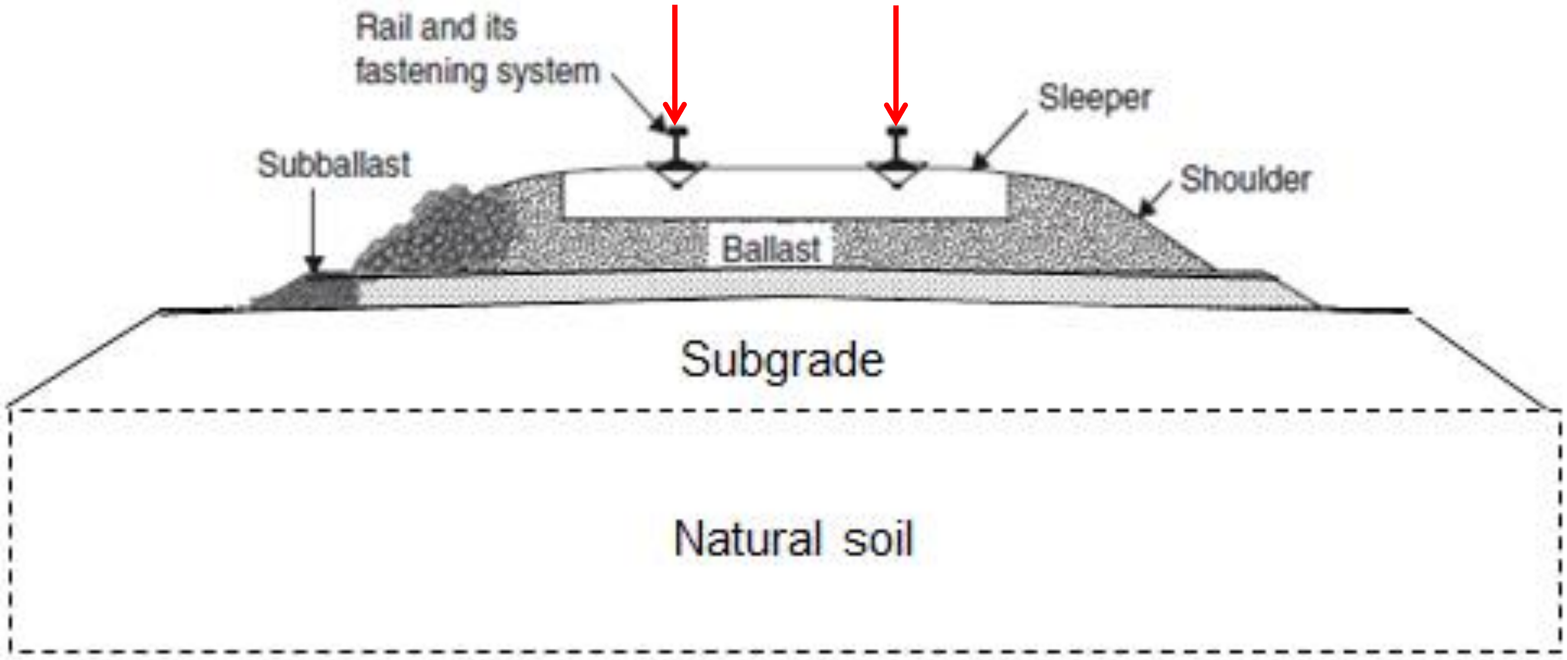




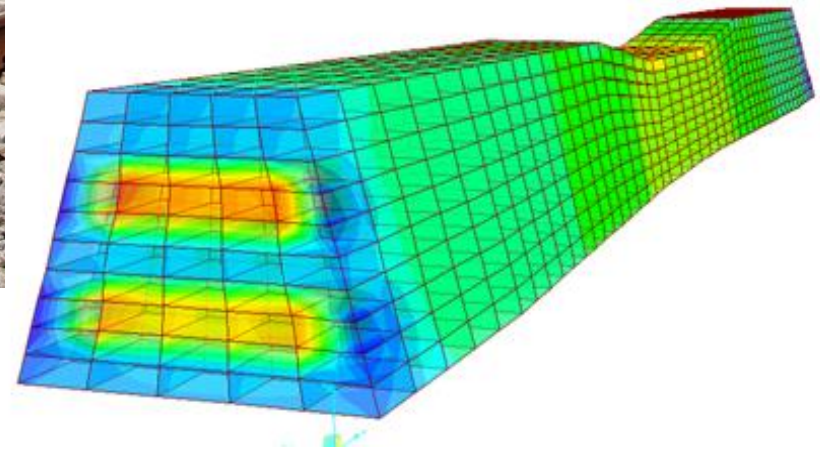
- Increased speed results in higher impact.

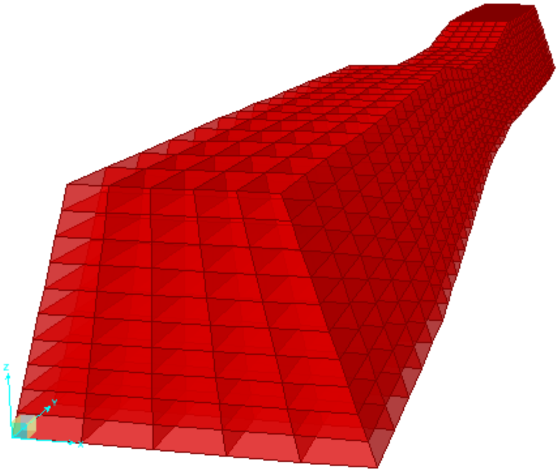
Assessment of bearing pressures

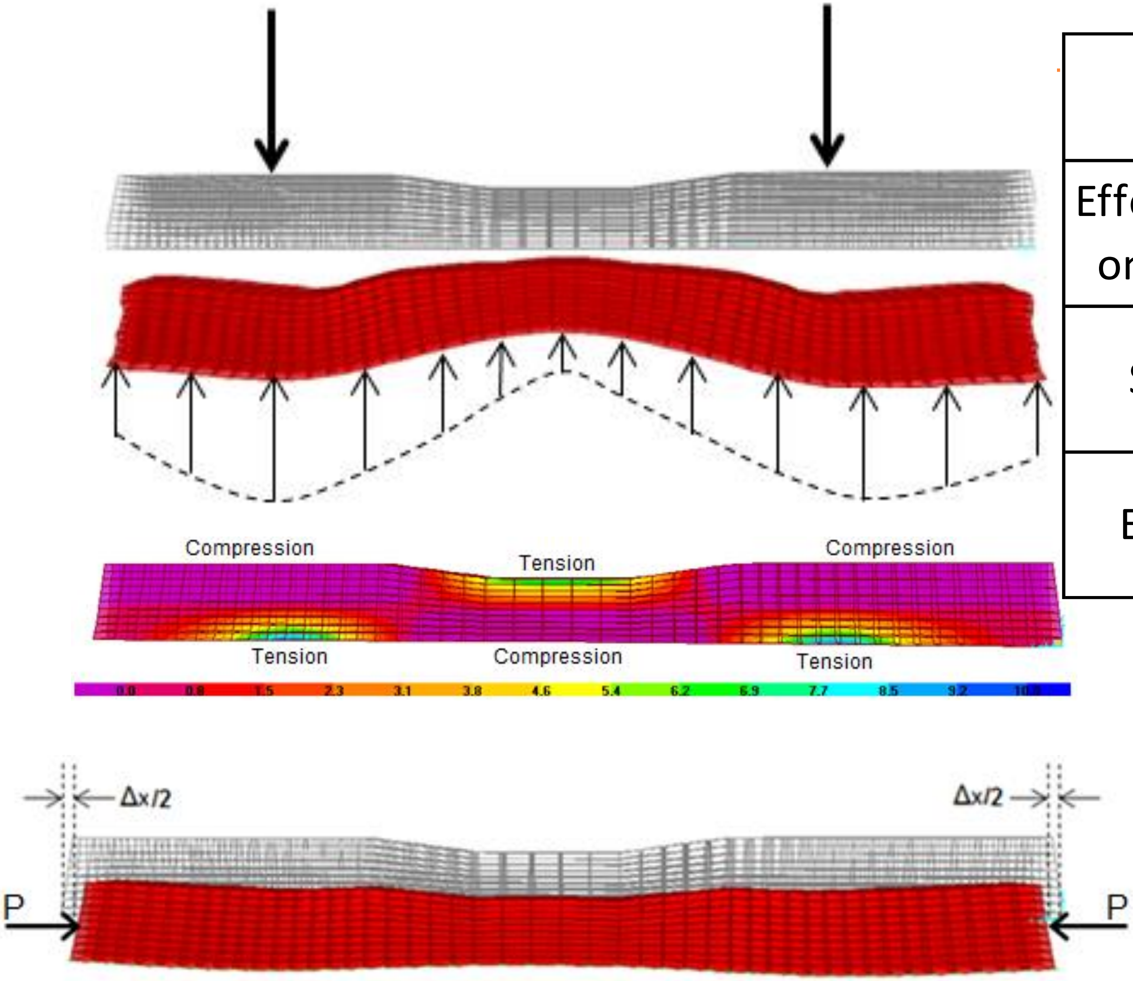
1. What is the average and the maximum values of the bearing pressure under the sleeper on the ballast?
2. What is the contact pressure between the ballast particles?
3. What is the transferred pressure to the subgrade / natural soil?



Contemporary railway between Ankara and Konya







Static axle force =	22.5	Ton-f
	49.6	Kips
Effective static axle force on the sleeper below =	11.3	Ton-f
	24.8	Kips
Sleeper base area =	0.70	m^2
	7.53	ft^2
Effective base area =	0.53	m^2
	5.65	ft^2

- Effective base area **~ 75%** of geometric base area

- Let us say that **50%** of wheel force is resisted by the sleeper under the wheel.

Axle force varying with the estimated dynamic impact force factors

			Sleeper bearing stresses				Ballast particle contact stresses	
DIF	**Axle force**		**Average**		**Maximum**			
	Ton-f	*Kips*	*Ton-f/m*^{2}	*psi*	*Ton-f/m*^{2}	*psi*	*Ton-f/m*^{2}	*psi*
1	11.3	24.8	16.1	22.9	21.4	30.5	107.1	152.4
1.5	16.9	37.2	24.1	34.3	32.1	45.7	160.7	228.6
2	22.5	49.6	32.1	45.7	42.9	61.0	214.3	304.8
2.5	28.1	62.0	40.2	57.1	53.6	76.2	267.9	381.0
3	33.8	74.4	48.2	68.6	64.3	91.4	321.4	457.2
3.5	39.4	86.8	56.3	80.0	75.0	106.7	375.0	533.4

- *Through the use of a preferred method: (Talbot, Boussinesq, Tschebotarioff, FEM, DEM) ballast and subballast thickness is chosen such that the tie pressure reduces to 1/3rd*

Subgrade bearing stresses			
Average		**Maximum**	
Ton-f/m^2	*psi*	*Ton-f/m*^{2}	*psi*
5.4	7.6	7.1	10.1
8.0	11.4	10.7	15.2
10.7	15.2	14.3	20.3
13.4	19.0	17.8	25.4
16.1	22.8	21.4	30.4
18.7	26.6	25.0	35.5

- *Assuming that only 20% of the tie area is in actual contact with the ballast*

Assessment of wheel-rail contact interface bearing stresses

- One can estimate the contact area from **Hertz Theorem**
- Typical wheel-rail interface bearing area **~ 2 cm^2 ~** *0.3 in^2*
- Rail steel strength **~ 900 MPa – 1,400 MPa** *(130,000 psi – 203,000 psi)*

DIF	**Wheel force**	
	Ton-f	*Kips*
1	11.3	24.8
1.5	16.9	37.2
2	22.5	49.6
2.5	28.1	62.0
3	33.8	74.4
3.5	39.4	86.8

- *Rail battering, plastification and likely plastic flow*

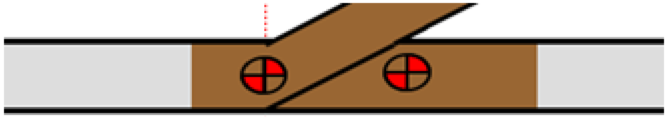
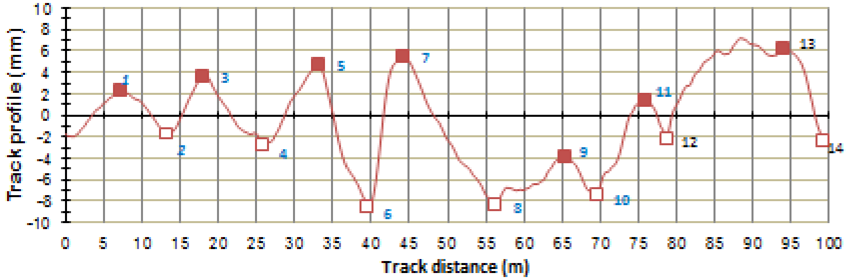
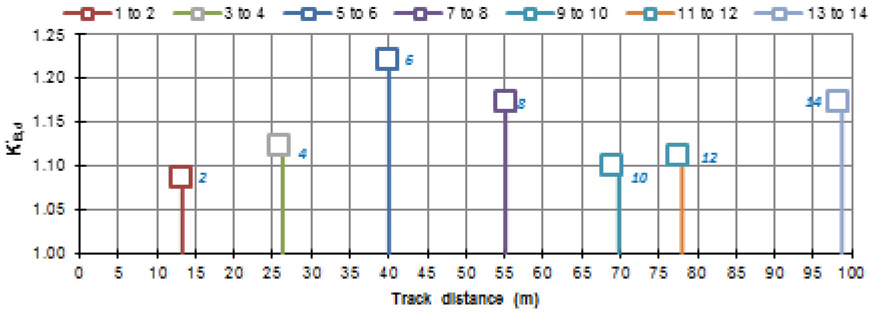
Track turnout geometry and sampling data from Network Rail

Provided by Dr. Mohamed Wehbi

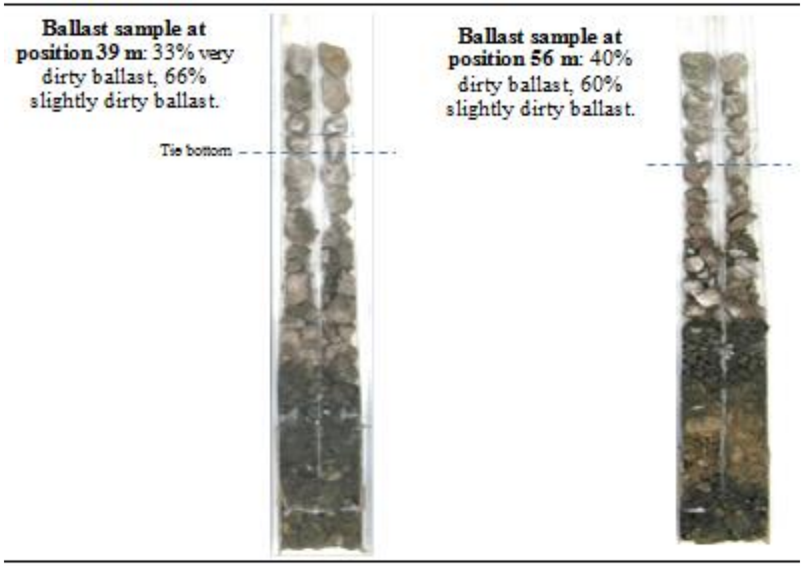
Case study 1: Site in England

- This track section is located in the mid-eastern part of England and carries a mixture of passenger trains (60%) and freight trains (40%) adding to traffic volume of 28 MGT/year with a maximum line speed of 160 km/h (100 mph).
- The section lays mainly on prepared formation with timber bearers for the 57 m (173 ft) long turnout section.
- The calculated impact factors along the track show that there are two main locations: positions 39 m (118 ft) and 56 m (170 ft), where the dynamic impact factors are relatively high, namely at.
- Position 39 m (118 ft) coincides with the location of the switch of the turnout where it is very difficult to maintain and tamp.
- Position 56 m (170 ft) coincides with a turnout crossing point.

Case study 1: Site in England

Layout	 ▢ Concrete sleepers ■ Concrete sleepers/bearers 🟧 Steel sleepers ⊕ Ballast sample
Direction of Travel	➔ ➔ ➔
Speed and traffic	161 km/h (100mph), 28MGT per year
Rate of geometry degradation	0.25 mm/year (0.01 in/year)
Track Geometry	
K'$_{B,d}$	

1. k=60 kN/mm for turnouts.
2. Steventon HST Powercar prevalent on the considered railway routes.
3. k_p = 3.7 kN/mm (21 kip/in)
4. k_w=0.2 kN/mm (1.1 kip/in).



Ballast sample at position 39 m: 33% very dirty ballast, 66% slightly dirty ballast.

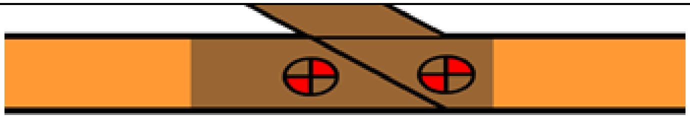
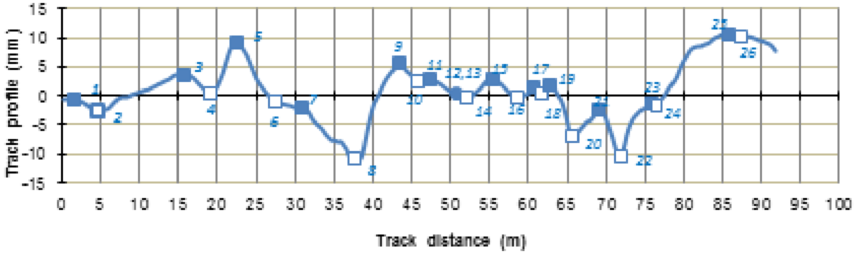
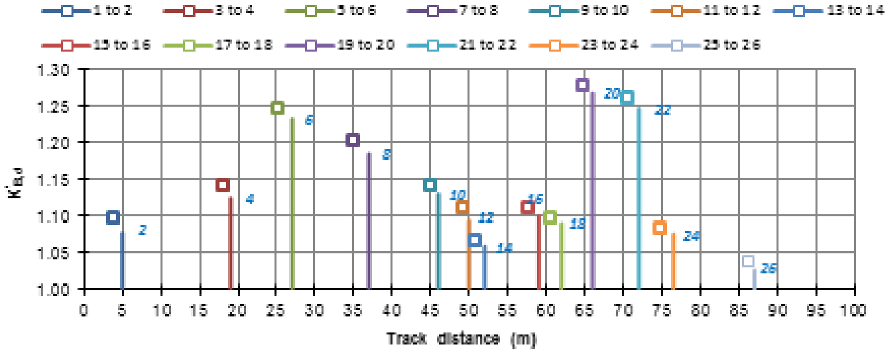
Ballast sample at position 56 m: 40% dirty ballast, 60% slightly dirty ballast.

- Tie bottom at 40 cm (15.7 in) below TOR. Cores extend 110 cm (43.3 in) below TOR.

Case study 2: Site in Scotland

- This track section is located in the northern part of Scotland in the UK and carries predominantly passenger trains (85%) with a traffic volume of 13 MGT/year with a maximum line speed of 200 km/h (125 mph).
- The section lays mainly on prepared formation with timber bearers for the turnout section, which is 45 m (137 ft) long.
- The calculated dynamic impact factors along the track show that there are three main locations where the impact factors are relatively high, namely at positions 28 m (85 ft), 66m (191 ft) and 72 m (218 ft).
- Position 66 m (191 ft) coincides with the location of the switch of the turnout where there it very difficult to maintain.
- Positions 28 m (85 ft) and 72 m (218 ft) coincides with the transition from/to steel sleepers to/from timber bearers.

Case study 2: Site in Scotland

Layout	
	▨ Concrete sleepers ▨ Concrete sleepers/bearers ▨ Steel sleepers ⊕ Ballast sample
Direction of Travel	→ → →
Speed and traffic	125 mph, 13MGT per year
Rate of geometry degradation	0.5 mm/year (0.02 in/year)
Track Geometry	
$K'_{B,d}$	

Ballast sample at position 26 m: 50% dirty ballast, 50% very dirty ballast.

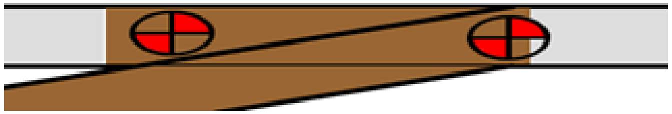
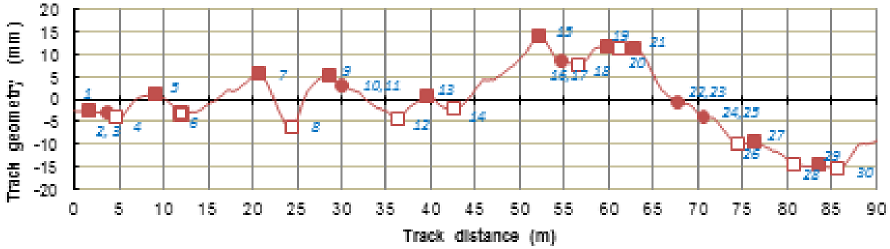
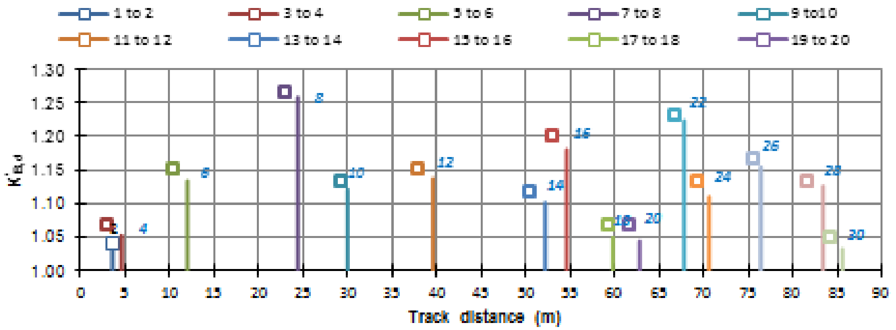
Ballast sample at position 66 m: 40% dirty ballast, 60% very dirty ballast.

- Tie bottom at 40 cm (15.7 in) below TOR. Cores extend 110 cm (43.3 in) below TOR.

Case study 3: site in Wales

- This track section is located in the mid-eastern part of Wales in the UK and carries a mixture of passenger trains (48%) and freight trains (52%) adding to traffic volume of 18 MGT/year with a maximum line speed of 144 km/h (90 mph).
- The section lays mainly on prepared formation with timber bearers for the turnout section, which is 55 m (167 ft) long.
- The calculated factors along the track show that there are two main locations where the impact factors are relatively high, namely at positions 24 m (73 ft) and 67 m (203 ft).
- Position 24 m (73 ft) coincides with a turnout crossing point. Position 67 m (203 ft) coincides with the location of the switch blade of the turnout where it is very difficult to maintain and tamp.

Case study 3: site in Wales

Layout	
	⬜ Concrete sleepers 🟫 Concrete sleepers 🟧 Steel sleepers ⊕ Ballast sample
Direction of Travel	➔ ➔ ➔
Speed and traffic	150 km/h (90 mph), 18MGT per year
Rate of geometry degradation	0.7 mm/year (0.0276 in/year)
Track Geometry	
$K'_{B,d}$	

Ballast sample at position 24 m: 45% very dirty ballast, 50% cohesive dirty ballast. Signs of poor drainage in the sample (standing water and blocked drainage pipes).

Ballast sample at position 67 m: 50% very dirty ballast, 50% cohesive dirty ballast. Signs of poor drainage in the sample (standing water and blocked drainage pipes).

- Tie bottom at 40 cm (15.7 in) below TOR. Cores extend 110 cm (43.3 in) below TOR.

Conclusions

Existing research... papers that present experimental studies from heavily instrumented test tracks

- Between highly conservative empirical approaches and highly detailed numerical/experimental approaches to understand and estimate the dynamic impact forces on railway tracks, there was a need for an intermediate approach that was plain enough to apply manually with acceptable accuracy.

- Dynamic impact force factors due to track roughness have been measured/modelled to show up to **DIF ~2.5**, that increased to **more than 2.5 and up to 5** for **abrupt rail-end drops** and **wheel flats**.

Estimation of dynamic impact force and evaluation of bearing stresses

- This study demonstrated the estimation of dynamic impact forces due to abrupt and rapid changes in railway track elevation with the Bezgin Method.

- Through the estimations of DIF, we were able to estimate the bearing stresses in ballast and subgrade and thereby judge the likely behaviors in these layers (excessive settlement, bearing failure, fracture failure).

- Through the estimations of DIF, we were able to estimate the likely increase in the wheel-rail interface bearing stresses through Hertz Theory and thereby judge whether the increased forces would cause impact batter on the rail and plastically deform the rail.

Correlation of dynamic impact forces with the damage observed in the turnout locations

- Balast condition data obtained from the three sites provided by Network Rail show a correlation between the estimated dynamic impact forces and the damage caused on the ballast.

- Repeated axle loading reaching dynamic impact forces that is **20% to 30%** higher than the static force values appears to have caused settlements at distinct turnout locations and ballast damage to varying degrees.

Future studies

Comparisons of the analytical results with numerical estimates of FEM and site measurements

- Ongoing study that compares the estimates of the proposed approach with the estimates of Jenkins Equation applied at turnouts.

- As part of our ongoing studies, we look for opportunities to compare the analytical estimates with numerical estimates obtained through finite element analysis of the numerical models of abrupt and rapid rail-end profile variations.

- Through collaborations, we look for opportunities to compare the analytical estimates with measurements obtained through instrumented test sites.

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Thank you

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