Measurements of rotational stiffness for precast concrete girder transport vehicles, part 2

C. Shawn Sun, Adam D. Sevenker, and Mostafa Abo El-Khier

- As a continuation of part 1 of this study, this paper presents field measurements for transport vehicles suitable for transportation of relatively typical precast, prestressed concrete girders.
- Field measurements were completed in Colorado, California, and Florida.
- Calculations for vehicle rotational stiffness based on the collected data are summarized.

Part 1 of this paper presented field measurements from sites in Georgia, Nebraska, and Utah. Part 2 details the measurements from three additional locations in Colorado, California, and Florida.[1] The vehicle configurations for the study featured combined air and leaf suspensions in Colorado, hydraulic trailers in California, and a unique jeep and dolly that can expand transversely in Florida.

Field measurements

Field measurements in Colorado

The team conducted field measurements in Denver, Colo., in April 2023. The vehicle consisted of a 2015 Kenworth T800 truck, two 2001 45-ton (41-tonne) trailers, and a 2001 steering dolly (**Fig. 1**). The dolly comprised a trailer connected via a fifth wheel to a steering dolly. The collected data included the basic dimensions of the truck, jeep, dolly, type of suspensions, tire specifications, heights of the roll centers, and other details (**Fig. 2**). The truck had two dual axles, the steering dolly had two dual axes, and each trailer had three dual axes. In this particular trailer and dolly, axis is defined as a line of tires perpendicular to the trailer centerline. Axle refers to the rod (or spindle) connecting the left and right suspensions that link two adjacent axes of tires. The truck uses air suspension, while the trailer in both the jeep and the dolly uses a combined suspension system: air suspension at the front dual axis and leaf suspensions at the two rear dual axes. The steering dolly uses leaf suspensions. The heights of rotation center above the ground are 25 in. (635 mm) at

Truck and jeep

Dolly

Figure 1. Views of the truck, jeep, and dolly.

Air suspension
at the truck and trailer

Leaf suspension at the dolly
and rear axles of the trailer

Height measurement
at the air suspension

Height measurement
at the leaf suspension

Figure 2. Suspensions.

the steering dolly, 22 in. (559 mm) at the air suspension of the trailer, and 20 in. (508 mm) at the leaf suspension of the trailer. The height of the girder soffit is 72 in. (1829 mm) at both jeep and dolly. The center-to-center wheel spacing is 72 in. at the steering dolly and 78 in. (1981 mm) at the trailer.

The team conducted the measurements on the vehicle rotational stiffness by placing a girder on the jeep and dolly with offsets of ±10 in. (254 mm) away from the vehicle centerline (**Fig. 3**). The primary equipment for tilt measurements was a tiltmeter. The girder was 159 ft (48.5 m) long and weighed 178 kip (792 kN). Due to the limited bearing width of the jeep bolster, offsetting the girder by 10 in. resulted in approximately three-quarters of the girder bottom flange resting on the bolster. According to the truck driver, the air suspension on the trailer had to be let out (zeroed) at loading. Therefore, the team took readings on the trailer at that time, with the beam loaded and zero air suspension. Then the driver inflated the air suspensions and readings were taken at the jeep and dolly. **Table 1** shows the measured tilts on top of the bolsters

Figure 3. Girder placement on the vehicle.

Table 1. Calculated vehicle rotational stiffness of the vehicle in Colorado

Item	Offset of girder centerline	Jeep (front trailer) θ_{Ji}, degrees				Dolly (rear trailer) θ_{Di}, degrees			
		Top of bolster		Under bolster		Top of bolster		Under bolster	
		Right	Left	Right	Left	Right	Left	Right	Left
Tilt change, degrees	Positive offset	3.000	3.160	2.500	2.769	2.213	0	1.562	1.905
	Negative offset	0	-2.150	-1.749	-1.721	0	-1.569	-1.551	-1.605
$K'_{\theta i}$, kip-in./radian	Positive offset	17,228	16,355	20,678	18,668	22,734	0	32,208	26,403
	Negative offset		24,045	29,556	30,037		32,060	32,426	31,341
Suggested $K'_{\theta i}$, kip-in./radian		16,355				22,734			
Number of dual axes		5.5				5.0			
Suggested $K_{\theta i}$, kip-in./radian/axis		2970				4547			

Note: $K'_{\theta i}$ = calculated rotational stiffness of the jeep or dolly in various cases; $K_{\theta i}$ =rotational stiffness of the jeep or dolly; θ_{Di} = tilt due to girder weight measured at the dolly support; θ_{Ji} = tilt due to girder weight measured at the jeep support. 1 kip-in. = 0.113 kN-m.

and under the bolsters with various offsets (**Fig. 4**). Table 1 also lists the calculations on the rotational stiffness of the jeep and dolly. The total vehicle rotational stiffness was 39,089 kip-in./radian (4416 kN-m/radian). The rotational stiffness at each dual axis was 2970 and 4547 kip-in./radian (336 and 514 kN-m/radian) at the jeep and dolly, respectively.

Figure 4. Tilt measurement locations.

Field measurements in California

The team visited a hauler in California and conducted field measurements in August 2022. The vehicle configuration consisted of a Peterbilt truck and a Goldhofer hydraulic trailer (**Fig. 5**). **Figure 6** shows the hydraulic trailer and cylinder. Each axle of the trailer is equipped with two sets of dual wheels or tires on each side—that is, a total of four wheels or tires on each side of the axle. The authors refer to this as a double dual-tire axle. Each unit consists of four double dual-tire axles.

Because a precast concrete girder was unavailable at the site, a steel frame and multiple steel panels and plates served as the load and were placed on the trailer with a loading offset of 21 in. (533 mm) away from the vehicle center to result in tilts. Three load cases were included. Load cases 1 through 3 had steel member weights of approximately 119, 153, and 183 kip (529, 681, and 814 kN), respectively. A plan view of the trailer is illustrated in **Fig. 7**. The trailer had a total of eight axles with axle 8 closest to the truck. The trailer consisted of three hydraulic groups (or circuits) that were independent from each other. Hydraulic groups AB, C, and D formed a stability triangle. The loading offset was limited within the stability triangle to avoid a trailer rollover. Based on the trailer manufacturer's input, the hydraulic pressures at all suspensions within each group were identical. Trailer dimensions are shown in Fig. 7. **Figure 8** depicts an elevation view of the trailer, where load case 3 is shown for illustration purposes.

Tilt readings were collected at each axle due to loads with a 21 in. (533 mm) offset. A tiltmeter was placed on top of the trailer deck, 10 in. (254 mm) off the deck edges. The tilt readings at various axles generally exhibited consistency among the three load cases. Axle 8, closest to the truck, showed the largest tilts among all axles. **Table 2** summarizes the detailed calculations on the rotational stiffness due to individual load

Figure 5. Field measurements in California.

Hydraulic trailer

Hydraulic cylinder

Figure 6. Vehicle details.

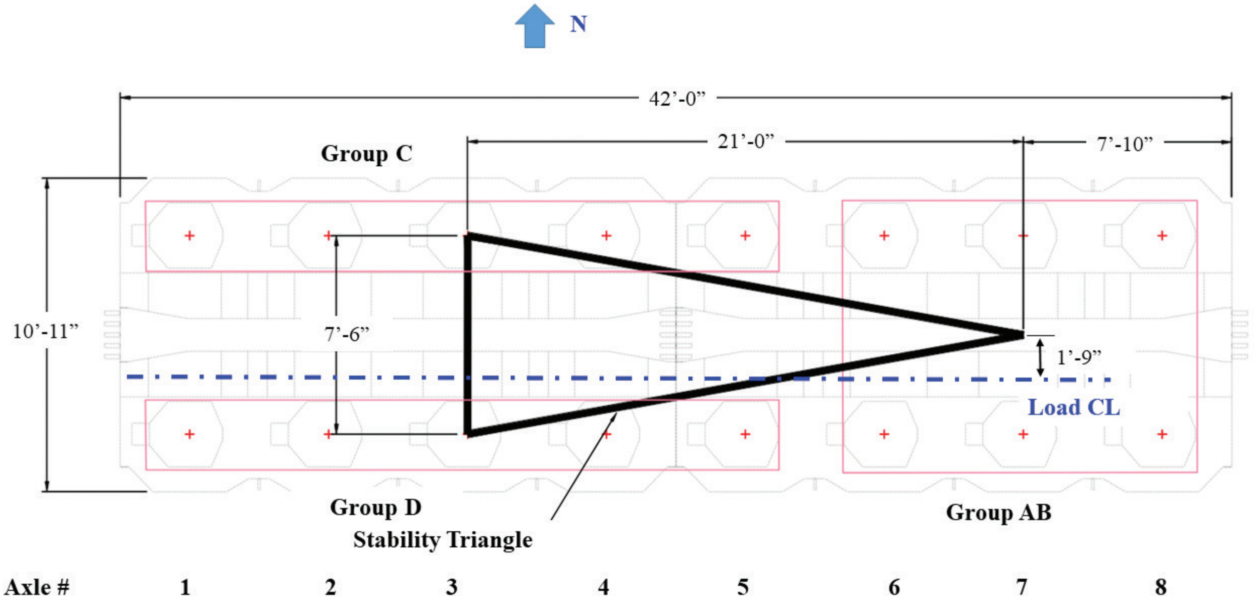


Figure 7. Plan view of the trailer. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

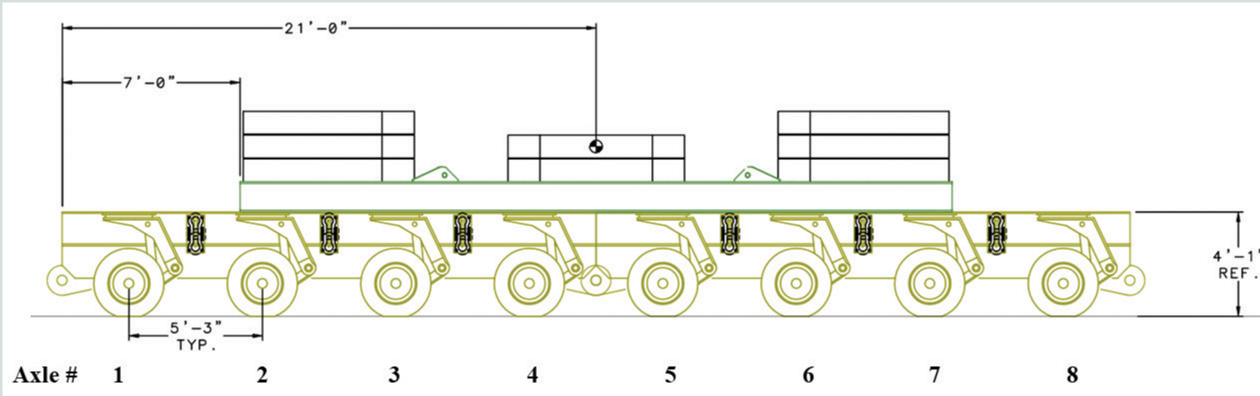


Figure 8. Elevation view of the trailer. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

Table 2. Calculated rotational stiffness due to various load cases of the vehicle in California

Axle number	Case 1, 118.8 kip				Case 2, 152.6 kip				Case 3, 183.1 kip			
	N		S		N		S		N		S	
	10 in. off edge	30 in. off edge	10 in. off edge	30 in. off edge	10 in. off edge	30 in. off edge	10 in. off edge	30 in. off edge	10 in. off edge	30 in. off edge	10 in. off edge	30 in. off edge
1	0.2666	n/a	0.5184	n/a	0.3833	n/a	0.6030	n/a	0.5311	n/a	0.6564	n/a
2	0.4382	n/a	0.5507	n/a	0.5875	n/a	0.6296	n/a	0.7176	n/a	0.7720	n/a
3	0.5537	n/a	1.0446	n/a	0.7280	n/a	1.1891	n/a	1.0702	n/a	0.9504	n/a
4	0.6318	0.6958	0.6370	n/a	0.8625	0.8907	0.8491	n/a	1.1335	1.1825	1.1231	n/a
5	0.4845	n/a	1.1527	n/a	0.6588	n/a	1.4068	n/a	1.5162	n/a	1.8578	n/a
6	0.6657	n/a	1.0938	n/a	1.3849	n/a	1.3810	n/a	1.6185	n/a	1.9592	n/a
7	1.2663	n/a	1.2598	n/a	1.5556	n/a	1.5331	n/a	2.2170	n/a	2.2186	n/a
8	1.2899	n/a	1.3427	1.3288	1.5777	n/a	1.6620	1.5318	2.1489	n/a	2.3615	2.3521
Average tilt, degrees	0.6996	n/a	0.9500	n/a	0.9673	n/a	1.1567	n/a	1.3691	n/a	1.4874	n/a
Average tilt (N and S), degrees	0.8248				1.0620				1.42825			
Average tilt, radian	0.0144				0.0185				0.0249			
Moment at groups C and D, kip-in.	1483				2231				2409			
K_θ, kip-in./radian	103,010				120,384				96,630			
K_θ, kip-in./radian/axle	12,876				15,048				12,079			

Note: K_θ = rotational stiffness of the vehicle; N = North; n/a = not applicable; S = South. 1 in. = 25.4 mm; 1 kip = 4.4482 kN; 1 kip-in. = 0.113 kN-m.

cases. For ease of calculations, an average tilt was taken among all axles in each load case. The vehicle's calculated total rotational stiffness was relatively comparable among the three cases, varying from 12,079 to 15,048 kip-in./radian (1365 to 1700 kN-m/radian) per axle. It is suggested that 12,079 kip-in./radian (1365 kN-m/radian) per double dual-tire axle be used as the minimum rotational stiffness.

Field measurements in Florida

The team visited a site in Orlando, Fla., and conducted the field measurements in May 2023. The company owned its own shipping vehicles. The hauling vehicle consisted of a 2016 Mack Granite Tractor and two 2016 Trail King TK170SD as jeep and dolly (**Fig. 9**). The jeep and dolly are identical and their axles are transversely expandable. The total width of the trailers (measured from the outside of the exterior tires on both sides) increases from 11 up to 18 ft (3.4 to 5.5 m) when the axles are expanded. The four dual tires on each side can be expanded hydraulically by extending the steel assembly above them. The truck includes two dual axles. Each trailer has four axes of tires and each axis consists of four dual tires (two dual tires on each side, for a total of eight tires). **Figure 10** clarifies the defined locations of axles and axes and distinguishes

Truck and jeep

Dolly

Figure 9. Views of the truck, jeep, and dolly.

Figure 10. Definitions of *axis* and *axle* in Trail King TK170SD trailer.

them from other tested trailers. In this particular trailer, *axis* is defined as a line of tires perpendicular to the trailer centerline. *Axle* refers to a line of the rod (or spindle) connecting the left and right suspensions that link two adjacent axes of tires.

The collected data included the basic dimensions of the truck, jeep, dolly, type of suspensions, specifications of the tires, and other details (**Fig. 11**). The truck, jeep, and dolly used leaf suspension. The height of rotation center above the ground was about 26 in. (660 mm) at the truck and 17 in. (432 mm) at the jeep and dolly. The height of the girder soffit was approximately 55 in. (1397 mm) above ground at both the jeep and dolly. The center-to-center wheel spacing was 158 in. (4013 mm) at jeep and dolly with expanded axles and 74 in. (1880 mm) without expanded axles. The wheel center is the middle point between the exterior dual tires, that is, suspension-to-suspension spacing.

The team conducted measurements of the vehicle's rotational stiffness by placing eccentric loads on the jeep and dolly. The primary equipment used for these rotational stiffness measurements was a tiltmeter. The girder used for this purpose was 179 ft (54.6 m) long and weighed 214 kip (952 kN). It was placed on the jeep and the dolly with offsets of either 12 or 18 in. (305 or 457 mm) from the vehicle centerline. To take measurements with two opposite offsets (±18 and ±12 in. [±457 and ±305 mm]), the bolsters had to be rotated 180 degrees. Although the dolly bolster was easy to rotate, the jeep bolster required some force to do so. Tilt measurements were taken both before and after the trailer axles were expanded. According to the truck driver, the front axle of the dolly can be maneuvered to turn left or right during transportation. **Table 3** shows the collected tilt readings corresponding to various cases and details the sequence in which the measurements were taken.

The rotational stiffness of the vehicle was calculated based on the measured tilts both on top of and beneath the bolsters. The team believed that the data collected at the jeep was inaccurate in three specific cases (that is, +18 in. [457 mm] expanded,

Leaf suspension at the truck

Leaf suspension at the jeep or dolly

Measurement at the truck leaf suspension

Measurement at the jeep or dolly leaf suspension

Figure 11. Vehicle suspensions and measurements.

-12 in. [305 mm] not expanded, and -18 in. not expanded) where the bolster was rotated 180 degrees and existing deformations were likely present in the mechanical connection. Because no new zero readings were taken after the 180-degree rotation of the bolster, the deformation was not canceled in the calculations, introducing errors into the stiffness results. The team attributes this existing deformation to the force that was required to rotate the jeep bolster. Therefore, the measurements in these three cases were excluded from the stiffness calculations. As a result, the total vehicle rotational stiffness increased from 78,181 to 134,584 kip-in./radian (8833 to 15,206 kN-m/radian) when the axles were expanded from 11 to 18 ft (3.4 to 5.5 m).

Because the jeep and dolly were the same models, the calculated rotational stiffness of the dolly is believed to be more reliable. **Table 4** shows that increasing the load eccentricity from 12 to 18 in. (305 to 457 mm) reduced the calculated stiffness by approximately 10%, indicating a minimal effect on stiffness due to various offsets. With an offset of 18 in., the calculated stiffness under bolster was increased by about 60% (that is, from 9466 to 15,104 kip-in./radian/axis [1070 to 1707 kN-m/radian/axis]) when the axles were expanded from 11 to 18 ft (3.4 to 5.5 m). Table 4 also reveals that the calculated rotational stiffness of the trailer at the top of the bolster and beneath the bolster were similar, considering the

Table 3. Measured tilts at the jeep and dolly in Florida

Trailer axles	Cases	Offset of girder centerlines from vehicle center, in.	Jeep θ_{Ji}, degrees		Dolly θ_{Di}, degrees	
			Top of bolster	Under bolster	Top of bolster	Top of bolster
Expanded	Before girder placement	n/a	-1.9501	-1.4400	-0.0946	0.0182
	After girder placement	0	-1.3863	-0.8690	-0.7142	-0.5703
		-18	0.3375	0.6064	0.8490	0.8701
		+18	-2.5505	-2.5733	-2.4826	-2.3890
Unexpanded	Before girder placement	n/a	-1.3890	-1.6686	0.0003	-0.0477
	After girder placement	0	-0.8822	-1.1679	-0.6551	-0.6581
		+12	-2.5375	-2.7156	-2.411	-2.3432
		+18	-3.6425	-3.756	-3.5448	-3.4661
		-18	0.9337	1.2262	1.3622	1.384
		-12	0.0501	0.4026	0.5262	0.5989

Note: n/a = not applicable; θ_{Di} = tilt due to girder weight measured at the dolly support; θ_{Ji} = tilt due to girder weight measured at the jeep support. 1 in. = 25.4 mm.

Table 4. Calculated stiffness of the dolly in Florida

Rotational stiffness $K_{\theta D}$, kip-in./radian		Expanded axles		Unexpanded axles			
		-18 in.	+18 in.	-12 in.	+12 in.	-18 in.	+18 in.
Under the bolster	Calculated $K_{\theta D}$	76,288	60,416	58,030	43,285	53,580	38,964
	Controlling $K_{\theta D}$	60,416		38,964			
	$K_{\theta D}$/axis*	15,104		9741			
On top of the bolster	Calculated $K_{\theta D}$	70,295	62,136	61,751	41,539	54,237	37,862
	Controlling $K_{\theta D}$	62,136		37,862			
	$K_{\theta D}$/axis*	15,534		9466			
Suggested $K_{\theta D}$/axis*		15,104		9466			

Note: $K_{\theta D}$ = rotational stiffness of the dolly. 1 in. = 25.4 mm; 1 kip-in. = 0.113 kN-m.
*The number of axes considered is four double dual axes.

field measurement tolerances. This similarity is attributed to the relatively stiff bolster, which does not cause substantial deformation when subjected to eccentric loads.

Discussion

Calculations of the vehicle rotational stiffness

The vehicle rotational stiffness was determined using the measured tilts at the jeep and dolly. In most of the conducted field measurements, the girder was placed on the vehicle considering three cases:

- without an offset
- with a positive offset
- with a negative offset

For illustration purposes, **Fig. 12** shows cases 1 and 2 to address the approach to rotational stiffness calculations. For simplicity, it was assumed that the rotational stiffness remained constant in both cases.

Case 1 without an offset When the girder was placed on the vehicle without an offset—that is, the girder centerline was aligned with the centerline of the jeep and dolly—the measured tilts primarily resulted from the effect of the girder lateral deflection and initial eccentricity.

$M_{r0} = K \times \theta'_0$

where

M_{r0} = resisting moment from the vehicle

K = rotational stiffness of the vehicle

θ'_0 = tilt of the vehicle measured at the bottom of the bolster

$M_{r0} = W \times (y \times \sin\,\theta_0 + \Delta_0 \times \cos\theta_0)$

where

W = weight of the girder

y = height of the girder center of gravity above the roll axis

θ_0 = tilt of the support measured at the top of the bolster

Δ_0 = effect of the lateral deflection and initial eccentricity at the girder center of gravity without any offset

$\Delta_0 = \bar{z}\sin\theta_0 + e_i$

where

$\bar{z}_0$ = lateral deflection of the girder center of gravity with full girder self-weight applied laterally

e_i = initial eccentricity of the girder center of gravity

$M_{r0} = W \times (y \times \sin\theta_0 + \bar{z}_0 \times \sin\theta_0 \times \cos\theta_0 + e_i \times \cos\theta_0)$

Thus,

$$W \times (y \times \sin\theta_0 + \bar{z}_0 \times \sin\theta_0 \times \cos\theta_0 + e_i \times \cos\theta_0) = K \times \theta'_0 \quad (1)$$

Case 2 with a positive offset When the girder was placed with a positive offset with respect to the vehicle centerline, the measured tilts were primarily attributed to the offset and the effect of the girder lateral deflection and initial eccentricity. Furthermore, the bolsters of some vehicles may exhibit additional deflection or rotation when an offset is involved.

$M_{r1} = K \times \theta'_1$

where

M_{r1} = resisting moment from the vehicle with an offset

θ'_1 = tilt of the vehicle measured at the bottom of the bolster with an offset

$M_{r1} = W \times (y \times \sin\theta_1 + \Delta_1 \times \cos\theta_1 + e \times \cos\theta_1)$

where

θ_1 = tilt of the support measured at the top of the bolster with an offset

Δ_1 = effect of the lateral deflection and initial eccentricity at the girder center of gravity with an offset

e = girder offset with respect to the vehicle centerline

$\Delta_1 = \bar{z}\sin\theta_1 + e_i$

$M_{r1} = W \times (y \times \sin\theta_1 + \bar{z}_0 \times \sin\theta_1 \times \cos\theta_1 + e_i \times \cos\theta_1 + e \times \cos\theta_1)$

Thus,

$$W \times (y \times \sin\theta_1 + \bar{z}_0 \times \sin\theta_1 \times \cos\theta_1 + e_i \times \cos\,\theta_1 + e \times \cos\theta_1) = K \times \theta'_1 \quad (2)$$

By subtracting Eq. (1) from Eq. (2):

$$W \times (y \times [\sin\theta_1 - \sin\theta_0] + \bar{z}_0 \times [\sin\theta_1 \times \cos\theta_1 - \sin\theta_0 \times \cos\theta_0] + e_i \times [\cos\theta_1 - \cos\theta_0] + e \times \cos\theta_1) = K \times \left(\theta'_1 - \theta'_0\right) \quad (3)$$

For very small angles, $\cos\,\theta_1 \approx \cos\theta_0 \approx 1.0$.

$\therefore (\sin\theta_1 \times \cos\theta_1 - \sin\theta_0 \times \cos\theta_0) \approx \sin\theta_1 - \sin\theta_0$

$(\cos\theta_1 - \cos\theta_0) \approx 0$

Equation (3) is simplified as follows:

$$W \times (y \times [\sin\theta_1 - \sin\theta_0] + \bar{z}_0 \times [\sin\theta_1 - \sin\theta_0] + e) = K \times \left(\theta_1' - \theta_0'\right)$$

or

$$W \times ([y + \bar{z}_0] \times [\sin\theta_1 - \sin\theta_0] + e) = K \times \left(\theta_1' - \theta_0'\right) \quad (4)$$

assuming $\sin\theta_1 \approx \sin\theta_0 \approx 0$

Thus, Eq. (4) can be further simplified as follows:

$$W \times e = K \times \left(\theta_1' - \theta_0'\right)$$

or

$$K = \frac{W \times e}{\theta_1' - \theta_0'}$$

In Eq. (4), even though $\sin\theta_1 - \sin\theta_0 \approx 0$, the term $y + \bar{z}_0$ can be a significant value. Therefore, it is conservative to ignore $(y + \bar{z}_0) \times (\sin\theta_1 - \sin\theta_0)$.

Effect of vehicle age and measurement frequency

Based on interactions with one of the vehicle manufacturers, the springs on the leaf suspensions should be inspected annually for cracks or broken components. However, it may be impractical to measure the vehicle's rotational stiffness on an annual basis. The research team does not have sufficient data to propose a specific frequency for measuring the rotational stiffness. If possible, the team suggests continuing to measure the rotational stiffness of the tested vehicles every few years to observe any variance that may result from aging.

Ground condition

Most of the field tests were conducted with vehicles parked on gravel or compact soil ground in a precasting yard. The team had intended to test the vehicles on various types of ground conditions, such as concrete or pavement, to evaluate their effect on rotational stiffness. However, this request could not be accommodated due to limited test time or site constraints. Nonetheless, the authors believe that the data collected on gravel or compact soil ground leads to a conservative estimate of rotational stiffness compared with what might be observed on concrete or pavement ground.

Contact between the girder and bolster

As mentioned in the literature review covered in part 1 of this study, Mast[2] suggested using a narrow bearing strip of hard material between the girder and the cross member to ascertain the eccentricity of the load on the trailer, as the cross member tilts under eccentric loads. This concern stems from the possibility of nonuniform loading on a wide girder bottom flange. To address this issue, the team attempted to install narrow steel plates as bearings during one of the field measurements. However, this installation was not allowed, as the precaster was concerned about girder stability. Despite this, the team believes that stress distribution on a bolster is a local problem and should not affect the calculations of the rotational stiffness. The local stress distribution can be considered as an internal force effect when examining a free-body diagram of the girder and vehicle (**Fig. 12**).

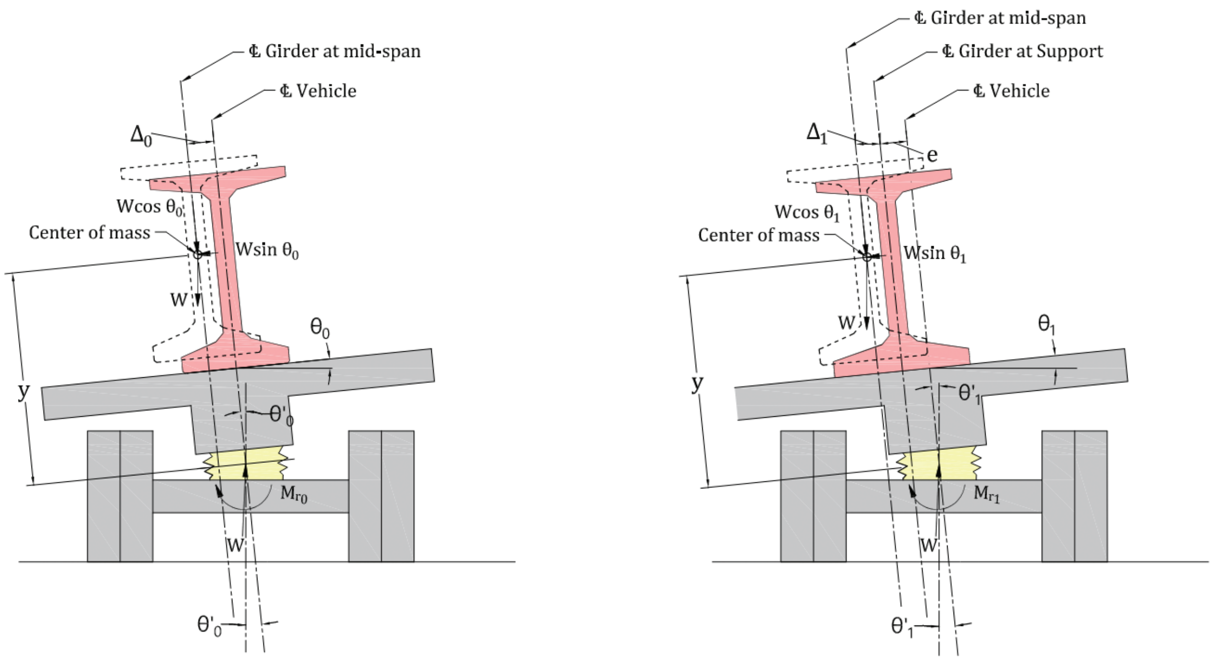
Use of tilts on top of or under the bolsters

The bolsters were designed with a turntable mechanism, allowing the girder to pivot during transportation. Eccentric loads may result in additional deformation, which is attributed to both the deflection of the bolster and the mechanical connection between the bolster and the trailer. In most of the field measurements, the tiltmeter was placed on top of and under the bolsters to gather the tilt data. The data collected on top of the bolsters could yield overly conservative rotational stiffness. This is because the bolster may exhibit additional deflection under an eccentric load, leading to unintended increased tilts. However, this added deflection does not occur during girder transportation because the girder aligns with the vehicle centerline. It was noted that a bolster with relatively low stiffness could result in up to a 67% difference in rotational stiffness, depending on whether tilts were calculated on top of or under the bolster (**Fig. 13**). If a bolster has relatively high stiffness, this difference becomes negligible (Fig. 13). To minimize the effects of additional deformation in the bolster, the tiltmeter should be positioned beyond the girder footprint on the bolster, but as close to the vehicle centerline as feasible.

The tilt data collected under the bolsters is unaffected by the bolster deformation, but it does not capture the effects due to deformation at the mechanical connection. It is likely that the mechanical connection is not perfectly rigid, leading to additional tilts when subjected to eccentric loads. This effect can occur during girder transportation, particularly when a vehicle encounters a significant cross slope. Using the tilts collected under the bolster may therefore result in an unconservative estimate of rotational stiffness. Consequently, for simplicity, it is recommended to use the lowest rotational stiffness calculated based on the tilts both on top of and underneath the bolsters.

Summary of vehicle rotational stiffness

Based on the collected data, including the data presented in part 1 of this paper, the vehicle's rotational stiffness per dual axle varied from 2146 to 5798 kip-in./radian (242 to 655 kN-m/radian) with leaf suspensions and ranged from 3120 to 3180 kip-in./radian (353 to 359 kN-m/radian) with



Without any offset

With an offset

Figure 12. Girder placement on the vehicle. Note: M_{r0} = resisting moment from the vehicle; M_{r1} = resisting moment from the vehicle with an offset; W = weight of the girder; y = height of the girder center of gravity above the roll axis; Δ_0 = effect of the lateral deflection and initial eccentricity at the girder center of gravity without any offset; Δ_1 = effect of the lateral deflection and initial eccentricity at the girder center of gravity with an offset; θ_0 = tilt of the support measured at the top of the bolster; θ_1 = tilt of the support measured at the top of the bolster with an offset; θ'_0 = tilt of the vehicle measured at the bottom of the bolster; θ'_1 = tilt of the vehicle measured at the bottom of the bolster with an offset.

With relatively low stiffness

With relatively high stiffness

Figure 13. Bolsters.

air suspensions (**Table 5**). For the jeep and dolly involving both leaf and air suspensions, the rotational stiffness at each dual axis varied from 2970 to 4547 kip-in./radian (336 to 514 kN-m/radian). The rotational stiffness of the hydraulic trailer was 12,079 kip-in./radian (1365 kN-m/radian) per double dual axle. The Florida trailer's rotational stiffness was 9466 kip-in./radian (1070 kN-m/radian) (unexpanded) to 15,104 kip-in./radian (1707 kN-m/radian) (expanded) per axis, based on the data collected at the dolly.

Figure 14 shows the ranges of vehicle rotational stiffness using various suspension types. This figure is provided only to demonstrate orders of magnitude for individual vehicles based on the limited data. It is not suggested to back calculate the number of axles required unless a vehicle includes modular units, such as the expandable vehicle used in Florida, or the hydraulic trailers used in California. Most of the vehicles include different jeep and dolly models and setups and exhibited stiffness variances among various axles. This makes it unreasonable to back calculate the number of axles blindly. Instead, the authors suggest determining the required stiffness for an entire vehicle that accounts for the stiffness contribution of the tractor, jeep, and dolly and suggest that haulers work closely with precasters to take necessary measurements and determine their vehicle's rotational stiffness prior to its use.

Conclusion

This paper presents comprehensive field measurements on rotational stiffness at various precasting plants or a hauler's yard. Precast concrete girders or known weights of steel members

Table 5. Summary of vehicle rotational stiffness

Field measurement location	Rotational stiffness, kip-in./radian per axle			
	Vehicle with leaf suspensions	Vehicle with air suspensions	Vehicle with air and leaf suspensions	Hydraulic trailer
Georgia	5798	3120	n/a	n/a
Nebraska	2146	3180	n/a	n/a
Utah	2904 to 3803	n/a	n/a	n/a
Colorado	n/a	n/a	2970 to 4547	n/a
California*	n/a	n/a	n/a	12,079
Florida†	9466 (unexpanded) to 15,104 (expanded)	n/a	n/a	n/a

Note: n/a = not applicable. 1 kip-in. = 0.113 kN-m. *Stiffness per double dual-tire axle

†Stiffness per axis with double dual tires at each side

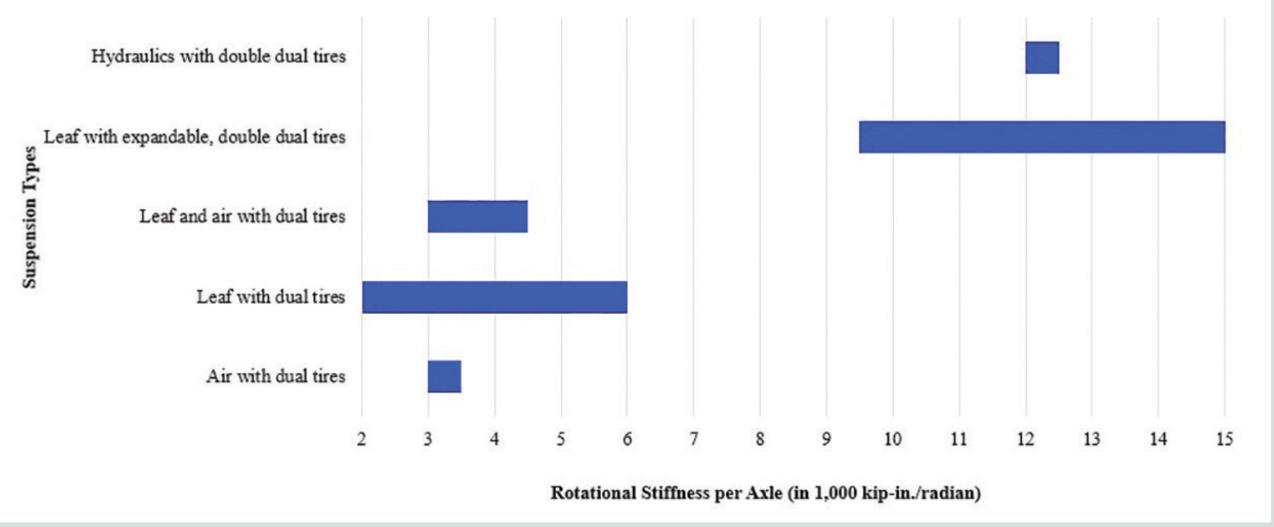


Figure 14. Ranges of vehicle rotational stiffness per axle or axis. Note: 1 kip-in. = 0.113 kN-m.

were positioned on vehicles at various eccentricities to induce tilting. This procedure facilitated the determination of the vehicle's rotational stiffness. The measurements considered a range of vehicles equipped with various suspension types, including leaf, combined leaf and air, and hydraulic suspensions. The vehicles tested had wheel spacings ranging from 6 to 18 ft (1.8 to 5.5 m), which corresponded to rotational stiffness values between 39,000 and 135,000 kip-in./radian (4406 and 15,253 kN-m/radian). Consequently, the rotational stiffness per dual axle or axis ranged from 3000 to 15,000 kip-in./radian (339 to 1695 kN-m/radian). The conducted field measurements allowed for the expansion of the existing database on vehicle rotational stiffness in the United States.

Acknowledgments

The authors would like to thank PCI for funding this research project. We are grateful to the project review committee members, including Jim Fabinski (chair), Richard Brice, Glenn Myers, Douglas Whittaker, and Brian Witte, for their guidance and support. Special thanks go to Jared Brewe and William Nickas for their leadership and efforts. The authors are also grateful to many precasters and haulers for hosting and assisting with the field tests. They include Richard Potts, Fletcher Smith, Alex Trammell, AJ Pickens, Todd Culp, Greg Malone, Brad Kohlwes, Christian Coronel, Lee Wegner, Brent K. Klopfer, James V. Mitchell, Colin Van Kampen, Tim Morley, Tom Turner, and Ed Green. We appreciate the guidance and support from Stephen Seguirant, Cameron West, and Austin Maue at Concrete Technology Corp. The assistance from various manufacturers, including Paul Gill at Elk River Machine Co., Charles Tucker at Tucker's Machine & Steel Services, Klaus Baehr at GOLDHOFER, and John Denney at Trail King Industries was truly appreciated. Last but not least, we would like to thank Maher Tadros, PhD, for his continuous support and guidance throughout the project.

References

1. Sun, C. S., A. D. Sevenker, and M. A. El-Khier. 2024. "Measurements of Rotational Stiffness for Precast Concrete Girder Transport Vehicles, Part 1." *PCI Journal*: 69 (2): 37–54. https://doi.org/10.15554/pcij69.2-04.

2. Mast, R. F. 1993. "Lateral Stability of Long Prestressed Concrete Beams—Part II." *PCI Journal* 38 (1): 70–88. https://doi.org/10.15554/pcij.01011993.70.88.

Notation

e = girder offset with respect to the vehicle centerline

e_i = initial eccentricity of the girder center of gravity

K_θ = rotational stiffness of the vehicle

$K_{\theta D}$ = rotational stiffness of the dolly

M_{r0} = resisting moment from the vehicle

M_{r1} = resisting moment from the vehicle with an offset

W = weight of the girder

y = height of the girder center of gravity above the roll axis

$\bar{z}_0$ = lateral deflection of the girder center of gravity with full girder self-weight applied laterally

Δ_0 = effect of the lateral deflection and initial eccentricity at the girder center of gravity without any offset

Δ_1 = effect of the lateral deflection and initial eccentricity at the girder center of gravity with an offset

θ_{Di} = tilt due to girder weight measured at the dolly support

θ_{Ji} = tilt due to girder weight measured at the jeep support

θ_0 = tilt of the support measured at the top of the bolster

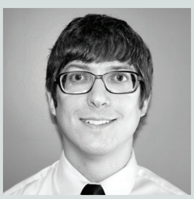
θ'_0 = tilt of the vehicle measured at the bottom of the bolster

θ_1 = tilt of the support measured at the top of the bolster with an offset

θ'_1 = tilt of the vehicle measured at the bottom of the bolster with an offset

About the authors

C. Shawn Sun, PhD, PE, is an assistant professor in the Department of Civil Engineering and Construction Management at California State University in Northridge.



Adam D. Sevenker, PE, is a partner at e.construct.USA in Omaha, Neb.

Mostafa Abo El-Khier, PhD, PE, is a structural engineer at e.construct.USA in Omaha.

Abstract

This paper presents field measurements of the rotational stiffness of three transport vehicles equipped with different types of suspensions: leaf, combined air and leaf, and hydraulic suspensions. The rotational stiffness was determined by measuring the tilts of the vehicles when a girder or known weights were placed on them at various eccentricities. One of the tested vehicles, which featured transversely expandable wheel spacings varying from 6 to 18 ft (1.8 to 5.5 m), exhibited an increase in rotational stiffness from 78,181 to 134,584 kip-in./radian (8833 to 15,206 kN-m/radian). This paper summarizes the rotational stiffness for all the vehicles tested by the authors. The field measurements conducted have enriched the existing database on vehicle rotational stiffness in the United States.

Keywords

Dolly, expandable axle, girder, girder stability, hydraulic trailer, jeep, long girder, roll stiffness, rotational stiffness, suspension, transport vehicle.

Review policy

This paper was reviewed in accordance with the Precast/Prestressed Concrete Institute's peer-review process. The Precast/Prestressed Concrete Institute is not responsible for statements made by authors of papers in *PCI Journal*. No payment is offered.

Publishing details

This paper appears in *PCI Journal* (ISSN 0887-9672) V. 69, No. 4, July–August 2024, and can be found at https://doi.org/10.15554/pcij69.4-03. *PCI Journal* is published bimonthly by the Precast/Prestressed Concrete Institute, 8770 W. Bryn Mawr Ave., Suite 1150, Chicago, IL 60631.

Reader comments

Please address any reader comments to *PCI Journal* editor-in-chief Tom Klemens at tklemens@pci.org or Precast/Prestressed Concrete Institute, c/o *PCI Journal*, 8770 W. Bryn Mawr Ave., Suite 1150, Chicago, IL 60631.