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Evaluation of Tractor-Trailer Combination Braking Performance in Different Operating Conditions

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Abstract: In the trials of the present work, a double-axle trailer with a carrying capacity of 6 tons and a hydraulically effective mechanical brake were used as a tractor towed car. There is a hydraulic brake system on each axle of the agricultural trailer. In order to separate the brake system on the axles from each other, a hydraulic mechanically controlled 2/2 directional control valve was mounted on both hydraulic brake system inlets. The study was carried out at constant speed (25 km h^{-1}), on stabilized road conditions, with 4 different braking modes and 4 different trailer loads. On stabilized ground, the braking acceleration (deceleration) of the tractor (without trailer) is 5.51 m s^{-2}. The braking acceleration of the combination is 2.15 m s^{-2} under the condition that the trailer's carrying capacity was 30% more loaded and without brakes, and the braking acceleration of the combination was 3.26 m s^{-2} when braking on both axles (4 wheels). The deceleration of the combination was above 3.5 m s^{-2} under the condition of braking on both axles at the rated load of the agricultural trailer, while it was below the standard value in other braking approaches.

Traktör-Römork Kombinasyonunun Farklı Çalışma Koşullarında Frenleme Performansının Değerlendirmesi

Anahtar Kelimeler
Tarımsal traktör,
Frenleme,
Yavaşlama,
Treyler

Öz: Bu çalışmadaki denemelerde 6 ton taşıma kapasiteli çift dingilli, hidrolik etkili mekanik frenli ve traktörle çekilir römork kullanılmıştır. Tarım römorkunun her iki dingiline de hidrolik fren sistemi bağlanmıştır. Dingillerdeki fren sistemini birbirinden ayırmak amacıyla, her iki hidrolik fren sistemi girişine birer adet hidrolik mekanik kumandalı 2/2 yön kontrol valfi monte edilmiştir. Çalışma sabit hızda (25 kmh^{-1}), stabilize yol koşullarında, 4 farklı frenleme şekli ve 4 farklı römork yükünde yürütülmüştür. Stabilize zeminde sadece traktörün (römorksuz) frenleme ivmesi 5.51 ms^{-2} olarak bulunmuştur. Römorkun taşıma kapasitesinin %30 daha fazla yüklü olduğu ve frensiz olduğu koşulda kombinasyonun frenleme ivmesi 2.15 ms^{-2}, her iki dingilde (4 tekerlekte) frenlenme yapıldığı koşulda ise kombinasyonun frenleme ivmesi 3.26 ms^{-2} olmuştur. Kombinasyonun frenleme ivmesi, tarım römorkunun anma yükünde her iki dingilde frenleme yapılması koşulunda 3.5 ms^{-2} üzerinde iken diğer frenleme uygulamalarında standartlardaki referans değerin altında kalmıştır.

1. Introduction

Fundamental power source of the agricultural mechanization is agricultural tractor with no doubt. Tractor in etymological manner means a machine that pulls something. However, agricultural tractors are special vehicles that are adapted to special conditions of connections between agricultural fields and civilized areas, unlike commercial tractors such as trucks. One of the equipment/machineries that is used

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together with agricultural tractors is agricultural trailers. Agricultural trailers are intensively used in transportation of agricultural goods from farms and fields to storages, depots, or process facilities while about 50% of annual tractor usage is spent for transportation [1]. Considering present tractor and trailer numbers in Turkey, one trailer exists for each tractor in the country [2,3].

Recently, changes have been realized in type approval regulations of agricultural tractors in our country and European Union countries, parallel to the increase in travel speeds of agricultural tractors. Modifications are done on numerous and variable components and systems of the agricultural tractors due to the and depending to the increasing travel speed capacities of the agricultural tractors. One of those components, and arguably the most important one, is the braking systems. The braking acceleration (deceleration) value of 2.5 m s^{-2} according to the outdated version of standard for agricultural trailers in our country [4], was increased to 3.5 m s^{-2}.

Brakes are one of the most important systems in a vehicle for a safe travel. The drive control system that lowers the vehicle travel speed and stops when desired is named as brake system. Therefore, high reliability and durability are sought from brake system of a vehicle. A vehicle should have the ability to decelerate and stop at every road and weather condition, in a rapid and safe manner. In our country, separate brake system of trailers from agricultural tractors, and manual braking necessity are serious problems relating to the braking safety of agricultural tractor trailer combinations. Most of the times, all braking task is borne by the agricultural tractor, reducing the braking effectiveness. In an emergency situation, simultaneous braking of the combination by the operator of agricultural tractor, using the brake pedal of the tractor and the brake lever of the trailer is unlikely. The braking system of the trailers are mainly activated by a hand lever. This mentioned circumstance necessitates a combined brake system for the agricultural tractor and trailer combination, which trailer brakes and tractor brakes can be activated from a single activation center in an emergency situation, while enabling separate braking for parking purposes [5,6].

When a vehicle is desired to be slowed down or stopped, vehicle inertia acts against those decision due to the conservation of momentum. Therefore, a force is needed to achieve braking action. This force can only be attained by the friction between the wheel of the vehicle and the road surface. In order to create a friction force, the relative motion of the wheels to the road surface should be lower than the vehicle speed. The brake systems, therefore, tries to lower the rotational speed of the vehicle wheels. In terms of conservation of energy, this process can be explained by energy conversion. Brake systems convert vehicle kinetic energy to heat, and eventually stop vehicles. Kinetic energy of the vehicle, is on the other hand, depends on vehicle mass and speed. The mass of the vehicle is directly and linearly proportional with the vehicle kinetic energy while the kinetic energy is proportional to the square of vehicle speed. In case of a twofold increase in vehicle speed leads to four times higher vehicle kinetic energy. Brake system is desired to overcome the vehicle inertia and consume the momentum. Accordingly, brake power should be much higher than the engine power. One rule of thumb is that brake power should be at least 8 times higher than the engine power of a vehicle [2,3].

At the instance of an emergency braking, time periods until stopping instance of the vehicle are listed as [7]:

- Instance of perceiving the danger
- Time period for driver decision making
- Time period for driver action initiation
- Time period for driver foot to reach the brake pedal
- Time period for brake mechanism to initiate
- Time period of brake force to act
- Time period for brake force to process
- Time period for brake force to reach its maximum

The vehicle continues to travel during braking, for all above mentioned time periods, depending on road and tire conditions, vehicle type, and brake system effectiveness (Figure 1).

Ahokas and Kosonen [8] investigated braking behavior of agricultural tractor and unbalanced (single or double axel without the ability of stand still at unconnected state) trailer in theoretical and experimental manners. The authors state that using ratio between the axle load and acceleration ratio for brake performance in terms of brake torque is more appropriate, and they favor this term for using as a performance indicator. In the mentioned work, the authors determine that engine speed and size of hydraulic cylinder have only 0.05 s portion in the total brake latency, latency time appears to be around 0.2 to 0.3 s, and the real problem is the trapped air in the hydraulic cylinder that may lead to latencies as much as 1 s. Hardness of determining braking distance and measurement of braking forces directly are mentioned in the paper of Bayrakçeken and Düzgün [9], while the authors calculate braking distances and deceleration values of vehicles with different travel speeds by using various mathematical expressions in the literature. Additionally, the authors state that friction relationship between the tire and the road is more effective in terms of mathematical modelling instead of friction coefficient and force between the brake linings and discs. Static and dynamic braking effectiveness values are examined for combination of an agricultural tractor and trailer with impact type mechanical brake system, double axel, and a capacity of 3 t by Örnek and Demir [10]. The distance for stopping slightly increases as braking deceleration slightly decreases depending on the carried load value. The authors state that travel speed of the tractor-trailer combination has the major effect on the braking effectiveness.

According to the surveyed national and international related scientific literature, no significant and similar reports has been encountered. Therefore, this work publishes new and original experimental data that can be utilized by scholars and industry members. The main aim of the present paper is to produce and evaluate scientific data on operational effectiveness of two axle agricultural trailer braking systems, which have hydraulic braking systems, and contribute reduction of traffic accidents that are attributed to the braking performance, considering the increase in travel speeds of agricultural tractor trailer combinations.

2. Material and Method

During the experiments, NewHolland TD 110D branded agricultural tractor was used, which is located in Faculty of Agriculture, Selcuk University. There is effective operation opportunity with the equipment that are tied by hydraulics thanks to the six-outlet hydraulic power supply. Five unit of oil bath discs that are mounted to the axle bar of differential gear box exist in that tractor that uses disc-hydraulic type brake system. Commanding each disc type brake can be done by separate pedals or mechanical steers. The pedals can be connected to each other when it is necessary for on-road conditions. Park brake is controlled by a mechanical lever and acts by the service brake. Technical specifications of the agricultural tractor for the experiments are given in Table 1.

On the trailer side, an agricultural trailer that is pulled with tractor and that has 6 t carriage capacity, tire wheels, double axles, leaf springs, sheet metal case, hydraulic effective mechanical brakes, damper operation towards rearwards was used during the experiments. Each axle of the agricultural trailer has hydraulic brake system. Wheel hubs and drums of the brake systems were made of different casting irons, and their internal surfaces were processed with turning in lathe. Technical specifications of the agricultural trailer are provided in Table 2.

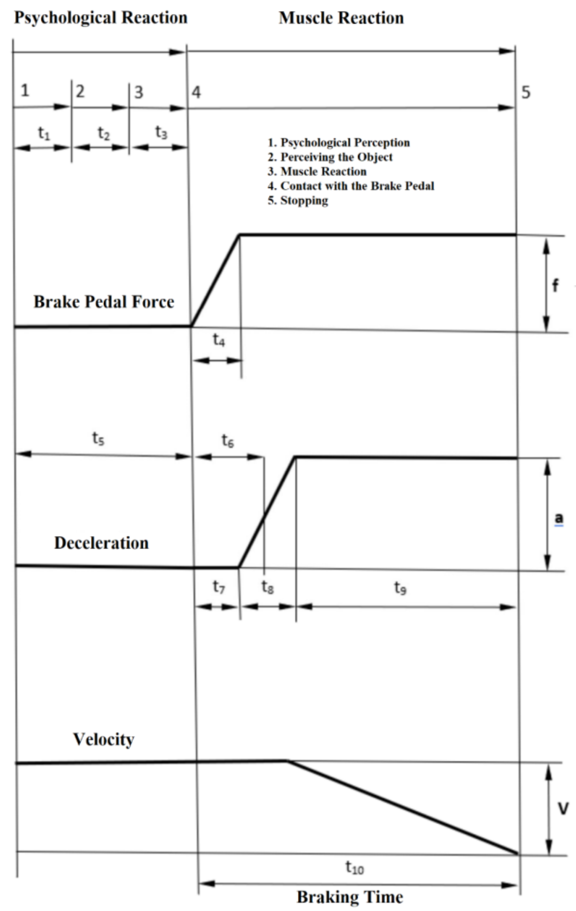

Figure 1. Decomposition of the braking [7]

Table 1. Technical specifications of the agricultural tractor for the experiments (TD 110 D NewHolland)

Fuel Type	Diesel
Number of Cylinders	4
Power	110 hp at 2300 rev min^{-1}
Torque	430 Nm 1400 rev min^{-1}
Cylinder Volume	3908 cm^3
Clutching	Dry type, double plate
Transmission	12 forward 12 rear
Brake System	Oil bath and 5 discs
Front Tire Inflation Pressure	1.7 bar
Rear Tire Inflation Pressure	1.6 bar
Weight	3900 kg
Axle Distance	2422 mm
Width of the Frontal Axle	1787-2180 mm
Width of the Rear Axle	1628-2028 mm
Length	4115 mm
Height	2657 mm
Weight on the Frontal Axle	1560 kg
Weight on the Rear Axle	2340 kg
Size of the Frontal Tire	13.6.R28
Size of the Rear Tire	16.9.R38

There are two hydraulic piston-cylinder mechanisms that are connected to braking cranks at front and rear axles of the agricultural trailers. Those mechanisms are simultaneously operated for the brake systems on the two axles by the hydraulic oil supply from the tractor hydraulic fluid pump.

Table 2. Technical specifications of the agricultural trailer

Total Length	5800 mm
Total Width	2100 mm
Total Height	2180 mm
Soil Space	390 mm
Distance of the Case Bottom from the Ground	1180 mm
Trace Width	1550 mm
Case Dimensions without Additions	4220×1920×60 mm
Axle Distance	2500 mm
Radius of the Minimum Trace Circle	3275 mm
Radius of the Minimum Turning Circle	3450 mm
Self-Weight	1950 daN
Empty Weight on the front axle	1000 daN
Empty Weight on the rear axle	950 daN
Useful Load	6000 daN
Lining Length	320 mm
Lining Width	50×6 mm
Lining Thickness	6 mm

Hydraulic mechanic commanded 2/2 direction control valve was used for each brake system on each axle of the agricultural trailer that was used during the experiments, in order to arrange braking options as trailer front axle braking, trailer rear axle braking, trailer double axel braking, and no trailer braking, by splitting the brake systems from each other. By this way, independent braking at the front or rear brakes can be done for a braking in desired time.

In order to determine the braking effectiveness of the agricultural trailed for steady static conditions, a special test bench was prepared. This mentioned test is actually examining the brake equipment of the trailer for resting on slopes. Since regulations impose a limit for road slopes, a maximum 70% of the weight per wheel with a brake equipment acts as a force that creates torque to rotate the wheels. This kind of scale was proposed by [10,11]. The scale is an approximation that enable evaluation of the static brake torque of a brake equipment. The mentioned test bench consists of a moment arm of 1000 mm length, a digital scale that is arranged to show the force, a workshop hoist, and a hydraulic jack. The calculation of static braking moment is done according to equation (1) [10,11].

$$M_d = 0.7m \times R_{et} \tag{1}$$

In equation (1), M_d is the minimum required braking moment or torque for the wheel to initiate turning in (Nm), m is the weight that is distributed to each wheel in (N), and R_{et} is the effective tire radius in (m). Figure 2 shows the test bench for determining static brake torque.

Resolution of the scale that was used for determining the static brake torque is 100 g while percentage systematic error of the scale is rated as 1%. The braking period time during experiments was detected by means of a digital stopwatch, and a speed radar branded as Dickey John DJCMS200 and mounted on the tractor was used during experiments to actual travel speeds for all tested conditions. Resolution of the stopwatch was 10^{-2} s while it's error ratio is ignored in respect of engineering scale of the investigation. Speed indicator has a resolution of 10^{-1} $m \cdot s^{-1}$ and its rated error is 0.5% in the measurement range.

Figure 2. The test bench for measurement of the static brake torque

Correlation between travel speed (velocity), travelled distance and acceleration (or deceleration) can be expressed as in equation (2) and (3).

$$a = \frac{\Delta V}{\Delta t} \tag{2}$$

$$V = \frac{\Delta S}{\Delta t} \tag{3}$$

In equation (2) and (3), a stands for acceleration or deceleration of the travelling object, while ΔV is the difference in travel speed and Δt is the passed time during the evet. In a similar manner, ΔS indicates the distance between the measurement points. Unit homogeneity is essential for all mathematical expressions and SI units are used in the present work.

The work was carried in two phases: In the first phase, static braking effectiveness was theoretically calculated, and in the second phase, static and dynamic braking effectiveness values were determined experimentally. Braking deceleration was tested for unloaded, 4200 kg, 6000 kg, and 7800 kg loaded conditions of the agricultural trailer. Prior to the experiments, 30 $km \cdot h^{-1}$ travel speed for the initiation point of the braking was planned. However, extreme jack-knifing was observed in the preliminary tests and therefore, the travel speed was reduced to 25 km h^{-1} for the initiation of the braking. Totally 16 different braking scenarios were assessed by the combination of four different braking strategy and four different agricultural trailer loads. Variance analyses were also conducted in order to determine the level of effects for dependent parameters of braking type and trailer loads on independent parameters such as braking deceleration, time, and distance.

3. Results

The comparison of calculated static braking moment and experimentally determined static braking moment, in the context of the present work, is introduced in Figure 3. The experimental static braking moment is above the theoretical one, as expected, since the theoretical one marks the minimum required value while the experimental one shows much higher capacities due to safety factor. The measured braking moment is 1920 Nm while the theoretical limit is changing between 309 to 1459 Nm. On the other hand, Demir and Çarman [11] calculated braking moment between 824-1063 Nm for an impact brake type system in agricultural trailers with impact brakes, and 20 to 30 mm impact stroke. Therefore, the calculated values as well as the measured one are deemed as valid and logical. As a conclusion for the static braking test, it is seen that trailer brakes have a static effectiveness greater than required minimum value with a significant safety factor.

For the second phase of the investigation, different braking scenarios by the combination of different braking strategies and loading decisions are compared by graphical presentation and qualitative evaluations. The braking deceleration values change between 2.15 and 4.76 $m \cdot s^{-2}$ for the different combinations. The agricultural tractor without a trailer gave a braking deceleration value of as 5.51 $m \cdot s^{-2}$ by the measurement during the tests. The lowest deceleration values are realized for the no-brake trailer scenario (Figure 4). Also, the loading amount of the agricultural trailer and the reduction in the braking deceleration of the agricultural tractor-trailer couple seem correlated to each other in a directly proportional manner. For the case of rear axle braking of the trailer, the correlation between the trailer loads and the reduction in deceleration values persist. Although the deceleration values of rear axle braking are higher than the no trailer braking scenario, the trend of decrease of the deceleration with the increasing load value is similar. Also, the braking deceleration by braking without the trailer brakes or trailer rear braking was less than the single agricultural tractor braking at a rate of 30 to 50% on stabilized ground. There is a significant improvement in braking deceleration when trailer front braking is adopted comparing to no trailer braking and trailer rear braking scenarios. However, the improvement become less significant after 6 t load value. On the other hand, by the double axel trailer braking, not only the braking deceleration values of the agricultural tractor-trailer couple become closer to the single agricultural tractor braking (without the trailer) but also the improvement is still significant for all load values of the trailer. The variance analysis indicate that both the load of the agricultural trailer and the braking strategies have a significant impact on the braking effectiveness of the couple ($P<0.05$). Experimentally attained results and data are low at a rate of 25 to 50% comparing to the theoretically calculated data of Nastasoiu and Ispas [12]. The cited work is a theoretical one and does not include factors such as slippage, irregularities that may emerge due to the real-world road conditions and experimental uncertainties. Also, load is not considered in the mentioned reference. Koyuncu [13] found average 3.01 $m \cdot s^{-2}$ braking deceleration depending on the increasing load on the tractor tow hook, in the study that the author used a single axle three tones agricultural trailer. Braking deceleration of the agricultural tractor-trailer couple decreases as nominal load amount of the trailer increases as stated in the paper of Örnek and Demir [10] who used a double axel balanced agricultural trailer. This means that the couple needs more time and more distance to stop. The braking deceleration of the agricultural tractor-trailer combination/couple is stated as about 2 $m \cdot s^{-2}$ for difference operational conditions.

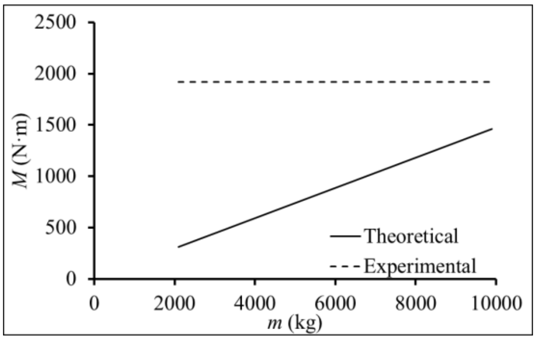

Figure 3. Comparison of theoretical and experimental static brake moment values.

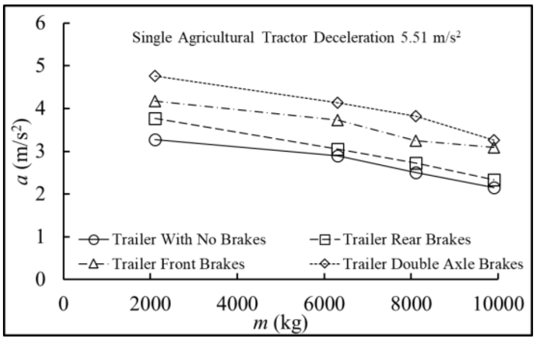

Figure 4. Deceleration values of the combination for different braking strategies.

The time for stopping the tractor-trailer couple changes between 1.46 to 3.23 s for different braking scenarios and loads (Figure 5). In accordance with the deceleration results, best to worst performing braking scenarios are trailer double axel braking, trailer front axle braking, trailer rear axle braking, and no trailer braking, respectively. As expected, carried load on the trailer increases stopping time. The single agricultural tractor can stop in 1.26 s where the couple with no trailer brakes able to stop in 3.23 s, which is not acceptable in terms of work safety, regulations, and standards. About 150% longer stopping time with no trailer brakes becomes lower and close to the single agricultural tractor stopping time as trailer double axel braking strategy is adapted. It is thought that mentioned facts justify the cost of trailer double axel braking.

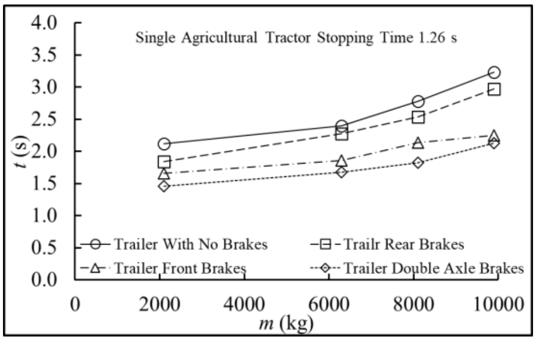

Figure 5. Stopping time of the combination for different braking strategies.

Figure 6 quantifies the stopping distance for all braking strategies and carried loads by the trailer. The stopping distance of the couple changes between 5.1 and 11.22 m for different braking strategies and carried loads. The single agricultural tractor is able to stop at 4.38 m distance. The distance for stopping reduces about 35% by trailer double axel braking comparing with the no trailer braking scenario. Braking scenarios changes the stopping distance at a rate of 30% while the carried load changes stopping distance at a rate of 50%. This also shows the importance of regulations for the carried load.

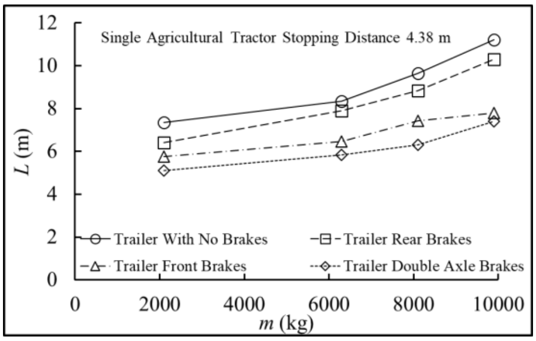

Figure 6. Braking distance of the combination for different braking strategies.

4. Discussion and Conclusion

In this work, the agricultural tractor-trailer couple/combination braking effectiveness is investigated for transportation issue, considering different braking scenarios, and carried loads by the trailer. Different trailer hydraulic braking strategies are introduced and evaluated for the first time.

The main features of the work are; emphasizing braking safety risks associated with agricultural tractor trailer couple during transport of agricultural goods or any other mass with relatively high speeds; utilizing existing technology and exhibiting an example of brake system adaptation to the trailer; and quantifying the proposed brake system performances.

Following essential conclusions can be asserted, considering the standards and regulations:

1. The results justify the cost of trailer double axel hydraulic braking strategy due to the work safety.
2. Carried load on the trailer has more impact on braking effectiveness than the braking strategy and therefore, regulations on the permissible carried loads is stressed out.
3. Trailer double axel hydraulic braking assures deceleration values of agricultural tractor-trailer couple is being compatible with the standards.
4. As an alternative, trailer front axle braking should be preferred over rear axle braking.
5. Presently, the trailer brakes are operated by parking lever manually. However, for conveniency and safety, trailer brakes should be activated from a single center with the tractor brakes.
6. In the context of the work, interviews with related technical agricultural tractor maintenance services reveal that tractor brake systems degrade earlier than expected due to insufficient or no trailer brakes.
7. The role of insufficient braking strategies attributed to the agricultural tractor-trailer couple is uncertain, referring to the readings and interviews on work safety and work accidents, in the context of the present work. Farmers seem not to care importance of trailer brakes due to relatively low travel speeds of the couple (40 km·h^{-1}).

Declaration of Ethical Code

In this study, we undertake that all the rules required to be followed within the scope of the "Higher Education Institutions Scientific Research and Publication Ethics Directive" are complied with, and that none of the actions stated under the heading "Actions Against Scientific Research and Publication Ethics" are not carried out.

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