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Operational Speed Analysis of LRT Trains on Curved Track Sections in the Kuningan Line (Long Spans)

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Abstract: Mass transit systems such as Light Rail Transit (LRT) offer an efficient and environmentally friendly solution to urban mobility challenges. The performance of LRT systems is highly influenced by track geometric design, particularly in segments involving curve radii and long-span structures. The analysis is based on technical parameters such as centrifugal force, track elevation (superelevation), and railway geometric standards as stipulated by national regulations. The findings indicate a reduction in operational speed on certain curved sections where the radius does not align with ideal design speeds, primarily due to geometric constraints and safety considerations.

Keywords: LRT, operational speed, curve radius, long span, Kuningan Line

INTRODUCTION

Transportation is an essential element inseparable from the dynamics of human life. Its functions are closely related to individual mobility, the distribution of goods and services, and the movement of production outputs. Considering that this system utilizes relatively new technology and infrastructure, it is crucial to ensure that all facilities and components including curved track segments are in optimal condition. Based on this background, and supported by previous scientific studies, the researcher is motivated to conduct a further analysis of the operational speed of LRT on curved track sections along the Kuningan Line (Long Spans), in an effort to ensure that performance and operational safety remain at an optimal level.

RESEARCH METHOD

Railway Geometry encompasses the dimensions and configuration of the track, both in horizontal and vertical aspects, including gauge width, gradients, curves, superelevation, and track widening. Its design must take into account efficiency, safety, passenger comfort, and environmental compatibility. In curved sections, particular attention is required due to the dynamic forces acting on the train and track, which influence operational speed and stability.

Horizontal Alignment in Railway Tracks

The horizontal alignment of a railway track refers to the horizontal layout or path of the track as viewed from above (plan view). It represents the track's direction on a flat plane, including straight segments, horizontal curves, and transition curves that connect differing directions.

Key Components:

1. Tangent (Straight Track):
   A straight section of the track with no directional change.
2. Horizontal Curve:
   Used when the railway track changes direction. These curves typically consist of: Simple Curve: A full circular curve with a constant radius. Transition Curve (Spiral): A curve that gradually changes radius to connect a straight segment with a circular curve, enhancing ride comfort and safety.
3. Point of Intersection (PI):
   The meeting point of two tangents (before a curve is introduced).
4. Deflection Angle (Δ):
   The angle of directional change between two straight track segments.
5. Curve Radius (R):
   The radius of curvature, which directly affects maximum operational speed and ride comfort.
6. Cant (Superelevation):
   The elevation difference between the outer and inner rails on a curve, used to counteract centrifugal force during turning and improve safety and stability

Calculate the Curve Length

The length of the horizontal curve is determined based on the curve radius (R) and the central angle (Δ). This length represents the actual arc distance that the train will travel along the curve.

Horizontal Curve Calculation Procedure

1. Calculating Deflection Angles and Curve Lengths

$$\Theta s = \frac{90\ x\ ls}{\pi\ x\ R}$$

$$\Theta c = \Delta s - 2\Theta s$$

$$Lc \ = \frac{\Theta c}{360^0} x 2\pi\ R$$

$$L \ = 2\ ls + lc$$

2. Calculating Coordinates and Offsets

$$Xc = Ls - \frac{Ls^3}{40\ R^3}$$

$$Yc = \frac{Ls^2}{6R}$$

$$P \ = Yc - R(1 \cos \Theta s)$$

$$k \ = Xc - R \sin \Theta s$$

3.Calculating Tangent Length and External Distance

$$Tt = (R + P)tg\frac{\Delta s}{2} + k$$

$$Et = (R + P)sec\frac{\Delta s}{2} - 2$$

Vertical alignment

Refers to the projection of the railway track on a vertical plane, consisting of straight gradients and vertical curves. The allowable gradient depends on the train type: adhesion locomotives are limited to 40‰, while rack rail systems can handle up to 60–80‰. Some countries classify terrain into flat (0–10‰) and mountainous (>10‰) tracks. For station yards, gradients are based on rolling resistance, typically 1.5–2.5 kg/ton. According to PD No. 10 of 1986, flat lines range from 0–10‰, mountainous lines from 10–40‰, rack rail lines from 40–80‰, and yard tracks from 0–1.5‰. The minimum radius for vertical curves depends on design speed: 8000 m for speeds over 100 km/h and 6000 m for speeds up to 100 km/h. Vertical curves are circular arcs connecting two gradients, with their length determined by the radius and the gradient difference. The basic form of the curve follows the equation:

$$\frac{d^2y}{dx^2} = \frac{1}{R}$$

Where:
y is the vertical elevation,
x is the horizontal distance,
R is the vertical curve radius

RESULT AND DISCUSSION

Horizontal Curve Analysis

In the horizontal alignment analysis for the Kuningan long-span section, the track direction is represented on a horizontal plane, including straight segments, horizontal curves, and transition curves that connect differing directions. At equilibrium, gravitational force equals centrifugal force.

Based on the practical formula from PD No. 10 of 1986, the required curve radius (R) can be calculated using:

$$R = \frac{8.8v^2}{h}$$

Where:

- R = radius of curvature (m)
- v = train speed (km/h)
- h = cant (superelevation) in mm

Assuming the maximum cant is 110 mm, the minimum radius can also be calculated using:

$$R_{min} = 0.076 \times v^2$$

For a design speed of 75 km/h:
$R_{min} = 0.076 \times 75^2 = 427.5$ meters
This radius represents the minimum allowable curve to ensure safe and comfortable train operation under the given conditions.

$$a = \frac{v^2}{gR} = \frac{h}{w}$$

$$a = \frac{75^2}{600 \text{ x } 9{,}81} = \frac{20.83^2}{9.81\, x\, 600} = 0.0737\frac{M}{S^3}$$

$$\frac{h}{w} = \frac{110}{1435} = 0.0766$$

Where:
G = gravitational component acting due to train weight
C = compensating component from rail cant (superelevation)
F_c = centrifugal force acting outward in a horizontal curve

Vertical Curve Analysis

A vertical curve is a curve in the vertical alignment of a railway track that connects two different gradients. These curves can take the form of:
Crest Curve: a convex curve transitioning from an uphill to a downhill gradient.
Sag Curve: a concave curve transitioning from a downhill to an uphill gradient.
The purpose of vertical curves is to provide a smooth gradient transition, ensure ride comfort, and maintain adequate forward visibility for safe operation.

Tabel 1. Table Vertical Curve Analysis

No	Grade In (%)	Grade Out (%)	Change	Interpretation
25	1.57	1.46	-0.11	Gentle
26	1.46	1.52	0.06	Gentle
27	1.52	0.01	-1.51	Gentle – Descending
28	0.01	-0.87	-0.88	Gentle – Downward
29	-0.87	-1.87	-1.00	Gentle – Downward
30	-1.87	-2.00	-0.13	Gentle – Downward

This table summarizes the analysis of the vertical curve layout, focusing on the Point of Vertical Intersection (PVI), curve length (L), algebraic grade difference (A), the start and end points of the curve (T_1 and T_2), and the maximum projection distance from the grade axis to the curve (denoted as *h* or *H*), which represents the vertical offset at the midpoint of the curve.

Tabel 2. vertical curve layout

No	PVI (m)	L (m)	A (%)	Start Point (T_1)	End Point (T_2)	h (m)
27	5657.48	40	1.51	5637.48	5677.48	0.0302
28	5720.07	25	0.88	5707.57	5732.57	0.00688
29	5774.14	30	1.00	5759.14	5789.14	0.01125

CONCLUSION

Horizontal Curve

The horizontal curve radius of 600 meters is greater than the minimum required for a design speed of 75 km/h, which is 428 meters. The planned rail superelevation of 110 mm lies between the minimum (29 mm) and standard (82.5 mm) values, making it technically safe and compliant with applicable standards. The transition curve length of 82.5 meters is sufficient to ensure a gradual directional change, preventing abrupt movement. Based on both Indonesian and Japanese standards, no track widening is required for a curve radius of 600 meters. Furthermore, centrifugal force analysis confirms that the superelevation effectively balances lateral forces, ensuring stable and comfortable train operation.

.Vertical Curve

The three vertical segments analyzed (Nos. 27–29) have radii exceeding 2600 meters, which is well above the minimum requirement of 1200 meters for a speed of 75 km/h. The gradient changes are within the safe range of 0.88% to 1.51%, with maximum projection distances (h) ranging from 0.006 to 0.03 meters, indicating smooth vertical transitions. All track gradients fall between −2.00% and +1.57%, which is significantly below the 4% (40‰) limit for mountainous routes. The start and end points of each vertical curve follow a symmetrical parabolic layout, ensuring a seamless transition between gradients.

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