

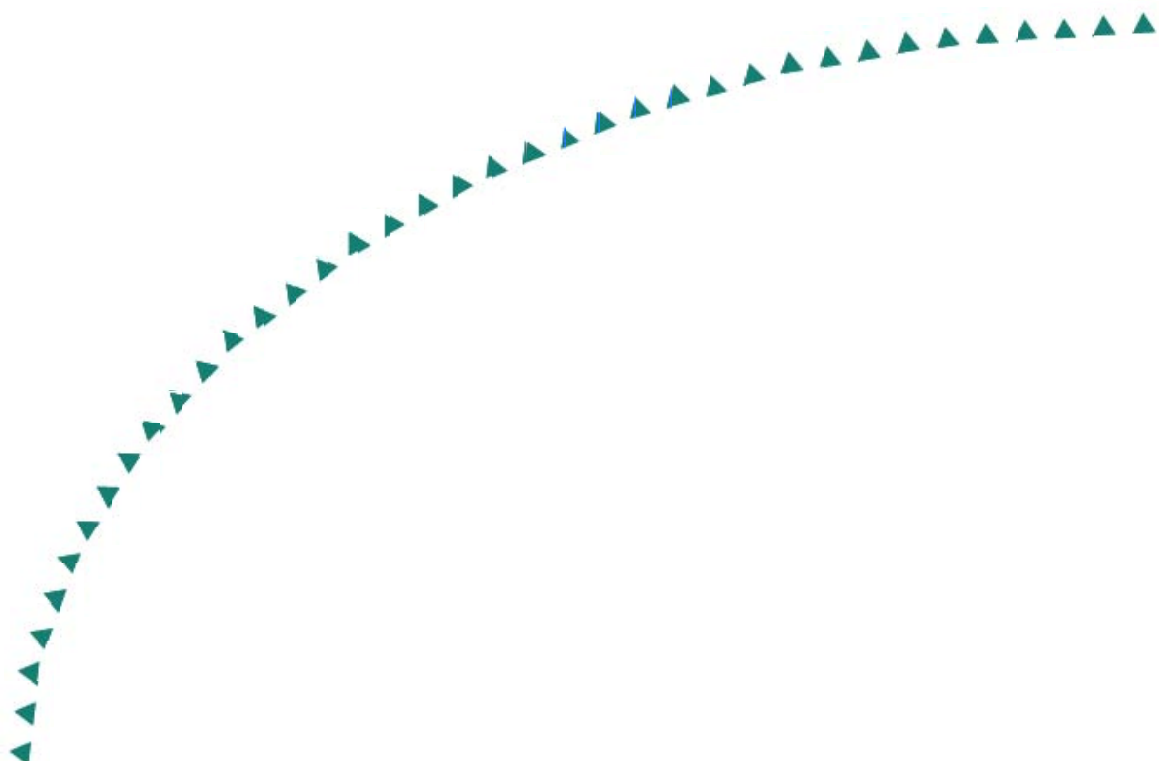
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Synthesis Report

Impacts of Overweight
Implements of Husbandry on
Minnesota Roads and Bridges



Synthesis



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Impacts of Overweight Implements of Husbandry on Minnesota Roads and Bridges

Synthesis Report

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Introduction

Farming is a large and important industry in the United States. Over the past few decades, the national industry has seen the number of farms decrease with a simultaneous increase in the average farm size. This is a common trend across the Midwest. With larger farms and continuously improving farming techniques, the need to increase production and efficiency has affected equipment carrying capacity and completely changed the tools being used. Most notably, larger and heavier agriculture equipment is being operated both off and on public highways and local roads. During select seasons, it is common to have single-axle loads on secondary roads and bridges that exceed normal load limits (typical examples are grain carts and manure wagons). Even though these load levels occur only during a short period of time during the year (fall for grain carts and spring for manure wagons), there is concern that they can do significant damage to pavements and bridges.

Minnesota Law (MS 169.801) exempts Implements of Husbandry from any and all road and bridge postings. The Law further exempts their operators from any and all criminal and civil liabilities for damages resulting from a passing implement. With the changing of farm practices, implements have continually grown in size and now have axle and gross weights that can significantly exceed the weights of the largest design and legal trucks. As a result of excessive axle loads and dimensions, road and bridge damage is occurring, and there is concern that damage could likely be magnified in the future.

Currently, Minnesota legal truck weights are limited by maximum axle weights, gross vehicle weights, and a maximum tire load, which cannot exceed 500 lbs per inch of tire width. However, implements of husbandry are only limited to the 500 lbs per inch of tire width with no axle or gross vehicle weight restrictions. Practically, this means that these implements can carry the same load as a three- to six-axle truck on only one or two axles (Rholl, 2004). It is worth noting that a load per unit of tire width is not a common metric used by engineers either during design or during evaluation of roadways or bridges and, as such, does not adequately predict the potential for damage. Growing concerns about the impact of heavy husbandry implements on pavements has resulted in research endeavors in Minnesota, South Dakota, and Iowa, where improved farming activity is occurring.

The objective of the work presented herein was to perform a synthesis study related to the impacts of heavy agriculture vehicles on Minnesota pavements and bridges and to identify those impacts. The scope, methods and results of the study are presented below.

Study Scope and Methods

To complete the synthesis, the research team thoroughly reviewed all of the documents provided by the Minnesota Department of Transportation (Mn/DOT) Research Services Section. Initially, the documents were reviewed with two primary goals. The first goal was to complete an impartial, scientific review of the procedures followed and assumptions made by the respective authors. The second goal was to collect quantifiable information for specific performance-based metrics relating implement weight and pavement/bridge damage/deterioration. As will be discussed later in greater detail, the synthesized literature revealed that a significant body of knowledge exists that relates implement weight to measured stresses and other pavement performance measures. These types of measured data are useful, meaningful, and scientifically applicable indicators as they represent actual responses under actual conditions. Unfortunately,

the same type/level of information did not exist for relating implement weight to bridge damage/deterioration. As a result, the research team made comparisons based on traditional design principles. Fortunately using design-based metrics allows for quantification of behaviors following procedures and measures that have been established to ensure the level of safety and/or performance required by the traveling public for transportation infrastructure. As such, using a design-based approach is, as with measured data, a viable approach.

Influence of Implements of Husbandry Weight on Pavements

The synthesis of the subject documents showed that there is a significant body of quantitative information validating the detrimental effects of heavy agricultural loads on local roads. Generally, implements of husbandry can be characterized as being “heavy”, having “large” transverse tire spacing(s), and being “slow” moving. All three of these characteristics have considerable adverse effects on the performance of roadway pavements.

County engineers widely believe that husbandry implements have a significant contribution to the degradation of roads (Oman 2001). Degradation of pavements has been specifically linked by numerous researchers to three common attributes of implements of husbandry: exceeding the 20,000 lb single-axle weight limit; having wide transverse tire spacing(s), which places heavy loads on pavement edges which can become critically stressed (this phenomenon can decrease the design life of rigid pavements by up to twenty times); and moving slowly, which increases the load duration, exacerbating rutting (permanent deformations) in flexible pavements (Oman 2001). Commonly identified pavement distress associated with overweight implements of husbandry can be characterized as fatigue cracking (various types) and rutting (permanent deformations). With respect to rigid pavements, damage manifests itself as transverse and/or longitudinal cracking, corner breaking, and cracking on the wheel paths. Flexible pavements and granular/unbound roads are typically most susceptible to rutting. In all cases, cracking and rutting increases pavement roughness which leads to poor pavement performance and accelerates the reduction in pavement life. Repeated heavy agricultural loads on rigid pavements have also been found to deteriorate pavement joint performance and cause faulting (elevation difference between the adjacent slabs), which also increases pavement roughness.

It is typically believed that wider balloon tires used on heavy agricultural implements cause less compaction of soil in agricultural fields. This is generally true because the balloon tires have a larger contact surface with the soil and therefore, induce lower stresses in the soil supporting the wheel load. The contention that the balloon tires create less damage than more typical tires on pavement is also generally valid except for the fact that balloon tires typically load the pavement closer to the edge than normal tires. The significant difference in the two conditions is that the supporting soil in agricultural fields is a continuous supporting system whereas, near the edge of the pavement a discontinuity in support is created. The increased stresses near the edge accelerate the deterioration in that area. This process continues by deteriorating the pavement from the edge inward once the original pavement edge is lost. Figure 1 shows a typical example of this type of deterioration.

A study completed by Iowa State University (Fanous 1999) that included both an analytical investigation and the collection of experimental field data showed that a single-axle, single-tire grain cart or liquid manure tank (honey wagons) with an axle load of 24,000 lbs has the same effect on an 8 in. thick rigid pavement as that caused by a 20,000 lb, single-axle, dual-tire semi-trailer. The comparison was based on the amount of bending stresses caused by each vehicle.

Tests on flexible pavements indicated that springtime stresses are much higher than stresses induced in the fall and summer due to thawing of the subgrade soils in the spring. The final report from that study (Fanous 2000) also indicated that tracked vehicles induced lower stress values in both rigid and flexible pavements. This reduced impact was attributed to the larger track-pavement contact area.



a. Overall pavement damage resulting from edge loading



b. Close-up view of pavement damage resulting from edge loading.

Figure 1. Photographs of pavement damage.

A study conducted in South Dakota (Sebaaly 2002), aiming to document the impact of various agricultural equipment on pavements, examined the impact of heavy loadings as compared to the 18,000 lb single-axle truck by instrumenting and monitoring both thick and thin pavement sections. The study collected data from pressure cells, surface deflection gages, and strain sensors. The specific vehicles investigated in this work were the Terragator 8013 (a single-tire on the steering axle and dual-tire on the drive axle), the Terragator 8144 (two tires on both the steering and drive axles), a grain cart (a single two-tire axle pulled by a tractor), and a tracked tractor (tracks on both the steering and the drive axle). Pavements are designed to maintain a specified serviceability and performance level under an estimated number of load repetitions over the design life. Different types of traffic are converted, based on the relative amount of damage/deterioration induced, to a reference single-axle load (18,000 lb)—this is commonly referred to as the Equivalent Single Axle Loading (ESAL). Load Equivalency Factors (LEF) are used to calculate the relative damage caused by different axle configurations based on measured or predicted strain or deformation metrics. In the study by Sebaaly (2002), the LEFs for fatigue cracking were calculated as the ratio of the tensile strain for a specific implement to the tensile strain from the 18,000 lb single-axle truck raised to the 5th power. Similarly, LEFs for rutting damage were based on the number of passes required to induce 0.5 in. of permanent deformation. Using this procedure, in combination with field measured strains and deformations where possible, it was found that, when empty, the tracked tractor and the Terragators were equally or less damaging than the 18,000 lb single-axle truck. However, the husbandry vehicles were found to be more damaging when they were loaded. In the same study, a theoretical model was used to compare the long-term effect of a variety of husbandry vehicles with the typical 18,000 lb single-axle truck. On a flexible pavement with 3 to 7 in. of hot mix asphalt, one pass of the loaded Terragator or one pass of the 60% overloaded grain cart was found to be equivalent to one to twenty trips of the 18,000 lb single-axle truck in terms of the amount of pavement life consumed by each pass. The results were even more pronounced on flexible pavements with thin asphalt layers (1.5 in. or less) over a 6 to 12 in. thick coarse aggregate base. Sebaaly (2002) reported that one trip of an empty Terragator was equivalent to 51-150 trips of the 18,000 lb single-axle truck. This means that if a pavement section is designed for 20 years of service with certain ride quality (serviceability), at the end of the design life, one trip of an empty Terragator consumes the planned design life 51-150 times faster than a standard 18,000 lb single-axle truck. Similarly, one trip of a loaded Terragator was 230-605 times, a legally loaded grain cart was 77-240 times, and an overloaded grain cart was 264-799 more damaging than the 18,000 lb single-axle truck.

Influence of Implements of Husbandry Weight on Bridges

The documents reviewed as part of this synthesis contained little quantifiable information relating the impacts of implements of husbandry on the structural performance of bridges. In fact, only two of the documents contained any relevant information. Although insightful, the information given in these two documents did not provide quantitative information that specifically related the influence of the weight of implements to bridge damage/deterioration. What the two documents did provide was a useful summary of the types of bridge failures that have been observed—in the laboratory in one case and in the field in the other—under “large” loads. The following two paragraphs briefly synthesize the applicable portions of the two pieces of literature.

In the work by Wood and Wipf (1999), the authors describe the procedures and results from testing four timber bridges in the Iowa State University Structural Engineering Laboratory. The four bridges were constructed from nominal 4 in. by 12 in. timber stringers removed from an existing bridge. Other bridge components, including nominal 3 in. by 12 in. deck planks, sill plates, and blocking, were fabricated from new timber. Loading of the 16 ft span bridges was applied at midspan through a 30 in. by 20 in. footprint (simulating a tire from a grain cart). Based on all four test results, which are briefly described in Table 1, the authors indicate that "...there appears to be good load sharing between the stringers" and "...bridge failures could all be characterized as sudden and were due to flexural failure of the bridge stringers."

Table 1. Summary of laboratory test results from Wood and Wipf (1999)

Bridge	Number of Stringers	Failure Load (lb)	Failure Mode
1	5	42,200	Bending – Sudden failure with load redistribution
2	5	40,100 ^e	Bending – Horizontal cracking of single member
3	3	27,200	Bending – Sudden failure initiated at a knot
4	3	36,300	Bending – Major flexural and horizontal cracking

^eestimated

An article by Rholl (2004), appearing in the September 2004 issue of Minnesota Counties, summarized several aspects of maintaining Minnesota's secondary road system. Although not specifically about relating bridge damage/deterioration and the passage of implements of husbandry, the author recounts one incident in which he "...visited a bridge site where a loaded implement had punched through the deck of the bridge." Further investigation by Rholl revealed that the implement was, in fact, legal under Minnesota's Implements of Husbandry Law. Although not addressed in detail in the article, Rholl indicated that the implement user was not liable for the damage and indicated that the "...user felt it was the County's fault for not building strong enough bridges."

Neither of the above describes, in sufficient detail, specific metrics that can be used to relate implements of husbandry to damage to families or the entire population of bridges. They do, however, illustrate two observed failure modes: bending and punching. Building on this information, two procedures were developed to relate two common bridge design conditions (bending and punching shear) to those that could be experienced under real-world implements of husbandry. The following paragraphs describe this in greater detail.

To investigate the influence of various types of implements of husbandry, the research team, working with the project oversight committee, first collected information on typical implements currently being used. To limit the scope, only two specific types of implements were investigated: grain carts and manure tanks. Data (e.g., gross weight, axle spacing, number of tires per axle, tire pressure, and loaded tongue weight) on implements from various manufacturers were collected. In addition, various tow vehicles were also identified and checked for their capability to tow the identified implements. In all, four grain carts and six manure haulers were identified. Herein, these will be referred to in generic terms, related to the number of axles, so as to not identify the specific implements. Additionally, to minimize variables between the various implements, the analyses described herein were completed assuming that a single four-wheel-drive tractor pulled each of the implements.

The bridge failure mode observed by Wood and Wipf (1999) was consistently bending in nature. Bending failures, like the ones they observed, are caused by failure of the primary members

under flexural loads. In design, flexural capacity is one of the primary design considerations. Thus, the maximum bending forces induced from the standard design truck were computed for single-span bridges with span length ranging from 20 ft to 140 ft. Similarly, the maximum bending forces from the identified implements of husbandry were also computed. Table 2 summarizes the results of these analyses where the ratio of the implement bending forces to the HS20 design vehicle (representative of a loaded semi-tractor trailer) bending force is shown as a percentage. It should be pointed out that for this analysis, dynamic effects were ignored, lateral load distribution characteristics for the design truck and the implements were assumed to be the same, and no allowance for multiple lane effects was made for either type of loading. Because a significant number of Minnesota’s bridges were designed using the older H20 design vehicle (a smaller box-style truck), Table 3 summarizes the ratio of the implement bending force to the H20 design vehicle. Similarly, Table 4 summarizes similar comparisons made for the vehicle commonly referred to as the “NAFTA truck” that is similar to 98,000 lb timber hauler’s truck recently permitted by law. As can be seen from these data, the implements investigated typically had higher resulting bending forces than the design vehicles and the “NAFTA truck”. This would indicate that these implements are imposing forces greater than those considered in design and would be indicative of an increased likelihood of damage/failure, like the examples shown in Figure 2, being induced.

Table 2. Ratio of implement bending moment to design vehicle (HS20) bending moment

Span, ft	Grain Cart Implement				Manure Tank Implement					
	Single Axle #1	Single Axle #2	Tandem Axle	Tridem Axle	Tandem Axle #1	Tandem Axle #2	Tandem Axle #3	Tandem Axle #4	Tridem Axle #1	Tridem Axle #2
20	215%	229%	191%	183%	136%	93%	168%	144%	152%	155%
40	159%	163%	163%	180%	109%	74%	139%	123%	137%	144%
60	153%	145%	154%	171%	100%	73%	128%	122%	125%	141%
80	156%	147%	160%	177%	105%	80%	132%	126%	128%	147%
100	158%	149%	163%	182%	109%	85%	136%	129%	134%	151%
120	159%	151%	166%	185%	112%	88%	139%	130%	138%	153%
140	160%	152%	167%	187%	115%	90%	141%	131%	140%	154%

Table 3. Ratio of implement bending moment to design vehicle (H20) bending moment

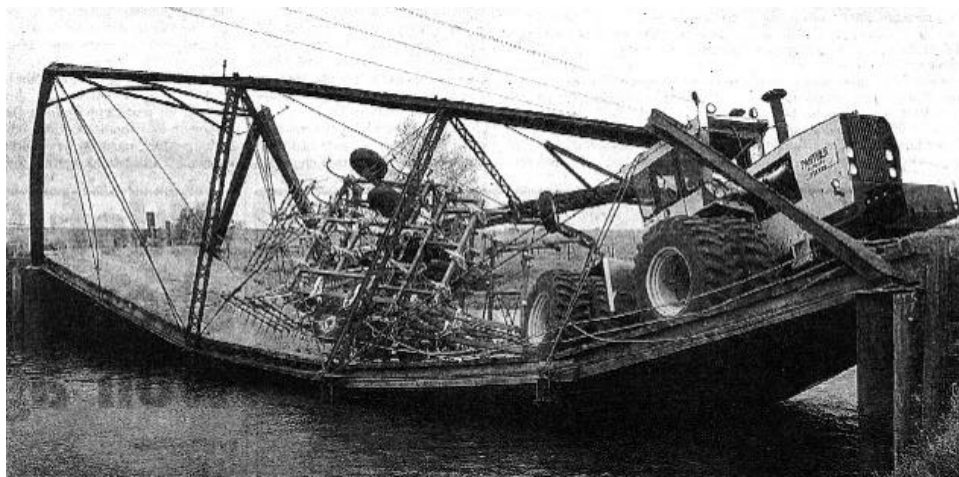
Span, ft	Grain Cart Implement				Manure Tank Implement					
	Single Axle #1	Single Axle #2	Tandem Axle	Tridem Axle	Tandem Axle #1	Tandem Axle #2	Tandem Axle #3	Tandem Axle #4	Tridem Axle #1	Tridem Axle #2
20	215%	229%	191%	183%	136%	93%	168%	144%	152%	155%
40	207%	212%	212%	234%	141%	96%	181%	161%	178%	187%
60	226%	214%	228%	254%	147%	107%	190%	180%	184%	209%
80	244%	230%	249%	276%	164%	126%	207%	197%	200%	230%
100	254%	241%	263%	293%	176%	137%	220%	208%	216%	243%
120	262%	248%	272%	304%	185%	145%	229%	215%	227%	251%
140	267%	254%	279%	312%	191%	150%	235%	219%	234%	257%

Table 4. Ratio of implement bending moment to NAFTA truck bending moment

Span, ft	Grain Cart Implement				Manure Tank Implement					
	Single Axle #1	Single Axle #2	Tandem Axle	Tridem Axle	Tandem Axle #1	Tandem Axle #2	Tandem Axle #3	Tandem Axle #4	Tridem Axle #1	Tridem Axle #2
20	192%	206%	171%	164%	122%	83%	150%	129%	137%	139%
40	165%	169%	169%	186%	113%	76%	145%	128%	142%	149%
60	179%	170%	181%	201%	117%	85%	150%	142%	146%	165%
80	170%	160%	174%	193%	114%	88%	144%	138%	140%	160%
100	156%	148%	161%	180%	108%	84%	135%	127%	132%	149%
120	148%	141%	154%	173%	105%	82%	130%	122%	129%	143%
140	144%	137%	150%	168%	103%	81%	127%	118%	126%	138%



a. Bridge Number 1



b. Bridge Number 2

Figure 2. Photographs of examples of bridges that have collapsed under farm implements.

In the article by Rholl (2004), a failure mode that could be classified as a punching failure was observed (see above). To investigate the types of punching shear stresses that implements of husbandry and design vehicles induce in bridge decks, a metric was developed. This metric assumes that the entire load from an individual vehicle tire is resisted by forces distributed across a surface through the deck that has a perimeter equal to the size of the tire patch. Using this assumption, one can calculate the load per unit perimeter for each implement and the design vehicle. The results of these analyses are shown for all vehicles (design vehicle plus grain carts and manure tanks) in Figure 3. In this instance, it is clear that a small number of implements exceed the punching shear condition resulting from the design vehicle.

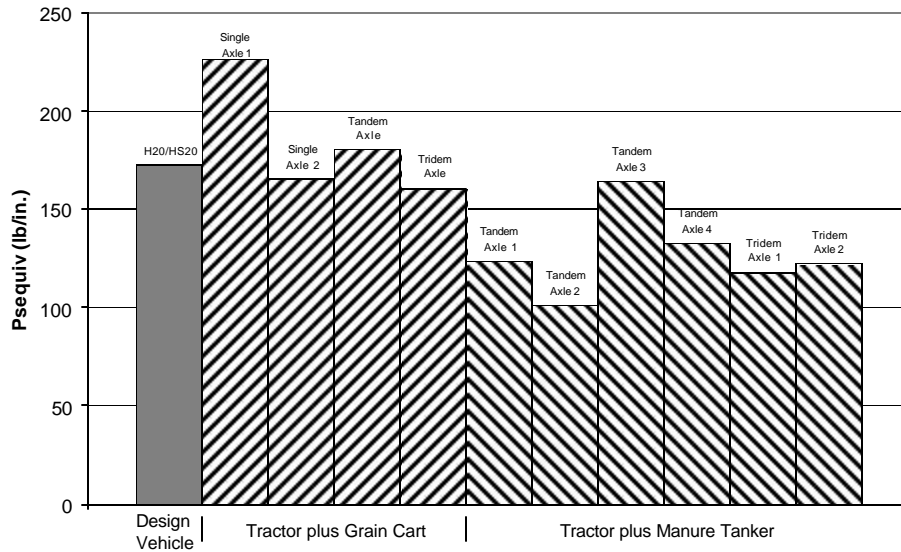


Figure 3. Bridge deck punching condition; design vehicles, grain carts, and manure tank implements.

Concluding Remarks

The technical literature that was synthesized and evaluated suggests that heavy agricultural vehicles cause detrimental impacts to Minnesota pavements and bridges. This technical literature, that included information from Minnesota and other Midwestern states, was supplemented with quantitative data as part of this study.

The performance characteristics of both rigid and flexible pavements are adversely affected by overweight implements of husbandry. Several studies with various agricultural vehicles showed that pavement life, in terms of the serviceability level of the pavement, rapidly decreases due to deterioration of the pavement which is manifested as cracking and rutting (permanent deformations). These findings are based on using field-measured metrics that are commonly used to determine damage levels relative to the design condition. This approach showed that implements can introduce damage levels of several hundred times that of the design condition. In addition to the heavy weight of the agricultural vehicles, their wide wheel spacing and slow moving characteristics further exacerbate the damage occurring to roadway systems.

Two structural performance measures were identified in the study for evaluating the impact of agricultural vehicles on bridges: bending and punching. Structural metrics were quantified for a variety of agricultural vehicles, and these values were compared with the design vehicle that is specified for the safe and serviceable design of bridges. The majority of the agricultural vehicles investigated create more extreme structural performance conditions on bridges than do the design vehicles when considering bending behavior. Only several of the agricultural vehicles exceeded design vehicle structural performance conditions based on punching.

The conclusion of this study validates the years of close observation of highway and bridge engineers that these heavy loads can cause potential problems in terms of both safety to the traveling public and added costs to the maintenance of the local system of highway infrastructure. It appears that the metric currently used to limit the weight of farm implements is not sufficient at predicting the potential for inducing damage to infrastructure.

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