EMERGENCY BRAKING

Research summary

R-76-30

L.H.M. Schlösser

Voorburg, 1976
Institute for Road Safety Research SWOV, The Netherlands

CONTENTS

SUMMARY

This report deals with an investigation concerning braking capacity of trucks if somewhere a failure accurs in the normal service brake. Purpose of the research was to get an insight in various secundary braking systems for trucks. Practical tests were carried out with a tractor-semi trailer combination. The performance of various split braking systems as well as spring brake actuators in terms of deceleration and lateral stability are shown.
The research findings were that with nearly all of the secundary braking systems it was possible to obtain sufficient deceleration to meet legal requirements for the braking path. The critical point however is the lateral stability. The report concludes with recommendations for requirements for secundary braking systems concerning lateral stability both on dry and wet road surfaces.

I. INTRODUCTION

Trucks are involved in accidents more often than private cars. On Dutch national highways the truck involvement quotient is about 1.5 times higher than for private cars. On motorways the figure is a little lower.*
Trucks differ from private cars in movement characteristics, dimensions and ergonomic features. In accident research however it will be particularly difficult to isolate the influence of each characteristic in contributing to the higher involvement quotient. Moreover, it is mainly found that accidents which are contributed to directly or indirectly by trucks having defective braking systems generally have very serious consequences.
So the Minister of Transport and Waterways in the Netherlands asked the Institute for Road Safety Research SWOV to undertake research into the functional requirements for auxiliary brakes.
The research was carried out by the ad-hoc working party on Emergency Brakes consisted of A. Dijks and W.A.M. van Blijswijk of the Vehicle Research Laboratory of the Delft University of Technology; J. van Genugten of Daf Trucks B.V. Eindhoven; G.J.M. Meekel of the Department of Road Transport RDW, The Hague, L.H.M. Schlösser of the Institute for Road Safety Research SWOV, Voorburg, the Netherlands.
The report is written by L.H.M. Schlösser.

E. Asmussen
Director of the Institute for Road Safety Research SWOV.

---

* Traffic accidents and road surface skidding resistance Institute for Road Safety Research SWOV, 1975.

II. PURPOSE OF THE RESEARCH

Having regard to the terms of reference and especially the policy aspects of the research, the ad-hoc working party formulated the following objectives:

1. Defenition of emergency braking;
2. Indicating possibilities of how emergency brakes can be obtained and tested in practise;
3. Comparison of the test results against systems already used in practise;
4. Drawing up functional requirements which emergency brakes must satisfy.

III. APPLIED RESEARCH ON EMERGENCY BRAKING

III.1. Emergency braking systems

In view of the great variety of braking systems in trucks allowed on the roads, for the research a choice was made from among these. The choice was based on a combination provided by Daf Trucks B.V. consisting of a Daf FT 2800 tractor and a tandem axle semi-trailer. The tractor had the standard dual circuit braking system and an automatic load brake apportioner (ALR) on the rear axle. The semi-trailer's brakes are separated via a double piping system. The semi-trailer has a hand operated control with which the pressure to the brake cylinders can be regulated depending on the truck's load. This control has three positions: empty, semi-loaded, fully loaded. The semi-trailer's tandem set has no compensator for the weight transference occurring during braking.
For testing purposes, the tractor's braking system was modified. By adjusting a number of valves a diagonal circuit separation could be obtained with which only the left front wheel and the right rear wheel could be operated. It was also possible, by means of valves, to brake only the front or rear axle (see Annexes 1, 2 and 3). The semi-trailer's braking system could also be similarly adapted. All the brake cylinders were spring brake actuator cylinders. They could be operated so that each axle could be braked individually. Diagonal braking was also possible with them both with the tractor and the semi-trailer.

III.2. Measuring programme

The investigation assumed that only one failure could occur at a time. Emergency braking in this context means any braking in which there is a defect in the braking system of the tractor or the semi-trailer. Possible defects are a leaking pipe or a defect in the load brake apportioner (ALR) etc.

A total of 200 measurements were made. Each braking system was measured at 40 km/h. After this the speed was stepped up to a maximum of 80 km/h. The measurements were made on both a dry and a wet road surface. There were also two conditions of loading: empty and fully loaded. The gross vehicle weight fully loaded was 325.000 N.

III.3. Measuring site

The measurements were made on a section of National Highway A1, not yet open to traffic. Measurements were made in two directions on carriageways 12 metres wide with a lateral incline of 1:50. With the aid of a sprinkler installation one road section (150 metres long) was kept constantly wet.
The friction coefficients on the measurement sections were determined with the measuring truck of the Vehicle Research Laboratory of the Delft University of Technology. The single-wheel trailer was fitted with the same tyre as the articulated vehicle. The measuring wheel was braked at a constant speed and μ_{xm}, the maximum braking force coefficient before the wheel locked and μ_{xb}, the braking force coefficient with the wheel locked, were determined.
The measurements were repeated several times and the results are given in the diagram (see Annex 4). As this diagram shows, the surface was rather rough, so that comparatively high decelerations were possible.

III.4. Measured values and equipment

In each measurement the following factors were recorded:
1. The speed was measured with a Peissler fifth wheel.
2. Deceleration during braking was measured with a Donner accelerometer.
3. After each measurement the braking path could be seen from the Peissler box. By fitting a switch to the brake pedal, the commencement of each braking was determined.

4. The angle between the tractor and the semi-trailer was measured with a rotary potentiometer. This was made possible by fitting a semi-circular disc near the connecting point on the semi-trailer, with a steel wire over it. The potentiometer was fixed to the tractor frame.
5. Kistler quartz pressure transducers were used by measuring the pressure in the brake cylinders.
6. Reed relays were mounted to establish whether a wheel locked or not. These are relays which close under the influence of a magnetic flux.
7. The measuring time was easy to ascertain because the commencement of the test was determined by marking and the end was at zero speed.
All the signals were noted on a UV-recorder. A Brush recorder was used with which 11 signals could be recorded. For the twelfth signal, the marking, a separate galvanometer was used. All the equipment could be fed from the tractor's 24 volt system by using converters.
After each measurement the vehicle's position relative to the driving direction was sketched.

III.5. Criteria

There were two criteria for evaluating the results:
1. The stability of the vehicle or the combination. As there are not yet regulations concerning lateral stability for all conditions tested in this investigation, the working party drew up a number of criteria for this research, both for solo tractors and for combinations.
These criteria regarded stability as inadequate:

a) If the solo tractor: (i) forms an angle of 20^0 or more compared with the drawing direction
(ii) shifts more than one metre to left or right.

b) If the combination: (i) jackknifes so that the angle between the tractor and the semi-trailer exceeds 10^0

(ii) shifts more than one metre to left or right.

The driver did not correct the combination in order to obtain a reproduceble test procedure. If it appeared during the measurement that instability was easy to correct, braking was evaluated as stable.

2. Deceleration was adequate when the average deceleration was at least 2,2 m/s^2. In the ECE a minimum deceleration for the auxiliary brake of 2,2 m/s^2 is required on a dry road surface. Since the maximum deceleration only occurred for a very brief time in a large number of measurements, an average deceleration was defined: $\frac{v_o}{t}$ in which

v_o = speed at commencement of braking

t = duration of braking.

For easy comparison the deceleration figures are given as an average deceleration for four measurements, that is at 40 and 80 km/h both on dry and wet road surfaces. When desirable differences are given, too.

IV. RESEARCH RESULTS

IV.1. The residual effect of the service brake when a circuit fails (Annex 1)

General findings

In nearly all the cases dealt with, the average deceleration after a circuit failure was still adequate.
The biggest problems in emergency braking are in vehicle stability rather than in deceleration, though this is sometimes very low. It is striking in this connection that diagonal circuit separation has little to offer.
Furthermore, this research has again demonstrated the great danger of locking wheels. Especially locking of the second axle causes problems. It is striking that an inadequatly braked semi-trailer pushes forward, relieving the second axle. In such a case an ALR on this axle does not decrease the brake pressure enough and wheel locking occurs.
In view of the foregoing, the difference in deceleration if axle 3 or 4 fails is very striking. Owing to the weight transfer in the tandem set, axle 3 makes a much bigger contribution to deceleration than axle 4.

Solo tractor

A normally braked tractor remains stable. If the front axle fails there are indications of very great instability if the rear axle locks, as on a wet surface. Failure of the rear axle caused no problems. In this case the front wheels locked, which may affect vehicle control. All diagonal braking were very unstable. It was impossible to correct diagonal braking.

Tractor with unladen semi-trailer

This combination normally braked causes no problems. Failure of

a tractor axle causes no problems. A semi-trailer braked normally at that moment apparently keeps the combination stable. A diagonally braked tractor causes an unstable combination pulling strongly to the left. Jackknifing occurs if the steering is not corrected.
Failure of an axle on the semi-trailer greatly relieves axle 2, causing it to lock especially on a wet surface. The combination will then jackknife. A diagonal circuit on the semi-trailer again causes stability problems. The reason in this case again is that the semi-trailer is not adequatly braked, so that axle 2 is relieved.
If only the tractor is braked, axle 2 locks and the combination jackknifes. Braking the semi-trailer alone gives a stable combination, but a low deceleration.

Tractor with laden semi-trailer

As expected, normal braking causes no problems relative to the criteria. Even if a tractor axle failed stability was still good. A diagonal circuit on the tractor did not cause the big stability problems of the empty combination. A slight correction in steering met the stability criterion.
Failure of one semi-trailer axle had no serious effects on stability, similarly to a diagonal circuit. Failure of all of the semi-trailer's and on the tractor's brakes caused no problems, apart from correcting the steering in the former case. But the deceleration is rather low.

IV.2. The effect of the braking system when the hand-operated auxiliary brake (spring brake) is used (Annex 2)

General findings

The average decelerations are adequate, but in this main group as well, stability is not as good as it ought to be. One reason is that braking power per axle cannot be regulated. If for

instance axle 2 in the solo tractor or the empty combination is braked to the maximum, locking and instability will occur. Braking power can be regulated for all axles at the same time with the auxiliary brake.
Another reason for poor stability is the relieving of axle 2 through the semi-trailer pushing forward. Another thing disclosed by the measurements was that the steering is difficult to correct because the driver has to handle the steering wheel with one hand and the auxiliary brake with the other.

Solo tractor

As regards stability, only the measurements in which the front axle was braked were good. In the other three cases axle 2 locked and the vehicle was very unstable.

Tractor with unloaded semi-trailer

With intact semi-trailer and auxiliary brakes on tractor: The results in this case are the same as for the solo tractor. Only if the first axle is braked with the auxiliary brakes stability is good.

With intact tractor and auxiliary brakes on semi-trailer: If axles 3 and 4 are braked, stability is good. Diagonal braking is still reasonable, but braking only axle 3 or 4 causes stability problems.

If all the axles of the combination are braked with spring brake actuators, axle 2 will lock and severe instability effects occur.

Tractor with loaded semi-trailer

With intact semi-trailer and auxiliary brakes on tractor: Diagonal brakes on the tractor do not give good results. Braking axle 1 or 2 or both goes well.

With intact tractor and auxiliary brakes on semi-trailer, except for an odd correction of steering, stability remained good in these measurements.
If all the combination's axles are braked stability remains good.

IV.3. The influence and effect of the automatic load brake apportioner on the tractor and the hand-operated control valve on the semi-trailer (Annex 3)

General findings

If only the solo tractor's rear axle is braked to the full, the deceleration is too low. This is due mainly to the wheels locking. In other cases the deceleration is adequate.
A defect in the ALR, so that it passes on the maximum pressure during braking, has the consequence that axle 2 will lock regularly. The excessive pressure is not the only cause, because locking is also encouraged by the ALR no longer regulating dynamically.
An incorrectly adjusted regulator on the semi-trailer, i.e. at "Full" with an empty combination, causes the braked wheels to lock, the semi-trailer provides too little braking power and pushes forward so that axle 2 is relieved. Especially on a wet road, the ALR will not decrease the pressure enough and axle 2 will lock.

Solo tractor

In this sub-group measurements were made with a tied-up ALR control arm. It appears that this makes the pressure to the 2nd axle too high and the wheels will then lock. Stability is very poor especially if only axle 2 is braked.

Tractor with unloaded semi-trailer

Only ALR tied up: stability very poor owing to locking of axle 2;

Only the brake regulator on the semi-trailer at "full". No problems on a dry road. On a wet road axle 2 locks, followed by instability.

Both regulators at "full". The combination was very unstable.

Tractor with loaded semi-trailer

ALR on tractor at "full": Jackknifing occurs through locking of axle 2, thus failing to meet the stability criterion.

V. CONCLUSIONS AND RECOMMENDATIONS

In evaluating systems for emergency braking if the service brake fails, the criteria were braking path, the appropriate average deceleration and the lateral stability. In addition, attention was paid to lost times and possibilities of correcting the steering.

If the service brake functions normally, an articulated vehicle both loaded and unloaded proved to satisfy the criteria of deceleration and stability, even if the brakes were fully applied. This was found to be possible only if there was an automatic load brake apportioner on the tractor's rear axle. If this is not fitted, as is still the case with many of the present vehicles, or if it fails, the artic is very unstable and will usually jackknife if the brakes are fully applied. With an intact service brake the solo tractor shows minor signs of instability at the end of the braking path on a wet surface. This is due to the limited possibility of regulating the brake force by the load brake apportioner. Without this facility, a solo tractor is very unstable under all conditions.

If the service brake becomes defective, part of the braking capacity may be retained because this brake has a residual effect or because hand-operated auxiliary brakes are installed. With nearly all applicable systems it was possible to reach the minimum deceleration of 2.2 m/s^2 needed to satisfy the requirements for the auxiliary brake's braking path.

Theoretical considerations and practical tests have shown that the total time lost when using separate hand-operated auxiliary brakes is greater than if the residual effect of the service brake is used. Moreover, hand-operated auxiliary brakes have the draw-back that the driver has to take one hand from the steering wheel. Experience shows that is then difficult, if not impossible, to correct the steering. Furthermore, it has not been proved that using spring brake actuators as auxiliary brakes produces higher decelerations than with the residual effect of the service brake, while it is then that the greater loss of time has to be compensated for

The practical tests showed that the biggest problem in emergency braking is the vehicle's lateral stability rather than deceleration. Instability occurs especially on a wet road surface.
The vehicle is unstable:
- if the tractor's rear wheels lock. The artic then usually jackknifes or a solo tractor turns round its vertical axis.
- if the semi-trailer in an artic does not brake sufficiently. The semi-trailer then pushes forward, taking the load off the tractor's rear axle, and easily causes jackknifing.
- if diagonal circuit separation is applied to the tractor, i.e. to the right front wheel and the left rear wheel or vice versa. The vehicle then pulls off course, and cannot be corrected owing to the big difference in braking capacity at the front and rear axles, so that a strong turning moment occurs in the tractor.

The-operated brake-pressure control of the quick-acting type on a semi-trailer only has any purpose on a reasonable rough surface. On a smooth surface the semi-trailer's wheels are already locked before the control acts, and its value under these conditions is dubious.

Recommendations

- For both tractors and semi-trailers it is recommendable, in case of emergency braking, to have a service brake residual effect of, say, 50% of the prescribed braking capacity of the service brake.
- The use of brake systems in which half the braking capacity of each axle is always available for emergency braking is preferable. For the front axle half the braking capacity of each wheel should be utilised.

- Brake regulations should include a requirement that trailer and semi-trailers should be equipped with auxiliary brakes or that the service brake have a certain residual effect in case it fails of, say 50% of the prescribed braking capacity of the service brake.
- Brake regulations should include a requirement regarding vehicle lateral stability when using auxiliary brakes or the brake's residual effect. Braking tests should be made on a wet surface with at least an empty artic and a solo tractor. The roughness of the road surface should be carefully defined.
- For more detailed research it is advisable to make smaller-scale tests into the behaviour during emergency braking of a combination of truck and trailer.

Maingroup 1.

The residual effect of the service brake when a circuit fails.

ANNEX 1

Page 1

Braking system	Conditions		Average deceleration	Locking of wheels				Stability				
	road	speed		tractor		trailer		angular deviation			shifting to left or right	
				front	rear	first	second	$<10^o$	$<20^o$	$>20^o$	<1 m	>1 m
Subgroup 1 solo tractor												
Normal braking	wet	80	4.6	X	X			X			X	
Failure of axle 1	wet	80	2.0		X					X		
Failure of axle 2	wet	80	3.8	X				X			X	
Diagonal braking	wet	80	2.4	X left						X		
Subgroup 2 empty combination												
Normal braking	dry	80	4.6	X right	X left				X		X	
Failure of axle 1	wet	80	2.6					X			X	
Failure of axle 2	wet	80	3.9	X				X			X	
Diagonal tractor	wet	80	3.1	X left				X				X
Failure axle 3	wet	80	3.8		X					X		
Failure axle 4	wet	60	4.2		X					X		
Diagonal semi trailer	wet	60	4.0		X					X		
Only trailer braked	wet	50	3.4		X					X		
Only semi-trailer braked	wet	80	1.6					X			X	

Maingroup 1.

The residual effect of the service brake when a circuit fails.

Braking system	Conditions		Average deceleration	Locking of wheels				Stability					
	road	speed		tractor		trailer		angular deviation			shifting to left or right		
				front	rear	first	second	$< 10^{o}$	$< 20^{o}$	$> 20^{o}$	< 1 m	> 1 m	
Subgroup 3													
laden combination													
Normal braking	wet	80	4.1				X	X			X		with steering correction
Failure axle 1	wet	80	2.9				X	X			X		
Failure axle 2	wet	80	2.9				X	X			X		
Diagonal tractor	wet	80	3.0	X left			X left				X		with steering correction
Failure axle 3	wet	80	3.1					X			X		with steering correction
Diagonal semi trailer	wet	80	3.2					X			X		
Only tractor braked	wet	80	2.3					X			X		with steering correction
Only semi-trailer braked	wet	80	2.3				X	X			X		

Maingroup 2.

Spring brake actuators

ANNEX 2

Page 1

Braking system	Conditions		Average deceleration	Locking of wheels				Stability					
	road	speed		tractor		trailer		angular deviation			shifting to left or right		
				front	rear	first	second	$<10^{\circ}$	$<20^{\circ}$	$>20^{\circ}$	<1 m	>1 m	
Subgroup 1													
solo tractor													
axles 1 + 2 braked	dry	50	3.5		X					X			
only axle 1 braked	wet	80	3.4					X			X		
only axle 2 braked	dry	50	3.4		X					X			
diagonal braking	wet	40	2.5		X					X			
Subgroup 2a	tractor spring brake actuators				semi-trailer normal service brake								
empty combination													
axles 1 + 2 spring br.	dry	80	3.3		X					X			
only axle 1 spring br.	wet	80	3.2					X					
only axle 2 spring br.	wet	60	2.7		X				X				
diagonal spring br.	dry	80	2.9										impossible to correct due to one hand steering
Subgroup 2b	tractor service brake				semi-trailer spring brakes								
empty combination													
axles 3 + 4 spring br.	wet	80	4.8	X		X left	X	X			X		
only axle 3 spring br.	dry	80	3.6		X left			X			X		with steering correction

Maingroup 2.

Spring brake actuators.

Braking system	Conditions		Average deceleration	Locking of wheels				Stability					
	road	speed		tractor		trailer		angular deviation			shifting to left or right		
				front	rear	first	second	$<10^{\circ}$	$<20^{\circ}$	$>20^{\circ}$	<1 m	>1 m	
only axle 4 spring br.	dry	80	3.9		X		X	X				X	
diagonal braking	wet	80	3.8	X							X		
all axles spring brake actuators empty comb.	dry	80	4.1	X	X		X			X			
Subgroup 3a	tractor spring brake actuators				semi-trailer normal service brake								
fully loaded													
Axles 1 + 2 spring br.	wet	40	3.4				X	X			X		
only axle 2 spring br.	wet	80	2.7				X left	X			X		
only axle 1 spring br.	wet	80	2.8				X left	X			X		with slight correction
diagonal braking	wet	80	2.7				X	X			X		with correction
Subgroup 3b	tractor normal service brake				semi-trailer spring brakes								
fully loaded													
axles 3 + 4 spring br.	wet	80	3.7		X right			X			X		correction necessary
only axle 3 spring br.	dry	80	2.8					X			X		with steering correction

Maingroup 2.

Spring brake actuators.

Braking system	Conditions		Average deceleration	Locking of wheels				Stability					
	road	speed		tractor		trailer		angular deviation			shifting to left or right		
				front	rear	first	second	$<10^{\circ}$	$<20^{\circ}$	$>20^{\circ}$	<1 m	>1 m	
only axle 4 spring br.	wet	80	2.9	X				X			X		with steering correction
diagonal braking	wet	80	2.8					X			X		with correction zigzag course
all axles spring brake actuators fully loaded	wet	80	2.9					X			X		

Maingroup 3.

The influence and effect of the automatic load brake apportioner on the tractor and the hand operated control valve on the semi-trailer.

Braking system	Conditions		Average deceleration	Locking of wheels				Stability					
	road	speed		tractor		trailer		angular deviation			shifting to left or right		
				front	rear	first	second	$<10^0$	$<20^0$	$>20^0$	<1 m	>1 m	
Subgroup 1 solo tractor with tied up ALR													
axle 1 + 2 braked	dry	60	4.9		X					X		X	with correction possible
only axle 2 braked	dry	40	1.9		X					X		X	instabel all conditions
Subgroup 2 empty combination all axles braked													
tied up ALR on tractor	dry	40	4.0		X				X		X		on wet surface jackknifing at very low speeds
manual regulator on semi-trailer at "full"	wet	60	5.2	X right	X	X	X		X		X		
Both regulation at "full"	wet	50	4.7		X	X	X			X		X	on wet surface no correction possible

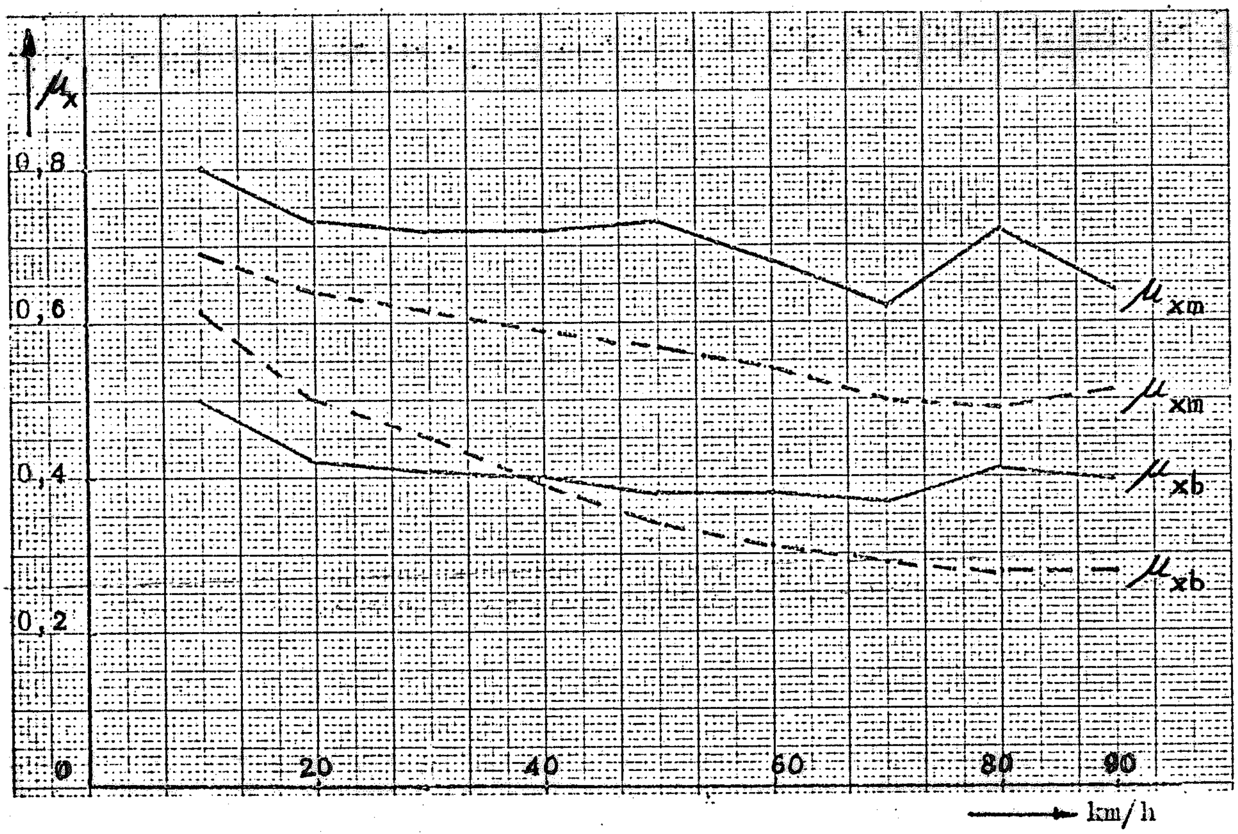
Maingroup 3.

The influence and effect of the automatic load brake apportioner on the tractor and the hand operated control valve on the semi-trailer.

Braking system	Conditions		Average deceleration	Locking of wheels				Stability				
				tractor		trailer		angular deviation			shifting to left or right	
	road	speed		front	rear	first	second	$< 10^o$	$< 20^o$	$> 20^o$	< 1 m	> 1 m
Subgroup 3 fully loaded combination Tied up ALR on tractor	wet	50	4.1		X		X left			X		X

Tied up ALR means: the control arm of the automatic load brake apportioner is fixed in the position on "full".

Coëfficients of friction on the measuring site



———— DRY

– – – – – WET

TIRE: MICHELIN E 20 X.

LOAD: 25500 N

PRESSURE: 6,25 BAR