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Predicting The Maximum Dynamic Deflection of Rigid Pavement Slab at Toll Road Due To Vehicle Load

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Abstract:

Several points along Indonesian toll roads have exhibited cracks in the concrete slabs very early, shortly after operation, especially on routes with high volumes of trucks transporting materials and industrial products. The most common failure modes in rigid pavements are fatigue cracks in the concrete slab and/or erosion of the material in the subbase. Both are related to excessive stress and deflections in the concrete slab. Currently, vehicular loading is commonly modeled as a static load in concrete design guidelines, although it has a dynamic nature. However, dynamic analysis of concrete pavements has attracted researchers' attention. The American Association of State Highway and Transportation Officials (AASHTO) conducted experimental tests on concrete pavements to determine the effect of vehicle velocity from 3.2 km/h to 95.6 km/h using different single-truck configurations. The AASHTO results showed that increasing vehicle speed from 3.2 km/h to 95.6 km/h decreased pavement responses by about 29%. This research was intended to predict dynamic deflection through implementation of the Pasternak–Vlasov foundation model and primary data. Deflection was successfully calculated through numerical analysis using the finite element method. The results revealed the maximum deflection occurring at a vehicle speed of 2 km/h. Attention was also paid to a vehicle speed of 40 km/h, which produced relatively higher deflection than the others.

Keywords: *rigid pavement slab, moving load, vehicle load, Pasternak*

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INTRODUCTION

The addition of toll road length in Indonesia has been very rapid in recent years. According to data from the Toll Road Regulatory Agency (BPJT) of the Ministry of Public Works of the Republic of Indonesia, in 2025 there are toll roads in operating phase with a total length of 3,020 km, consisting of 75 toll road sections (AASHTO, 1993; Alisjahbana & Wangsadinata, 2003). Toll road construction continues in the following years both for government and private initiatives (Chan et al., 2023; Endo et al., 2021; Rohman, 2022). From technical point of view, toll roads generally use rigid pavement/concrete. Rigid pavement consists of a subbase layer, base layer, and a surface in the form of concrete slabs with varying thicknesses and concrete strengths (Balai Perkerasan dan Lingkungan Jalan, 2021; Darestani et al., 2006; Gibigaye et al., 2016).

Cracks found in the concrete slab very early, not long after the road was operated, especially on toll roads with large volumes of vehicles (trucks) transporting materials and industrial products The most common failure modes that occur in rigid pavements are fatigue cracks in the concrete slab and/or erosion of the material in the subbase. Both are related to excessive stress and deflections in the concrete slab (Beskou & Muho, 2023).

Currently, vehicular loading is commonly modelled as static load in concrete design guidelines although it has a dynamic nature. However, dynamic analysis of concrete pavements has been attracting researcher's attention (Alisjahbana, 2020; Avramidis & Morfidis, 2005). The American Association of State Highway and Transportation Officials (AASHTO) conducted an experimental test of concrete pavements to determine effect of vehicle velocity from 3.2 km/h to 95.6 km/h by using different single truck vehicles (Kneifati, 1985; Limkatanyu et al., 2013). The AASHTO result showed that increase vehicle speed from 3.2 km/h to 95.6 km/h decreased pavement responses by about 29% (Bayraktarova et al., 2022).

Study of dynamic response of pavement due to moving loads such as vehicles and aircraft has received significant attention in recent years because of its relevance to design of pavements and airport runways. Some of these limitations of analytical solutions have been largely overcome by the development of high-speed computers and efficient numerical techniques such as Finite Element Method. By using the Finite Element technique, concrete pavements can be effectively and accurately modeled including dynamic interaction between the moving load and pavement and a realistic representation of suspension system (Parjoko, 2012).

RESEARCH METHOD

This research was run by taking primary data for concrete slabs, vehicles and subbase geotechnical parameters. There are also scenarios in numerical analysis then numerical analysis was conducted. Figure 2 shows the flow of research.

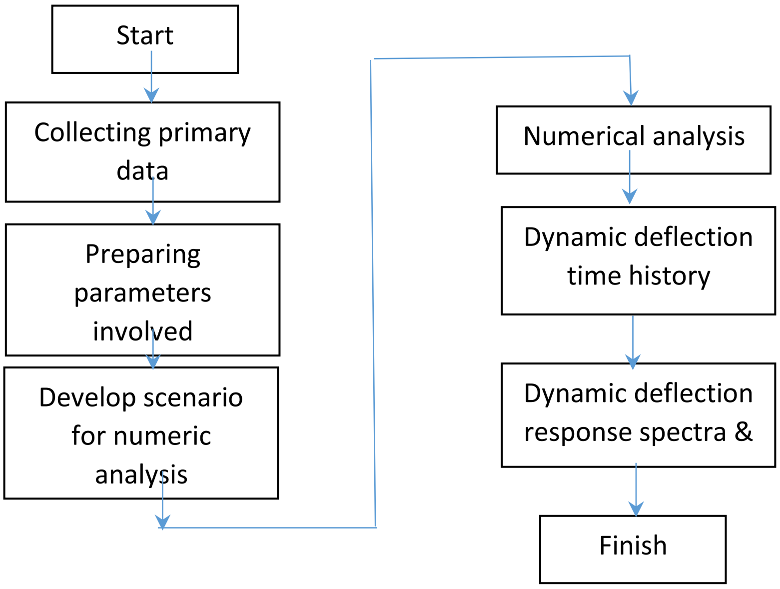

Figure 2. Flow of research

RESULT AND DISCUSSION

Primary data

Rigid pavement on toll road

The location to obtain primary data is in Cikampek – Palimanan (Cipali) toll road which part of trans Java toll road. Cipali toll road stretches from Cikampek (Karawang regency) to Palimanan (Cirebon regency). Total length of Cipali toll road is 116 kms. Figure 3 and Figure 4 show plan and cross section of rigid pavement.

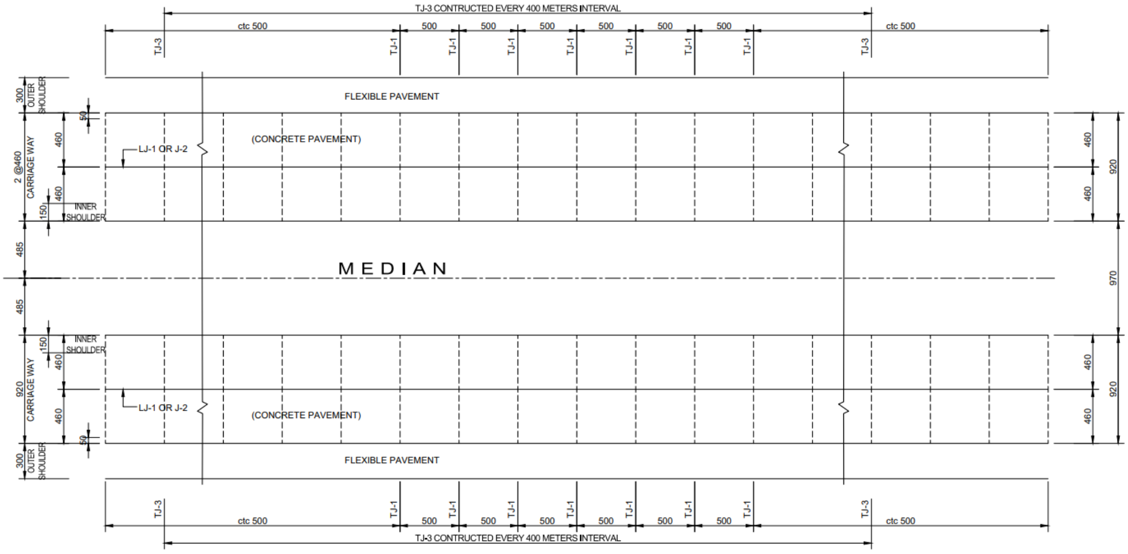

Figure 3. Plan of concrete pavement

Original design of Cipali toll road is two lanes for each direction. Typical dimension slab is 5.0 x 4.6 m. Comprehend cross section is presented on the following.

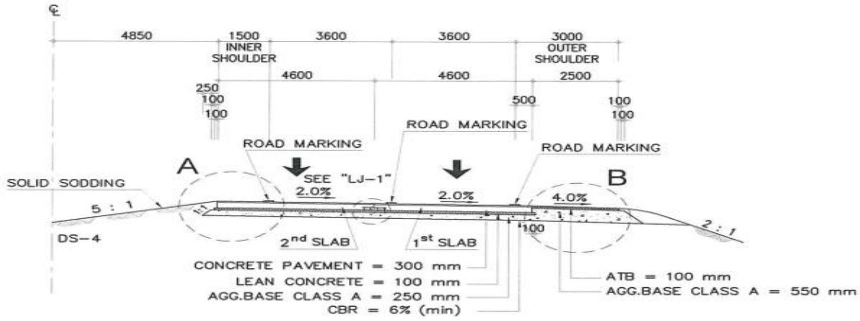

Figure 4. Typical cross section of concrete pavement

Geotechnical data

Intended geotechnical data were required to provide & support whole parameters to run dynamic analysis. The most important parameters are subbase reaction modulus and shear modulus. These parameters are media to show interactions involving dynamic/moving loads, slabs and layer beneath the slab. Geotechnical data were grabbed by using hand auger to take undisturbed soil samples (UDS). The depth of boring was 60 cm from subbase surface with a total point of 20 boreholes. As common, the UDS were sent to soil mechanic laboratory.

Laboratory tests provided result that specific gravity (Gs) of soil ranges from 2.555 - 2.679 ton/m3, while density (□wet) ranges from 1.64 – 1.78 (ton/m3). To calculate m0, the unit weight of soil took 1.723 ton/m3.From sieve analysis and Atterberg limits test, soil classification has been successfully defined. Plasticity index (PI) ranges from 24.49 – 44.84%. By implementing Unified Soil Classification System (USCS), it was shown that the soil type are silts and clays. It comprises MH (inorganic silts), CH (inorganic clays of high plasticity) and OH (organic clays of medium to high plasticity). While AASHTO classification showed, soil classification is silt clayey with liquid limit above 40%.

Mechanical properties were also successfully produced through laboratory tests. The relevant mechanical properties result was internal friction angle (□□□ From 20 UDS, the internal friction angle ranges 2.100 – 5.330. The most relevant mechanical properties for this research were modulus elasticity (E) which was produced by Triaxial laboratory test (Table 1). It was useful to determine the subbase reaction modulus.

Table 1Geotechnical data

Bore Hole	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
E_{TRX} (kN/m^2)	12,100	11,200	10,300	9,300	9,300	11,200	12,100	14,000	12,100	9,300
E_{TRX} (MN/m^2)	12.10	11.20	10.30	9.30	9.30	11.20	12.10	14.00	12.10	9.30

Bore Hole	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
E_{TRX} (kN/m^2)	14,000	9,300	9,300	11,200	16,800	18,700	15,900	12,100	16,800	18,700
E_{TRX} (MN/m^2)	14.00	9.30	9.30	11.20	16.80	18.70	15.90	12.10	16.80	18.70

Modulus of elasticity from Triaxial (ETRX) as presented above statistically has 12.685 MN/m2 as the average. The maximum value was 18.700 MN/m2 and 9.300 MN/m2 as the minimum value. After elastic modulus was made available, the subbase reaction modulus was calculated.

AASHTO 1993 provides equations to calculate subbase reaction modulus as expressed below (AASHTO, 1993; Setiadji, 2010).

$$k=E/0.492 \qquad (7)$$

Calculating k from AASHTO equations are listed in the following table.

Table 2. Subbase reaction modulus (k)

Bore hole	**E_{TRX} (MN/m^2)**	**k-AASHTO**
1	12.1	24.59
2	11.2	22.76
3	10.3	20.93
4	9.3	18.90
5	9.3	18.90
6	11.2	22.76
7	12.1	24.59

Bore hole	E_{TRX} (MN/m^2)	k-AASHTO
8	14.0	28.46
9	12.1	24.59
10	9.3	18.90
11	14.0	28.46
12	9.3	18.90
13	9.3	18.90
14	11.2	22.76
15	16.8	34.15
16	18.7	38.01
17	15.9	32.32
18	12.1	24.59
19	16.8	34.15
20	18.7	38.01

From table 2, it can be concluded the maximum k is 38.01 MN/m3 (borehole 16). The following equation 8 is ratio between k1 (higher layer of spring) and k2 (lower layer of spring) (Kneifati, 1985).

$$n_{k_1 k_2} = \frac{k_1}{k_2} \qquad (8)$$

Avrimidis and Morfidis suggested 7 as the value of n_{k1k2} particularly for soft soil with low elastic modulus [4]. Therefore, for this research subbase reaction modulus (kf) was calculated as 38.01/7 = 5.34 MN/m3.

Traffic data

Vehicle data in this research are essential since taken from a very important toll road in Indonesia. It is Cikampek – Palimanan (Cipali) toll road which plays role as nerve of Java island logistics. The vehicle velocity and load become inputs for dynamic analysis. The following table and chart show vehicle data.

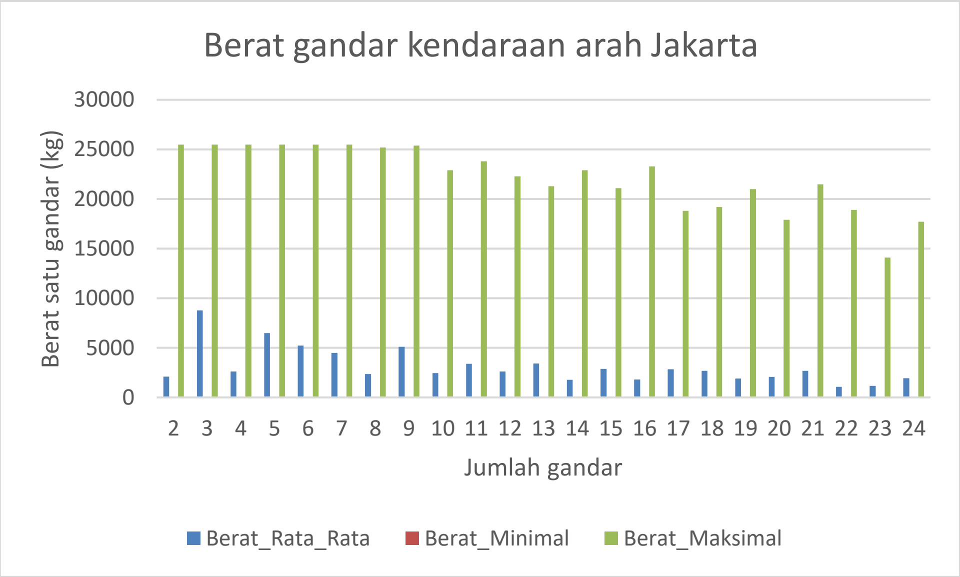

Figure 5. Vehicle's axle load

Figure 5 describes load of axles. Vehicle with two axles, the maximum axle load is 25.500 kg or 25.5 tons.

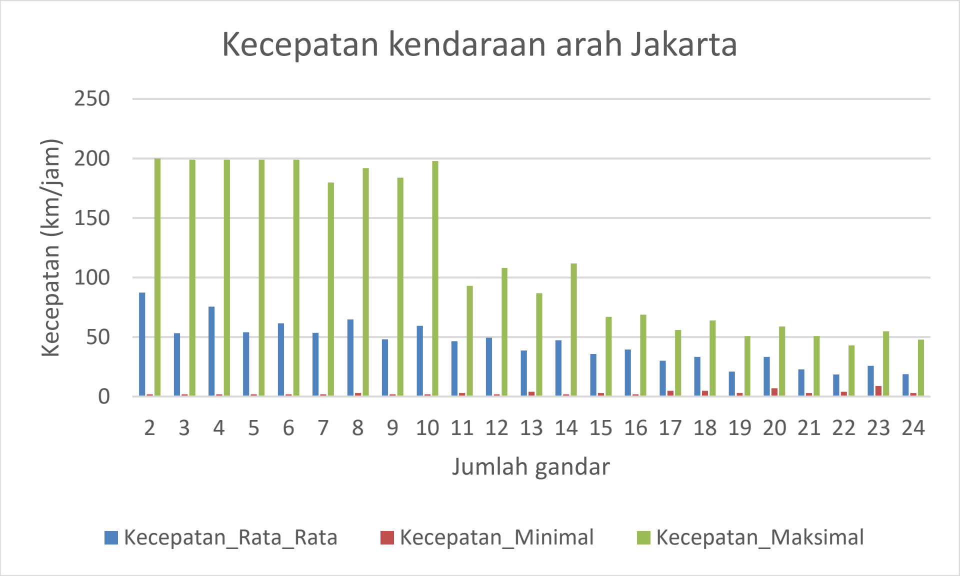

Figure 6. Vehicle speed

Figure 6 shows vehicle speed Jakarta direction. For vehicles with two axles the maximum speed is 200 km/hour, average speed is 87 km/hour, and the minimum is 2 km/hour. These speed data become parameters in numerical analysis.

Parameters involved

Parameters required to conduct analysis in general consist of vehicle parameters, concrete slab specification and geotechnical modulus. From section 4, all primary data have been available and able to be analyzed.

Vehicle parameters

Numeric analysis required vehicle parameters to simulate the characteristics which affect dynamic behavior of slab. Vehicle parameters are listed in table 3.

Table 3. Vehicle parameters

No.	Parameters	Notation	Value	Data source
1.	Axle load	P_0	25.500 kg	Data real
2.	Maximum velocity	V_0	200 km/h	Data real
3.	Average velocity	V_0	87 km/h	Data real
4.	Minimum velocity	V_0	2 km/jam	Data real

Concrete slab specification

Slab dimensions are 5.0 m x 4.6 m (a x b)

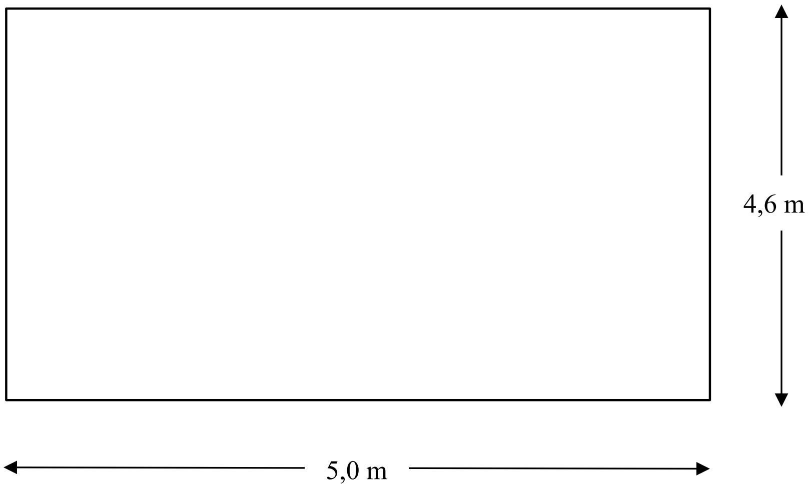

Figure 7. Slab dimension

Comprehend slab material properties are listed in table 4

Tabel 4. Slab material properties

No.	Parameters	Notation	Value	Data source
1.	Length of slab (axis x)	a	5.0 m	Data real
2.	Width of slab (axis y)	b	4.6 m	Data real
3.	Slab thickness	h	0.30 m	Data real
4.	Reinforced concrete unit wight	ρ	2,500 kg/m^3	Reference
5.	Concrete compressive strength	f_c'	25 MPa	Data real
6.	Concrete elastic modulus axis x	E_x	58.8 x 10^9 Pa	Data real
7.	Concrete elastic modulus axis y	E_y	49.0 x 10^9 Pa (E_y = 83% E_x)	Reference
8.	Poisson's ratio concrete slab x	ν_x	0.18	Reference
9.	Poisson's ratio concrete slab y	ν_y	0.15	Reference
10.	Rotational restraint x axis	k_{rx}	1.0 N.M/rad/m	Reference
11.	Translational restraint x axis	k_{sx}	150 MN/m/m	Reference
12.	Rotational restraint y axis	k_{ry}	0.4 N.M/rad/m	Reference
13.	Translational restraint y axis	k_{sy}	120 MN/m/m	Reference

Geotechnical parameters

Table 5 consists of properties of subbase which required for numerical analysis.

Tabel 5. Material Properties Subbase

No.	Parameter	Notation	Value	Source
1.	Subbase reaction modulus	k_f	5.43 MN/m^3	Data real
2.	Subbase shear modulus	G_s	6.23 MN/m^2	Reference
3.	Unit weight of soil	M	1,723 kg/m^3	Data real
4.	Dynamic active soil depth	H_s	5.0 m	Assumption
5.	Reduced mass of foundation soil	m_0	2,428 kg/m3	Calculated

Analysis and discussion

After dynamic parameters are available, analysis starts. Numerical analysis was executed by implementing finite element method.

Scenario and limitations

Numerical analyses were carried out by taking scenarios as follows:

Table 6. Scenarios on numerical analysis

Items	Parameters
Range of truck velocity	2 – 200 km/hour
Type of vehicle	2 axles
Range of w	4 – 91 rad/sec
Axle load	25.500 ton
Subbase reaction modulus, k_f	5.43 NM/m^3
Shear modulus, G_s	6.23 NM/m^2

Numerical analyses also took important assumption as the limitations [3].

1. Deflection was measured at slab middle point (a/2 and b/2)
2. Deflection was calculated during load within slab $(t \leq t_0)$
3. The concrete slab is placed on a Pasternak - Vlasof foundation which has a spring stiffness modulus (k_f) and shear modulus (G_s).
4. The dynamic load is assumed to always work and be attached to the center plane of the plate as a concentrated resultant load P_0 (single point load).
5. The magnitude of the concentrated load P_0 used as the average central load is the resultant of the standard axle load of a double wheel or single axle vehicle wheel.
6. The vehicle load is modeled as a harmonic load moving in a straight line at a constant speed. The working load function is $\mathrm{P(t) = P_0(1 + \alpha cos\omega t)}$.

Time history deflection

The main purpose of conducting numerical analysis was to obtain maximum absolute deflection for each truck velocity for certain soil condition. The following figures depict time history deflections, for few vehicles speed.

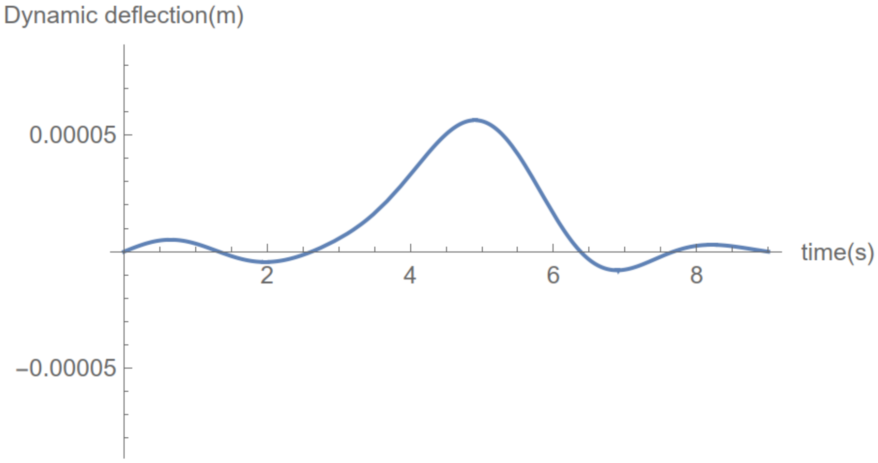

Figure 8. Time history deflection for 2 km/hour

Figure 8 shows time history deflection for 2 km/hour. The absolute maximum deflection is 5.639 x 10-5 m.

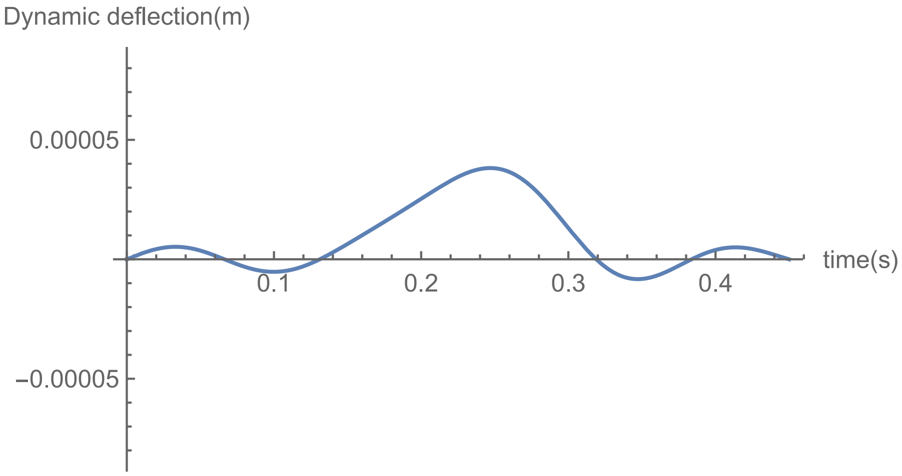

Figure 9 Time history deflection for 40 km/hour

Figure 9 shows time history deflection for 40 km/hour. The absolute maximum deflection is 3.810 x 10-5 m.

Response spectra

Time history deflection showed maximum absolute deflection for each velocity. The following table is listed as the maximum deflection (see table 6).

Table 6. Maximum absolute deflection

Vehicle Velocity (km/hour)	Max. absolute deflection (m)
2	5.639E-05
20	3.322E-05
40	3.810E-05
87	3.546E-05
120	3.609E-05
160	3.530E-05
200	3.601E-05

By using abovementioned values, response spectra were constructed. Figure 10 shows dynamic deflection response spectra for vehicle velocity ranges 2 – 200 km/hour.

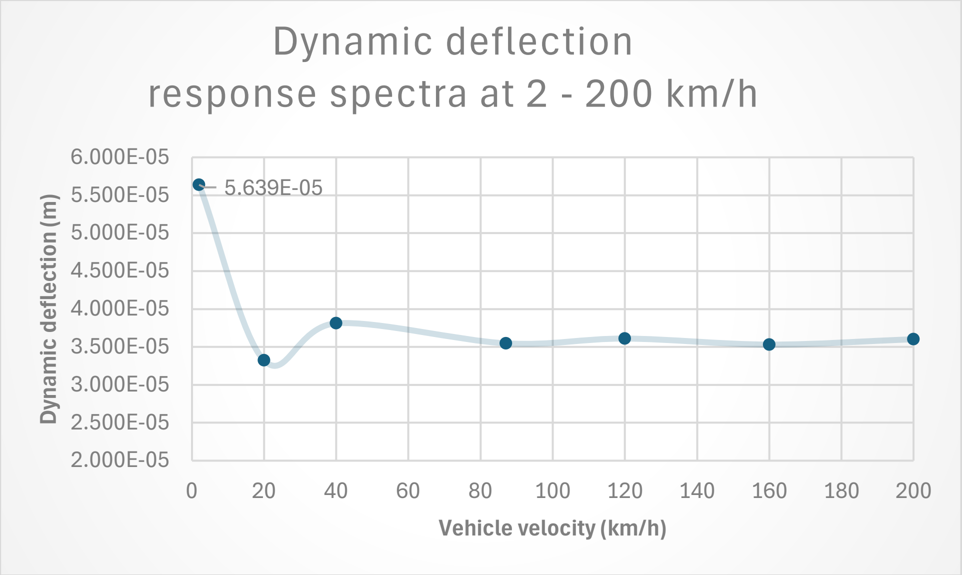

Figure 10. Dynamic deflection response spectra at 2 – 200 km/hour

From figure 10, it can be found the maximum dynamic deflection resulting at 2 km/hour vehicle velocity (5.639 x 10-5 m). By taking this result, defined critical velocity is 2 km/hour. Other findings, 40 km/hour, also produced higher deflection (3.810 x 10-5m) than other

velocities.

CONCLUSION

The numerical analysis of dynamic deflection effectively identified the critical velocity of rigid pavement slabs on toll roads at 2 km/h, derived from the Pasternak foundation model incorporating 5 meters of soil inertia. Although vehicles traveling at such low speeds (2 km/h) are rare on toll roads—where primary data indicate an average speed of 87 km/h—response spectra analysis revealed that higher velocities produce smaller deflections. For future research, investigators could extend this model to validate findings against real-world sensor data from high-traffic toll sections in Indonesia, exploring variable soil conditions and multi-axle truck configurations to refine critical velocity thresholds under diverse loading scenarios.

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