1. Introduction

Road and bridges are important assets for countries, as they require substantial investment but contribute enormously to the economic development and wealth creation, by providing efficient and safe transport connections between homes and workplaces, between raw materials producers and industrial processing sites, between ports and their hinterland, between warehouses and shops, etc.
The costs for road consist of an upfront investment in the design and construction of the network, followed by regular maintenance and repairs to keep the structures in optimal condition, as well as upgrades to accommodate increasing and changing traffic flows.
Countries around the world have set weight limits for vehicles (and for axles, axle groups, combinations of vehicles, …) using the road network. The main objectives of these limits are to preserve the road infrastructure and to ensure the road safety characteristics of the vehicle. Indeed, damage to the structural properties of road and bridges is mainly caused by the heaviest vehicles – which in practice means trucks.
In this paper, based on (Breemersch, Knight, Fontul, Vieira Gomes, & Jacob, 2022), we summarize the results of an extensive literature review on the technical and economic aspects related to overloaded vehicles, along with the findings of a consultation of stakeholders (and more literature review) on the prevalence and intensity of overloading across the world.

2. Weight limits around the world

2.1. Europe

Heavy vehicle weight limits in Europe are relatively consistent due to the common legislation set by the European Union (OECD-ITF, 2019). Several countries not in the EU have adopted the same rules so as to benefit from access to the EU market.

- With the exception of Italy and France, the weight limit for a non-driven single axle is 10 tonnes. For driven axles, the general rule is 11.5 tonnes, though several exceptions exist (up to 13 tonnes).
- Lorries at 2 axles are generally capped at 18 tonnes. For 3 axle rigid lorries, EU countries are at 26 tonnes.
- Most EU countries have a 36 tonne limit for 4 axle road trains, though some go up to 38 or even 40 tonnes.
- 5 axle articulated vehicles have a general limit of 40 tonnes (44t for intermodal). Larger vehicles up to 8 axles as an EMS (European Modular System) combination are usually limited to 60 tonnes, though countries like Sweden (71 tonnes) and Finland (76 tonnes) have higher limits still, and are conducting trials at even more weight (and length).
- Non-EU countries generally have lower limits than EU countries, though limits for vehicles that are mostly active in international transport have been harmonised with EU limits.
- The Netherlands has a 50 tonne limit for 5 axle articulated vehicles and allows EMS combinations up to 60 tonnes. Gemanry allows EMS but only up to 40 tonnes, while the Czech republic allows 48 tonnes for EMS.

2.2. Americas

Table 1: Weight limits in the Americas

Country	Weight per non-drive axle	Weight per drive axle	Lorry 2 axles	Lorry 3 axles	Road train 4 axles	Road train 5 axles and +	Articulated vehicles 5axles and +
USA (Federal)	9.1	9.1	36.3	36.3	36.3	36.3	36.3
Canada (interprovincial)	7.7	7.7	16.35	24.25	46.5	46.5	62.5
Canada (Quebec)	9	10	17.25	25.25	35.5	51.5	53
Argentina		10.5					49.5/52.5/60/75
Brazil	6	8.2	17	25.5	24		45/57/74
Mexico	6.5/11	12.5	19	27.5	38	54	66.5
MERCOSUR (Brazil, Argentina, Uruguay, Paraguay)	6	10.5	18	25.5	18		45

2.3. Africa

Table 2: Weight limits in Africa

Country	Weight per non-drive axle	Weight per drive axle	Lorry 2 axles	Lorry 3 axles	Road train 4 axles	Articulated vehicles 5axles and +
Malawi	8	8	16	24	18	56
Mozambique	8	8	16	24	18	56
Namibia	8	8	16	24	18	56
South Africa	8	8	16	24	18	56
Tanzania	8	8	12	24	18	56
Zambia	8	8	12	24	18	56
Zimbabwe	8	8	16	24	18	56
Cameroon	13	13				50
UEMOA[1]	6/11.5/12	6/11.5/12	18	26	38	51

[1] UEMOA: Ivory Coast, Benin, Togo, Burkina Faso, Senegal, Mali, Niger, Guinee Bissau

2.4. Asia & Pacific

Table 3: Weight limits in Asia Pacific

Country	Weight per non-drive axle	Weight per drive axle	Lorry 2 axles	Lorry 3 axles	Road train 4 axles	Articulated vehicles 5axles and +
Australia	7	7	15	23	30	130
New Zealand	7.6	7.6				
China	10	10	18	25	36	49
Japan	10	10		20	36	36
Singapore	12	12	19	28	39	46
South Korea						40
Taiwan	9.5	9.5	15	25	35	42
Thailand	11		15	25	37	50.5
Vietnam	10	10	18	24/30	34	48
Indonesia						
Pakistan		12	22.5	33	33	
India	11.5		19	28.5	40	55
Malaysia	12			27		53
Cambodia	11			30		40
Kyrgyzstan	11.5	11.5		32		44
Tajikistan	10	10				40
Uzbekistan	11.5	11.5		32		44
Turkmenistan	10	10				36
Azerbaijan	10	10		32		44
Georgia	11.5	11.5		24		44
Turkey	11.5	11.5		32		44

2.5. Conclusion

2 types of weight limits were considered in the overview above: gross vehicle weights and axle loads.

- Gross vehicle weights differ greatly between countries and continents, from as low as 36 tonnes to as high as 130 tonnes (or more with special permits). Higher weight limits are generally set in countries that aim to maximise the potential of their fleet, though motives for this may vary: in developed countries, the aim is to improve productivity and reduce costs, while in developing countries, it may be more about meeting demand with existing fleet, as new vehicles may not be purchased easily.
- Maximum axle loads are directly related to infrastructure damage and therefore relate closely to the budget available for road infrastructure investment. They vary from as low as 6 tonnes up to 13 tonnes.

3. Overweight vehicles around the world

A survey was conducted among PIARC members to collect information on the prevalence and intensity of overloading around the world. Most European and North American countries and regions report high compliance rates, with violations typically limited to 10% of the fleet, or even less. LMIC report much lower compliance levels, with the share of overweight vehicles ranging from 15 to 40% in Latin America, up to 80% and more in South-East Asian countries like Thailand and Indonesia.

Table 4: Share and intensity of overloads in different countries

Country	Share of overloaded vehicles
Estonia	11%, usually limited to 10t
Portugal	37.5% (data from 1999)
Russia	40%
Hungary	1% overloaded, 0.4% by more than 5 tonnes
France	1-8% overloaded, 5% by more than 10%
Ukraine	21.5% of vehicles, but for tridem axles up to 60% are overloaded
Brasil	77% of vehicles, 10% of axles, mostly single axles
USA	0.5% overloaded (60% GVW, 20% axle, rest bridge formula)
Argentina	30% of vehicles overloaded by at least 20%
Mexico	14.3% overloaded, decreasing
South Korea	0.07%
Taiwan	14.2%, axle overloads mostly on tandem
Pakistan	33-48%
Thailand	33%
Malaysia	24-29%, but only 8% on motorways
Indonesia	30-98% based on axle load
South Africa	15-20%, lower on primary roads
Cameroon	In 1996 85%, 1/3 by 20-40%, 1/3 by over 40% In 2014 reduced to 5.9%
UEMOA	Senegal 18%, Togo 6%, Ivory Coast 17%, decreased by 20% since 2013
Austria	40 000 non-compliance with loading limits per year

The most cited reason for overloading is cost saving, facilitated by a lack of enforcement. Other causes (negligence, customer pressure, …) were generally not considered to be very relevant.

4. Effects on pavements

4.1 General relation between weight and pavement damage

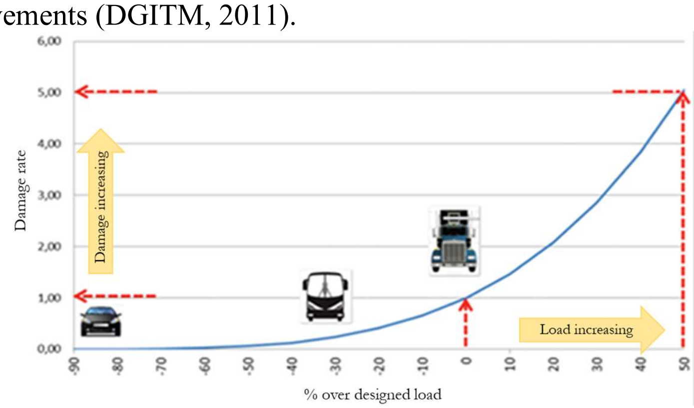
Several studies have been conducted in Europe and the USA since the 1950´s, with the AASHTO report (National Academy of Sciences - National Research Council, 1962) considered as one of the earliest and still most important references in the field. The conclusion reached was that the pavement damage increases exponentially with the load with a power between 4 and 4.5 (Figure 1**Error! Reference source not found.**) – this is also known as the "fourth power law", which implies for example that if 10% of overloading induces 46% more damage, 50% of overloading results in 5 times more damage.

This ESAL (equivalent standard axle load) methodology allows the wear factor to be calculated individually for each axle. The aggressiveness of an axle may be assessed through the "load equivalent factor (LEF)" which is relative: it is the ratio between the damage created by the load and the damage created by the equivalent reference axles.

$$LEF = \frac{N_{ref}}{N_x} = \left(\frac{P_x}{P_{ref}}\right)^n$$

where:
LEF – Load equivalent factor
P_x *– the actual axle load*
P_{ref} *– the equivalent reference standard axle load (generally of 80 kN)*
N_x*– number of* P_x *load applications*
N_{ref}*– number of standard axle load applications*
n – damage factor, power law (generally 4, "fourth power" for asphalt pavements).

However, the coefficient of the power law is highly dependent on the type of pavement tested (gravel, bituminous and concrete) and the distress criteria (fatigue, permanent deformation). Some values are presented herein and vary from 2.4 to 6.6 based on AASHTO, Rolt (1981) cited by (Musbah, 2017), 5 to 6 for flexible pavements in France, 8 to 10 in the case of flexible pavements with weak subgrade (Saarenketo, 2020) and 12 in the case of semi-rigid pavements (DGITM, 2011).



5.

Figure 1 ***Damage Caused by Overloaded Vehicles adapted from (Fioravanti, 2015)***

The life span of the pavement decreases with the overloading as shown in Figure 2.

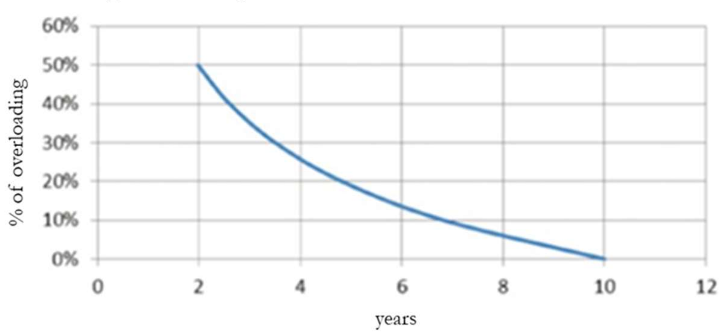


Figure 2 ***Life span of a pavement vs % of overloading adapted from (Fioravanti, 2015)***

4.2 Other aspects

The effect of overloading on the pavement residual life depends on different factors such as type of traffic, load distribution, vehicle wheel and suspension and also on type of pavement

and its condition, thickness, unevenness, cracking etc. (NCHRP , 1993); (Saarenketo, 2020), ROADEX project research results and e-learning packages; (COST 334, 2001); DIVINE project (1998); (OECD ITF, 2011).
Besides overloading, environmental factors such as temperature and water presence, mainly in the pavement structure, can significantly affect pavement deterioration.

Table 5: influence of different factors on pavement service life (H= high, M= medium, L= low)

	Influence on pavement service life*			
	Type of pavement			
	Unpaved	***Flexible***	***Semi-rigid***	***Rigid***
Vehicles configuration				
Axle load	H	H	H	H
Group of axles	M	M	L	L
Wheels and tyres	M	M	L	L
Load distribution	H	H	M	M
Suspension	M	M	L	L
Pavement characteristics				
Type of pavement	H	H	Only above over design load	Only above over design load
Unevenness	M	M	L	L
Environmental factors				
Temperature	L	H	L	L
Drainage and water presence	H	H	L	L

The main concern is that a combination of these factors (namely thin or unpaved roads, asphalt concrete stiffness not adequately designed for service temperature, poor road maintenance and overloading, due to lack of enforcement) can represent critical scenarios, and most frequently occur together in low- and middle-income countries (LMIC). This combination can drastically reduce the pavement lifespan to (much) less than half of the designed one.
The most affected by overloading are indeed unpaved roads, mostly present in LMIC, because overloading will result in secondary rutting and corrugation, increasing the dynamic impact of the load and accelerating the pavement deterioration.
Flexible pavements, with thin asphalt wearing courses and weak subgrade will also suffer exponentially with increasing overload, leading to accelerated fatigue cracking and secondary rutting. It is to be highlighted that total failure (breakage) can be reached in only few days in flexible pavements (e.g. secondary roads), if heavy traffic passes, with loads that exceed the ones that were designed for.
For fatigue damage, rigid and semi-rigid pavements are more sensitive to the dynamic load increase because of the higher power in the fatigue law (between 10 and 12), and, consequently suffer increased aggressiveness from overloads.

4.3 Mitigation

Overloaded axles is the main mechanism that results in a disproportionate level of road damage. The consequences of this can be specifically mitigated in different ways: by better vehicle loading practices, reducing the frequency and severity of overloading through enforcement, the use of 'road friendly' suspensions and by proper road design, for heavy traffic and local temperature conditions. The leading principle in road infrastructure design should be to account for the real world situation, and not an ideal situation with perfect

compliance. This of course requires a good understanding of real vehicle loads, and thus proper monitoring practices.
Additionally, there are good practices that extend the pavement service life, such as good distribution of load among the vehicle axles, use of twin tyres, and one of the most critical: proper road maintenance in order to minimise road unevenness, corrugation and to prevent the water stagnation on the surface and water infiltration into the pavement structure.

5. Bridges

5.1 Impacts

Bridges are complex structures (Structurae, n.d.), and the response of the structure and its elements could be different when there is an overload of individual axles, groups of axles, full vehicles or groups of vehicles, depending on the span length and spatial sensitivity to the loading cases. The effects of overloads also depend on the materials used, on the parts of the bridges (sub-structures), on the bridge design, and on the combination of traffic loads with other actions.

Moderate overloads are the most frequent and should be accounted for in the design and maintenance strategies of bridges. Extreme overloads (50% and more) should be exceptional and require a different approach, based on detection and enforcement, since these can cause severe damage and even bridge collapse, even on well-designed and healthy bridges.
Fatigue is also a concern, mainly for steel and composite bridges. Heavy but legally loaded heavy vehicles contribute to crack propagation in steel structures, and may reduce the bridge lifetime.

It is neither obvious nor as simple as with pavements, to understand and assess the load effects and potential damage to bridges due to overloading. The assessment of load effects, strains and stresses, and of their extreme values, requires information on a myriad of factors, including traffic loads (can be collected through e.g. WIM data), load configuration (spatial distribution on the bridge deck), influence lines or surfaces (transfer function relating loads and load effects), and could best be calculated using specific software.

5.2 Mitigation

There is a global trend to increase the maximum permitted vehicle mass of heavy duty vehicles (for freight transport efficiency and CO_2 saving), though traffic volumes of heavy vehicles are still expected to increase. This leads to increasing pressure on existing bridges, and could bring a reduction of their lifetime and greater safety risks. Therefore, accurately monitoring the growing traffic loads (both in weight and in number) on bridges will be crucial, along with a closer follow-up of the condition of bridges. Enforcement of weight restrictions near the most sensitive bridges, is above all, essential to protect bridge assets and guarantee safety.

6. Road safety

6.1 General considerations

Indirectly, overloading of HGVs will reduce the safety of all road users if it results in degradation of the road surface that is not compensated by more frequent maintenance. Directly, it influences the safety performance of the overloaded vehicles in a wide variety of, sometimes complex, ways. Rollover stability and the severity of collisions with other heavy vehicles or rigid objects will always be adversely affected. Braking, steering, handling, load security, and the risk of structural failure may all be adversely affected, depending on exact vehicle specifications, configurations and the magnitude and distribution of the overload. Importantly, not all drivers of overloaded vehicles will experience all these effects in normal driving, which risks driver complacency.

6.2 Effects of overloading on collision frequency and severity

There is a general consensus that the number and severity of crashes in the presence of overload are related to both physical effects and influencing factors and that this relationship is variable from country to country (ERSO, 2016).
This issue has been analysed by several authors who have identified an increase in accident rates with heavier vehicles. However, it is important that this is put into context. Larger heavy vehicles often have a much higher rate of serious accidents per vehicle.km compared to a smaller vehicle. However, when this indicator is normalised per tonne km, the order may be reversed because it takes many smaller vehicles to carry the same mass of load as a larger vehicle. Similarly, the context will change very significantly in different countries with different economies, different urban and interurban freight flows, different infrastructure and different vehicle quality standards.
The percentage of heavy vehicle occupant fatalities in 2016 relative to all road deaths worldwide, observed in (World Health Organisation, 2018), was assessed in (Breemersch, Knight, Fontul, Vieira Gomes, & Jacob, 2022).

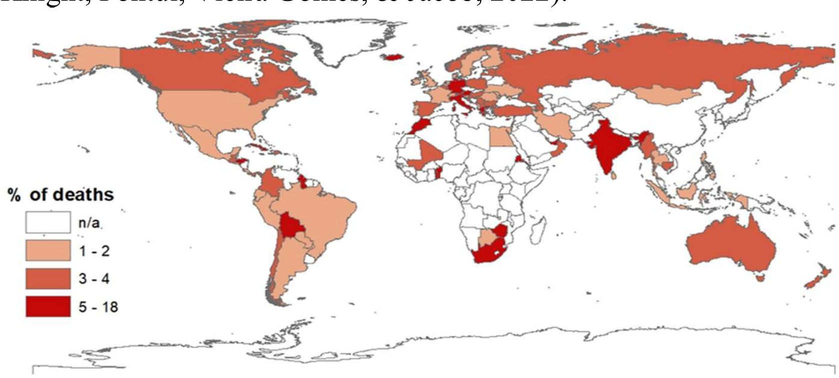


Figure 3: Percentage of drivers and passengers of truck deaths

Although heavy vehicle occupant fatalities cover only a small proportion of the total fatalities resulting from collisions involving these types of vehicles, it was possible to assess the expected variation across the world. Around 23% of the countries have a fatality rate of less than 1%, indicating that these types of road users do not represent a particular risk in these countries. The intermediate risk groups of 1-2% of deaths and 2-4% of deaths are represented in 19 and 34% of the countries, respectively. The critical group with the highest percentages of deaths covers about 24% of the countries, and as such deserves special attention in order to boost its reduction. This group includes Zimbabwe, with 18% of the deaths, Togo with 11%, Malta with 9% and the United Arab Emirates with 8%.

Although most countries do not collect detailed statistics, it was possible to analyse the statistics on accidents involving HGVs for the territories of Great Britain and Portugal and for the particular case of Scotland. In the Portuguese data, overloading is recorded where one of the vehicles involved in the accident was overloaded, regardless of whether this condition had an influence on the accident. In Great Britain and Scotland, overloading is only recorded if the police officer attending the scene considers that it may have contributed to the cause of the crash. The results of the analysis are presented below:

Table 6: survey response on road safety

Country	**Proportion of all where HGV involved where overloading was present (Portugal) or contributory to cause (GB/Scotland)**	
	Collisions	Fatalities
Portugal	0.3%	1.2%
GB	1.0%	0.3%
Scotland	1.3%	0.0%

It can be concluded that as a proportion of the total HGV safety problem in each country, the contribution of overloading is relatively low. However, each of these countries would be classified as high performance and each would report a high standard of vehicles, periodic technical inspections and weight enforcement. Even despite the low proportion and high standards, it is important to note that the safety effect of overloading is not zero. In countries with lower vehicle quality standards or less effective enforcement, the contribution could be substantially worse.

7. Economic impacts

The cost-benefit comparison for overloading is skewed, as can be suspected given the 4th power relationship between the amount of overload and the damage: 5% overload means 22% extra damage; 20% overload means 107% extra damage – doubling the maintenance needs and the required budgets for infrastructure managers (who are funded by either a government budget, income from tolls/access fees, or both) to keep roads in proper condition.

From the perspective of transport operators, the price setting for road freight transport services is generally non-linear, but a higher cargo weight will almost always mean a higher price. However, the increase in transport price is not necessarily proportional to the increase in the costs for the operator, as only variable costs are impacted (to some degree). This would entail that taking more cargo on a trip would lead to higher profits for operators, creating an incentive to maximise the cargo per trip, up to and in some cases over the legal limits, i.e. overloading; unless there is a strong enough incentive not to do so (a function of the level of fines, the chance of detection and the possibility to avoid a fine e.g. by bribing). A proper fine system with progressively higher penalties as the overload increases can act as an important deterrent for overloading, provided that there is enough enforcement. (Euritt, 1987) describes the logic behind a fine structure in Texas that effectively discourages overloading by using a stepwise increase in the additional fine per excess weight carried.

Overloading causes a quasi-linear improvement in the profits of transport operators, but the costs to the infrastructure manager (and thus society as a whole) increase to a much higher degree.
However, it should be noted that, from a broader perspective, there can be cases where overloading is beneficial to society as a whole, as illustrated in a case study for Brazil (Ghisolfi, et al., 2019), which compared a strict, moderate and tolerant policy regarding heavy vehicle weight enforcement. Under specific circumstances, the lower operational costs, combined with lower environmental costs from carrying additional cargo, were shown to outweigh the costs to infrastructure and safety.

8. Prevention and mitigation

There is a 4 step approach to prevent and mitigate the effects of overloading.

1. The first is drafting of proper legislation that sets limits in function of the budget available for road network maintenance, and foresees proper enforcement methods within budget limits as well.
2. Governments and road administrations should pay specific attention to the education of drivers as part of the efforts to prevent overloading. Providing information on proper loading procedures can help avoid axle overloads, which are, more often than gross vehicle weight overloads, inadvertent. On the other hand, prevention should also highlight the risk of overloading, not just to road infrastructure managers, but to other road users and to drivers themselves.
3. Solving the issue of overweight vehicles cannot be done without proper enforcement. In HIC, high-speed Weigh-in-motion (WIM) is commonly used for detection of overloaded vehicles on the primary road network, although infractions are mostly confirmed by using static weighing scales (fixed or mobile). Some countries also use WIM for direct enforcement. In LMIC, the use of WIM is less common, and limited to specific parts of the road network. The largest overloads often occur on secondary or local roads, e.g. in the vicinity of mining or forestry activity. Even when in-road detection systems are installed, drivers often bypass these locations.
4. Penalties for overweight vehicles are typically either financial (fines), operational (immobilisation of the vehicle) or institutional (loss of reputation of the company). Fines should be sufficiently high to act as an effective deterrent (combined with a high enough chance of getting caught), and are ideally progressive (fines per weight unit of overload increase as the overload increases), to be in line with the damage they cause to the road infrastructure. When fines are not high enough, immobilisation of the cargo can provide a stronger disincentive, as this not only creates a financial loss for the operator, but also creates operational issues for the operators towards their customers, who do not appreciate late deliveries. A more formal "loss of reputation" penalty can also be considered by legislators, though this can also have unwanted economic effects like unemployment if the company goes bankrupt.

As for the best practices to fight overloading, representatives from HIC often refer to the further development of WIM for direct enforcement as the most effective measure, though the importance of education should not be neglected. In LMIC, more effective enforcement of existing weight limits, presumably by the deployment of more staff and an increase of fines, is the most realistic option, as budgets do not allow for a more extensive deployment of WIM equipment.

9. Conclusions

The study found that overloading of vehicles remains relatively frequent in most parts of the world, the amount by which vehicles are typically overloaded is quite variable, in some cases very high, and the results are very damaging and expensive. The damage caused by overloaded vehicles to pavements is particularly disproportionate because it is related to a higher power of the axle weight. While the factor of safety inherent in many bridge designs means that the damage due to overloaded vehicles is less frequently observed, the consequences when it does occur can be extreme in terms of bridge collapse or even just the considerable congestion and delay that occurs if a bridge is closed for an extended period to allow remedial works to fix problems caused by overloading. The effect on safety can be kept relatively low where the magnitudes of overload remain relatively low and the quality of vehicles and infrastructure are good, but is expected to be much larger where that is not the case.

Solutions for the problem of overloading need to focus on 4 areas: changing the economics of road freight transport, strong enforcement (using WIM if possible), high quality infrastructure and high quality vehicles.

A lack of data on the degree and consequences of overloading likely contributes to the limited sense of urgency to tackle the issue, particularly in low and middle income countries, while these are especially sensitive due to the composition of their road network, mostly unpaved and thin flexible pavement, more extreme climatological conditions and lower quality vehicles. Building a better knowledge base can help the case for policy intervention.

10. Acknowledgement

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