Degradation of steering and suspension components affecting driver-vehicle performance during emergency situations

by Peter W Arnberg and Olle Odsell
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FOREWORD

The present research was conducted at the National Swedish Road and Traffic Research Institute. Mr Olle Odsell was responsible for the vehicles and the technical aspects of the study. Dr Peter W Arnberg was responsible for selection and training of the subjects and the ergonomical aspects of the study.

Particular acknowledgement is due to Mr Olle Nordström for his active cooperation throughout the study.

This is the third report in a project that covers effects of component degradation on vehicle handling. The two earlier reports (in Swedish) are:


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VTI REPORT NO. 109A
DEGRADATION OF STEERING AND SUSPENSION COMPONENTS
AFFECTING DRIVER-VEHICLE PERFORMANCE DURING EMERGENCY
SITUATIONS

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ABSTRACT

The report deals with the effects of free play in steering and wheel suspension components on vehicle handling, with special attention to the performance of the driver/vehicle system in emergency situations.

A field study has been carried out in which 33 subjects drove a Volvo 142 and a Saab 99 in both original condition and with certain degradations in steering and wheel suspension. The cars were driven on a test track where the drivers were exposed to two different types of surprise situations in which quick avoidance manoeuvres were necessary. The cars were equipped with instruments for the registration of speed, side acceleration, and steering wheel movement. After having driven the cars, the drivers made a comparative rating of the handling qualities of the cars.

The test method used in the study is evaluated and a comparison is made with other methods for testing vehicle characteristics. Based upon the results from the present study and from other similar studies, in USA and Sweden, conclusions are drawn regarding the effects of free play in steering and suspension on vehicle handling and traffic safety. Consequently, some general recommendations are given for the evaluation of degradation in steering and suspension components at annual vehicle inspections.

VTI REPORT NO. 109A
DEGRADATION OF STEERING AND SUSPENSION COMPONENTS AFFECTING DRIVER-VEHICLE PERFORMANCE DURING EMERGENCY SITUATIONS

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SUMMARY

The purpose of this project is to investigate the effects of free play in steering and wheel suspension components on the handling of passenger cars. Earlier tests within the project have proved that average drivers are able to compensate for degradations in steering and wheel suspension surprisingly well, and to drive vehicles impaired by such defects on roads and on difficult test tracks with almost intact precision. Despite this fact, many drivers have judged these vehicles to be unsafe in traffic, due to bad handling characteristics. A conceivable explanation of this difference between the drivers' judgements and their results is that the drivers may doubt their ability to compensate for the degradations in emergency situations as they can in well trained test situations.

In the test described in this report 33 drivers drove, either a Volvo 142 or a Saab 99 in both original condition and with certain degradations, on a closed test track. During the drive they were exposed to situations in which they had to make avoidance manoeuvres, like when an obstacle suddenly appears on the road. In particular, two situations were studied, one where the driver was prepared to some extent to make an avoidance manoeuvre, and another where he was completely unprepared. The speed, lateral acceleration and the steering wheel movements of the cars were registered, as were the number of lane marking cones hit and whether a suddenly appearing obstacle was run over or not.

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The results show that driving precision was almost exactly the same with the degraded vehicles as with the original ones, and the recorded values didn’t show any greater risk for loosing control of the vehicles with degradations. However, the degraded vehicles required more steering activity from the drivers. It can be argued that this would be tiring, but earlier tests within the project has shown that average drivers can compensate very well for free play even during long driving periods.

The behaviour of the driver dominates the system and the driver has in all tested driving-tasks been able to compensate for the degradations in steering and wheel suspension. Generally, the drivers noticed the defects in the cars and some of them judged the worn cars as unsafe in traffic. It seems that free play in the steering gives the driver an uneasy feeling, and therefore drivers tend to exaggerate the importance of the degradations with regard to traffic safety.

The investigations conducted so far indicate that free play in steering and wheel suspension components does not affect the handling characteristics of the vehicle to such an extent that it can be regarded as unsafe in traffic. But that does not mean that free play is acceptable without reservations. Generally applicable limit values for free play in steering and wheel suspension components cannot be given on the basis of impaired handling characteristics alone. The limit values should mainly be based upon the risk of component failure (e.g. separated ball joints), and upon economic considerations as well, (e.g. if free play in tie-rod ends causes increased wear of tires). Free play in tie-rod ends and in bushings of the wheel suspension may, when braking, give steering effects of different size depending on the design of the chassis. The path deviations are normally small, especially when the driver compen-
sates with the steering wheel, but earlier tests have shown that asymmetric play in the bushings for live rear axles can produce rather large path deviations when braking.

The judgement of free play at the mandatory periodic vehicle inspection in Sweden is based mainly upon the above mentioned factors and because of that very small amounts of play are accepted in ball joints. In other components, where the risk of total failure is very small, larger amounts of play can however be tolerated.

It is essential to point out that the degradations mentioned in this study would be the result of normal wear. Very large amounts of free play in, for instance, the steering is normally the result of some component failure, and this can be immediately be seen to be unsafe because important information from the steering wheel about the vehicle and the road is significantly decreased.

The tests which were carried out addressed themselves to certain components only, and combinations of many components with free play as well as other vehicle parameters, such as heavy loads, defective shock-absorbers, low air-pressure in the tires etc, were not tested. It can be assumed that the effects of free play are larger at high speeds, but the driving tests have, of safety reasons been made in relatively low speeds. However, despite this, the results provide no reason for changing the criterion used today for judging free play in steering and wheel suspension, at the periodic technical inspection of passenger cars in Sweden.
BACKGROUND

1.1 General

During the past few years periodic vehicle inspection has become compulsory in many countries (in Sweden since 1965). As a consequence of this, interest has increased in studies on the effect of wear and tear, adjustment, and free play on vehicle handling characteristics.

It is generally assumed that a vehicle with high degrees of wear in several components, is a greater risk in traffic than a new vehicle. This is not only because the probability of breakdown of components such as the tie-rod ends, the brake cylinders, etc is increased, but also because it is felt that worn components degrade handling.

Despite this assumption, very little is known about which worn components have the greatest effect on the driver/vehicle system. Similarly, it is not known to what degree a component or a group of components in combination may be allowed to deteriorate before they effect the vehicle's handling characteristics to the extent that the accident risk is increased.

Many investigations have been carried out to determine the proportion of total accidents than can be directly attributed to component wear. The results of these studies vary considerably. However, the majority of them state that vehicle defects were the direct, contributing or possible contributing reason for 3 to 25% of the investigated accidents.

When looking at the mechanical defects, faulty brakes and defective tyres were cited most often. Although statistical data for defects in steering or wheel suspension is very limited, several investigators state
such defects were possibly the main contributing factor in 1 - 5% of traffic accidents.

The question of car handling and its importance to traffic safety is difficult to answer. For example, is it necessary to specify a standard for each make and model of car, or is it enough to set a general minimum vehicle standard? According to an extensive study in the USA (Fancher et al 1972) the difference in handling between new passenger cars of different types and models is greater than the difference between new and used vehicles of the same type. From a safety point of view perhaps one should concentrate on those vehicles which have the worst handling characteristics. On the other hand, a general improvement of the vehicle population will take place if degraded vehicles, which originally handled well, were also repaired.

The main difficulty today is that there is no generally accepted way to objectively measure vehicle handling with regard to safety, and therefore, it is not possible to determine any minimum standards. Investigations continue in this area both in Sweden and internationally but until measures are developed, it is often necessary to resort to comparisons of simple values, such as maximum speed, lateral acceleration, and subjective judgement on handling.

Theoretically the best method for determining acceptable degradations would be to study how drivers cope with driving defective vehicles in real traffic situations. However, this is not only potentially dangerous but also means that complete control of trials and subjects is virtually impossible. Therefore, it is necessary to conduct experiments on closed tracks in simulated traffic situations.
In the past when measuring vehicle handling characteristics, researchers have tried to minimize the effect which the driver has on the test. This has been done by using trained test drivers, by establishing well-defined steering manoeuvres (e.g. turning the steering wheel to a predetermined position), or by eliminating the driver entirely by using automatic steering. Such so-called "open loop" tests give very good opportunities to compare objective measurement data because such tests are almost completely reproducible.

These tests, however, need to be viewed very carefully since it is not necessarily true that the measurements obtained are relevant for normal drivers in traffic. Therefore, in order to ensure that the results from a test are generalizable to the traffic situation, an "open loop" test must be combined with the so-called "closed loop" test. In closed loop tests the driver adjusts the vehicle's movements during driving. In this way it is possible to determine whether or not the driver can compensate for the vehicle's altered characteristics. To lessen the influence of different driver behaviours in such tests, many subjects need to be used. Then powerful statistical methods can be used which allows accurate measurements of performance across degree of mechanical fitness of the vehicle.

1.2 Literature search

A search of available literature regarding the effects of component wear on handling was carried out. Three rather extensive reports dealing with the problem were found, (Clayton Manufacturing Company 1969, Cornell Aeronautical Laboratory 1971 and Highway Safety Research Institute, Michigan 1972). The Michigan study reports results from an extensive simulation program. The program calculated how alternations in different vehicle...
components, affected vehicle handling in six different well-defined manoeuvres and showed which components were most likely to have an influence on vehicle handling. To further study the effect of these critical components a full-scale test using real vehicles was also undertaken.

The results of the three reports were in some cases contradictory, but all concluded that reasonable amounts of free play in steering and wheel suspension components does not necessarily degrade vehicle handling to a great extent. It is important to note, however, that all three of these investigations have dealt with handling at the limit of the vehicles' capacity, (i.e. so called "limit performance"). They have also typically used automatic steering devices or trained test drivers with high levels of preparedness who drove vehicles for very short times. It was therefore felt that it was necessary to investigate how "average" drivers can cope with degraded vehicles during "normal" driving for long periods of time.

1.3 Previous study

In 1974 - 75 the National Swedish Road and Traffic Research Institute (VTI) carried out a test in which 12 "average" drivers each drove 9 vehicles with different degradations, ranging from front end misalignment to free play in steering and wheel suspension components. The degraded components in the test were chosen on the basis of the results from the report by the Highway Safety Research Institute in Michigan. The vehicles were driven on a test track for almost two hours. The track consisted of three different manoeuvres: a straight line tracking task, a double lane-change and a serpentine tracking task. During these manoeuvres, speed, steering wheel angle, yaw velocity, lateral acceleration and the
vehicle's tracking error from the mid-line were recorded. After the test, the drivers judged the handling and traffic safety of the different vehicles.

The results showed that normal drivers can compensate even over long periods for relatively large amounts of free play. However, despite the results, drivers judged that several of the defective vehicles were extremely difficult to handle and that these vehicles should not be allowed in traffic. This discrepancy suggested that further research was necessary to investigate whether the drivers' judgements of the defective vehicles' traffic safety were justified or not. Perhaps the drivers were afraid that they would not be able to compensate for the defects in the same way in an emergency situation.

The following work within the project was therefore oriented towards degraded vehicles in emergency situations and the current report investigates whether "average" drivers can adequately compensate for free play in steering and wheel suspension components even in critical situations, i.e. when an unprepared driver has to quickly manoeuvre the vehicle out of a potentially dangerous situation.

METHOD

2.1 General

It is, of course, difficult to simulate a realistic surprise situation which can be repeated several times with the same subject. Since the object of the experiment was to compare the characteristics of vehicles in different conditions, it was necessary to restrict the drivers to a pre-determined set of steering manoeuvres.
that could be repeated. To accomplish these goals, the test was divided into two main situations, one where the driver was required to complete a trained avoidance manoeuvre but without knowing when, and another where the driver was totally unprepared. The test was conducted on a 1.7 km long loop track at the Scandinavian Raceway in Anderstorp, (see figure 1, 2 and 3).

2.2 Lane change manoeuvre

Approximately 400 meters of the straight track was marked with plastic cones to give three lanes for a lane change manoeuvre.

In this test a lane change could be required at any one of 10 "gates" by a light signaling system. The driver was required to change lanes and drive through a gate when the light in front of the gate was lit, otherwise the driver was required to drive straight ahead. By using a control panel located at the side of the track, the experimenter could, before each run, choose which course a vehicle should take as it went through the track. The light at each gate entrance was activated as the car drove over a pneumatic hose at a pre-determined distance from the gate.

Because of the relatively short pre-warning time and because the driver did not know when and how often a lane change was required, the test situation provided an element of uncertainty despite the well-rehearsed nature of the task.
"gate" 20 13.3 alt. 16.7 25 measured in meters dots mark plastic cones

Figure 1. Test track at Scandinavian Raceway in Anderstorp

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2.3 **Surprise situation**

In a separate section of the track loop, an isolated surprise situation was created. A 150 x 40 cm cylindrical styrofoam filled rubber bag was dropped in front of the car from a container attached to the underside of a bridge spanning the track. The bag was completely safe to run over and it could be dropped at a chosen time before the vehicle passed under the bridge. The aim was to cause a surprise situation in which the driver was forced to execute a vigorous lane change manoeuvre in order to avoid running over the obstacle. The subjects were asked in advance whether they could accept being exposed to a total surprise situation and none refused.

2.4 **Subjects**

A total of 33 subjects was used, 16 drove one car and 17 the other. All subjects were men aged between 20 to 60 years who had regularly driven at least 10 000 kilometers per year during the last three years.

To lessen the need for training on the two types of car used, the subjects were chosen, with the help of the local car salesmen's register, from owners of either a Volvo 140 series or a Saab 99. They were well paid and highly motivated to participate in the experiment.

2.5 **Training**

The drivers were familiar with the type of vehicles used in the experiment but extensive training was required to get the subjects acquainted to the lane change signaling system.
Figure 2. Lane-change track

Figure 3. Surprise obstacle falling from bridge

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Training was done in the subjects' own cars in two stages. The first stage consisted of subjects driving behind a research vehicle at a relatively low speed to learn the track, while the second stage consisted of individual instruction. Continuous information was given by the experimenter concerning what mistakes the driver had made (e.g. braking, driving over cones). The subjects drove one by one and gradually increased their speed until they could easily drive through the entire track at 60 km/h.

2.6 Vehicles

Two 1972 cars were used: a Volvo 142 and a Saab 99, both equipped with automatic transmission. Measurement and recording instruments were mounted in the back seat. The experimenter sat in the front passenger seat. Both cars were equipped with Michelin ZX steel radial tires, set to a pressure of 180 kPa all round. Each vehicle was driven both in original and defected condition, (free play in the steering and the wheel suspension). In this test only those defects which were judged to be the most serious in the previous experiment (Arnberg & Nilsson 1976) were used. These defects were (see figure 4):

Volvo 142  Play in steering gear giving 15° free angular movement at the steering wheel when the wheels were oriented straight ahead. This was achieved by unscrewing the adjustment screw on the steering box.

Saab 99  Free play 3 mm in right outer tie rod end and 10 mm free play in bushing for rear axle location bar. These defects were achieved by replacing the original components with machined components.
Figure 4. Simplified illustration of test vehicles with defects in steering and wheel suspension

Free play 3 mm in right outer tie rod end

Free play 10 mm in bushing for rear axle location bar

Play in steering gear giving 15° free angular movement at the steering wheel
2.7 Procedure

The subjects drove each test car for two 45-minute sessions after becoming familiar with it on the way to the test site from the paddock (~1 km). During the first test session half of the subjects drove cars in the original condition and the other half drove cars which had been modified. The subjects naturally did not know in advance the condition of the test cars.

Each test session consisted of eleven laps of the track loop. The first two laps were considered training laps with only one or two lane changes per lap. Then three laps followed with three lane changes per lap. Before these laps the subjects were instructed to concentrate fully, because many lane changes would occur during each lap. The test session ended with six laps in which the drivers were instructed to drive in a relaxed manner, because only a few lane changes would be required during the six laps. During three of these laps, no lane changes were required while during the remaining three, one or two changes were required.

For the first 16 subjects (8 on each car) the lights were set to light up one second before the car reached the gate (at 60 km/h). For the rest of the subjects, the pre-warning time was decreased to 0.8 seconds to further increase the effect of surprise.

After the subjects had driven the eleventh lap and were on their way back to the paddock, the obstacle was dropped in front of the car from the bridge. The container holding the bag was opened when the car was at a distance of 40 meters from the bridge. It took approximately 1 second from the time the container was opened until the obstacle reached the ground. Since the drivers could see the obstacle when it was in the air, they had at least 2 seconds to execute an avoidance manoeuvre.

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The second test session included the same program in the lane change track as the first, except that the laps were driven in a somewhat different order. This was done in order to counteract the previously learned patterns. The obstacle at the bridge was dropped during the sixth lap, i.e. the first lap in the section of "relaxed" driving.

2.8 Measurements

The following measurements were taken for all cars:

1. Speed (a control variable)
2. Maximum side acceleration (giving a measurement of how much of the available friction was used)
3. Steering wheel angle sums (total of degrees turned during a steering manoeuvre, see figure 5)
4. Steering wheel movements (stating how many steering wheel movements of various sizes were made during a steering manoeuvre. Steering wheel movements were measured in five different intervals: 4 – 12°, 12 – 20°, 20 – 28°, 28 – 36° and over 36°, see figure 5).

Recordings were made during one lane change per lap as well as during the surprise incident. The measurement equipment was started and stopped at the same distances before and after each measured steering manoeuvre. These distances were chosen so that the vehicle was stable and was being driven straight ahead both at the beginning and at the end of the recording period.

The number of cones knocked down and whether the surprise obstacle was hit were also recorded.

The accelerometer was placed on the floor behind the front seats. As no compensation was made for the roll
steering wheel angle left (°)

steering wheel angle right (°)

steering wheel angle sum = 70° + 60° + 5° + 105° + 115° + 35° + 15° + 10° + 5° = 420°

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<tr>
<td>4°-12°</td>
<td>3</td>
</tr>
<tr>
<td>totally &gt;4°</td>
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</tbody>
</table>

Figure 5. Registration of steering wheel angle sum and steering wheel movements (example)
of the car, the side acceleration values should not be considered as actual lateral acceleration values.

2.9 Ratings

Following each drive, the drivers were asked to evaluate the vehicle's handling. After the completion of all testing they were asked to rate which vehicle was best, why, and what differences they had noticed about the cars. They should also state if they considered that any of the vehicles would be unsafe in traffic and make a comparison with their own cars.

3 RESULTS

3.1 General

The lane change test was relatively difficult conceptually, and it was considered to be near the performance limits of an average car driver. Although the prescribed speed of 60 km/h produced rather high lateral accelerations, there was very little risk of losing control of the vehicle. The maximum side accelerations measured was in the order of 5 - 7 m/s², i.e. about 0.5 - 0.7 g (g = gravity 9.81 m/s²). As the friction number was estimated to approximately 1.0 on the dry track, a relatively good margin was available.

In the beginning of the training, many subjects were doubtful if they would be able to perform the lane changes at 60 km/h, but most drivers learned the task quickly. It was obvious that many of the subjects had never driven a car in such a demanding manoeuvre and they expressed surprise that it was possible to steer a car through such sharp turns at the prescribed speed.
3.2 Speed

With very few exceptions the subjects were successful in maintaining a constant speed during the lane changes. The difference in the arithmetical means (see figure 6) between original and degraded vehicles was not significant. The difference between the Volvo and the Saab can believably be due to the fact that the speedometer in the Saab was more stable and easier to read than that in the Volvo.

3.3 Side acceleration

The maximum side acceleration during a steering manoeuvre varied considerably for the same person during different lane changes, depending on how quickly he reacted to the light. If one looks at the individual mean side acceleration during the test, there is no tendency for higher values with either of the vehicle conditions. The mean side acceleration for all subjects together show the same result, - no significant difference between original and degraded vehicles -, (see figure 6).

To test whether difference in mean speed affects the comparison, a standard for side acceleration at 60 km/h was calculated using the following formula:

\[ a_{60 \, \text{km/h}} = \left( \frac{60}{V} \right)^2 \cdot a \, (\text{m/s}^2) \]

The formula is derived from the formula for centripetal acceleration:

\[ a_c = \frac{V^2}{r} \]

The standard implies that the vehicle is driven with the same curve radius \( r \) as in the real measurements but with the speed 60 km/h instead of with the real speed.
Figure 6. Arithmetical means per lane-change for all subjects (a total of 469 lane changes for 31 subjects)

<table>
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<tr>
<th>Car</th>
<th>Volvo original</th>
<th></th>
<th>Volvo degraded</th>
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<th>Saab original</th>
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</tr>
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v km/h. The standard does not produce any significant differences in side acceleration and therefore does not alter the previous conclusions.

3.4 Steering wheel angle sum

The steering wheel angle sum show the sum of all steering wheel movements during a manoeuvre and can therefore be called a measure of drivers' performance. Both the Volvo and the Saab present significant differences (dependent t-test 5% level, Ferguson 1966) in the arithmetical means for all subjects (see figure 7).

The greater difference with the Volvo was possibly due to the amount of "play" in the steering at midpoint; approximately $15^\circ$ in the modified form, as compared with approximately $4^\circ$ in the original form. In the Saab no equivalent difference in "play" existed because only the tie rod at one front wheel was modified for free play.

3.5 Steering wheel movements

The number of steering wheel movements of different size gives a further measurement of the driver's performance.

The degraded Volvo required more steering wheel movements than the original vehicle, in all movement size classes. This was to be expected due to the nature of the modification. In particular, the number of small steering wheel movements increased considerably in the defective car, and it was seen that it demanded greater attention from the driver.

The small differences in steering wheel movements found
Figure 7. Arithmetical means for steering wheel angle sum per lane change
3.6 Number of cones hit

The function of the plastic cones was to mark the track exactly so that the lane change test could be replicated accurately on each session. However, depending on the driver's attentiveness, reaction time and driving ability, the path taken varied a lot. During the first half of the test (with a one second pre-warning), very few drivers failed to turn into the correct gate. However, during the second half (prewarning of 0.8 seconds) several drivers reacted too slowly to successfully complete the lane change. For the entire test, an average of one cone was knocked over at every third lane change. However, the spread between different drivers was large. The cone most often knocked over was the one in the inner-turn when driving into the new lane.

No significant differences were found between the mean number of cones knocked over per lane change for the original and modified vehicles. Most of the drivers drove over somewhat fewer cones during the second test drive than the first.

In a few cases, cones were driven over even on straight stretches between gates. Here, a significant difference was found between the Volvo's two different conditions. Thus, a total of nine cones were knocked over by the defective Volvo while no cones were knocked over by the Volvo in original condition. This shows that it was more difficult to keep the degraded Volvo on a straight course in the 2.5 m wide lanes.
3.7 **Surprise incident**

The rubber bag drop from under the bridge was a total surprise for the drivers on the first test drive. During the second test drive they were more cautious when driving past the bridge, but many admitted that they were surprised even the second time. They had expected that the obstacle would drop again during the last lap and not during the middle of the test drive.

Immediately after the surprise incident, the drivers were interviewed by the experimenter (a psychologist) concerning how they had experienced the situation. Almost all of the drivers felt the situation was realistic and many were shaken by how ineffectively they had reacted – even those who had succeeded in avoiding driving over the obstacle. All subjects thought that the test was fruitful and instructive.

Most drivers made an avoidance manoeuvre to the left without braking, some veered to the right off the track, and in several cases the driver drove straight onto the obstacle with almost no decrease in speed. Although the drivers in general were aware of the obstacle approximately 2 seconds before they reached it at 60 km/h, the obstacle was run over in 25% of the cases. It was run over more often in the first test drive than in the second (39% and 10% respectively).

Another 20% of the cases were not usable for evaluation since the driver drove too slowly, drove in the middle of the road or braked suddenly. The remaining cases (55% of the total) managed to avoid the bag with comparable manoeuvres, and they resulted in the following arithmetical means for side acceleration and steering wheel angle sums:
The variation around the means was large. Scores depended on how early the driver noticed the obstacle, in which direction he swerved and where on the track he was driving before he saw the obstacle. Statistical tests (independent t-test 5% level, Ferguson 1966) showed that although the relatively large differences between the means, they were not significant, except for the steering wheel angle for the Saab. However, due to the inaccuracy of the means (because the above variation) no definite conclusions concerning the effect of the degradations can be drawn.

### Ratings of handling qualities

After each test session the driver was asked to rate the handling and the safety of the driven car.

The degraded vehicles were rated to be considerably worse than those in original condition and considerably worse than the drivers' own cars (see figure 8). For both the Saab and Volvo the differences between the ratings of the defective vehicle and the original vehicle and between the ratings of the defective vehicle and their own vehicle are significant (dependent t-test 5% level, Ferguson 1966). The degraded Saab was rated
Very difficult to drive

$T =$ rated limit for what can be tolerated in traffic
$D =$ rated limit for what the driver would accept for daily use
$S =$ standard deviation

Figure 8. Rating of handling qualities
to be at the end limit for what the driver would accept for daily use but it was well within the traffic safety limit. The defective Volvo was, however, near the traffic safety limit, and about half the subjects felt that it would be dangerous in traffic. The ratings were very compatible with the ratings of the same vehicles in the previous test, (Arnberg and Nilsson 1976).

The free play in the steering of the Volvo was noticed by most subjects and this probably affected their ratings. The defects on the Saab was somewhat harder to notice, as the tie rod end on only one front wheel had free play. Many of the drivers could not determine what was wrong with the Saab, but some thought that the car's handling was "untrustworthy".

4 DISCUSSION

4.1 Evaluation of the method

The short pre-warning time (0.8 - 1 second) during the lane change test made the driving task relatively difficult and the drivers had to be very attentive when driving past each pair of lights. The surprise level was not especially high, but even so it was considerably higher than on the marked-out lane change track used in the earlier experiment (Arnberg and Nilsson 1976) where drivers knew in advance exactly how they should drive. The short pre-warning time meant that the drivers did not have enough time to compensate for possibly known defects in the car, as is the case in critical traffic situations.

The dropped bag was completely unexpected the first time, and even the second time most drivers were not expecting it. The incident was experienced as very
realistic and many subjects felt that all car drivers should be exposed to such a situation so that they could better judge risks in traffic and be aware of their own driving limits.

The surprise was so great that afterwards many subjects had difficulty in describing how they had reacted and how the car had handled. For this reason, many could not judge the handling characteristics of the car in this situation. However, speed, side acceleration and steering wheel movements were recorded and these values together with observation could provide a good description of the incident. Those drivers who swerved past the obstacle generally attained side accelerations of the order of 0.6 - 0.8 g. These very high values can be compared to the values of 0.2 - 0.4 g which are normally seen in traffic (Bergman 1973, Arnberg 1976). It is, however possible that the high side acceleration values recorded at the drop of the bag partly were the result of the avoidance manoeuvre training that the drivers received on the lane change apparatus. Without this training, presumably lower side accelerations may have been reached and more hits of the obstacle would have occurred.

Many previous investigations have emphasized the difficulties of using average drivers in a test which tries to evaluate vehicle handling. In the past, attempts have been made to minimize subject variability by using well-trained test drivers or automatic steering. However, with such methods it can be difficult to determine if the test actually measures those aspects of vehicle handling which are of importance in actual traffic. Because the interaction between driver and vehicle determines handling in traffic, it is essential that one studies the complete system. Both methods have their justification and may be seen as complementing each other.

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In this test, the surprise incident (the rubber bag dropped in front of the car) simulated an actual critical traffic situation very well. The incident caused different drivers to perform quite different manoeuvres. Therefore, no accurate conclusions about the vehicles' handling could be drawn. The method can be said to have high validity but low reliability. It should, however, be possible to increase the reliability by limiting the road situation a bit more. Care should, however, be taken so that the realism of the situation is not reduced. The method could be used to good advantage when studying vehicle handling, especially as a complement to totally reproducible methods of the "open loop" type.

The method of lane change using lights as signals was shown to be relatively reliable but was perhaps a little unrealistic because of the "unnatural" reason for veering. The test showed, however, that by using many subjects and appropriate statistical methods, one can measure and judge vehicle handling with accuracy.

4.2 Evaluation of the results

Free play in steering and wheel suspension unquestionably alters the handling of a car, although the investigations conducted so far indicate that the tested degradations have not been sufficient to appreciably lower the drivers ability to manoeuvre the vehicle. During normal driving, free play forces the driver to make more steering wheel movements and path corrections. The previous test (Arnberg and Nilsson 1976) has, however, shown that car drivers with average driving skill can compensate quite well for free play even during long driving periods.
Free play in tie-rod ends and in the bushings of the wheel suspension can give undesired steering effects when braking. The effects vary depending on the car's chassis design and on which component that has free play. The path deviations are normally small, but a previously conducted investigation (Nordström & Roland 1976) demonstrated that asymmetric play in the bushings of live rear axles can produce considerable path deviations during braking. Generally the driver can compensate for such path deviations with the steering wheel, but a slanted position of the rear axle can give such a big steering effect during braking that special attention should be given to the rear axle bushings at annual car inspections.

In critical situations, requiring an extreme avoidance manoeuvre, the driver is the dominant factor in the driver-vehicle system. In none of the tested driving situations it could be shown that free play in steering and wheel suspensions seriously affected the driver's possibilities of manoeuvring the vehicle safely. Even so, many drivers rated the defective vehicles to be appreciably more difficult to handle than the original vehicles, and the defective Volvo was in many cases judged to be unsafe in traffic. Free play in the steering gave the drivers in uneasy feeling, but their ratings indicate that they overemphasized the importance of free play with regard to traffic safety. The reason for this might be that drivers noticed that they had to work harder to compensate for free play, and that they possibly felt that free play of this magnitude should not be approved at a car inspection.

Previous studies have shown that vehicle type (for example an over-steering vehicle compared to an under-steering vehicle) has a greater influence on performance than marginal worsening of handling caused by degradation of an individual vehicle. Another example
of this is that the 15° "play" in the steering of the modified Volvo is almost regarded as "normal" play in some American cars.

Applicable limits for acceptable free play in steering and wheel suspension components are consequently difficult to specify on the basis of impaired handling qualities. The limit values should instead be based primarily on the risk of failure of single components (e.g. separation of ball joints). Degraded components, such as bushings, steering gear etc, where little or no risk of failure exists, should not be rejected on the grounds of decreasing traffic safety. However, at the car inspection, consideration must be made of the fact that when wear and tear reach certain levels, their progress becomes accelerated and therefore much can happen in the period between two inspections.

When judging free play, economic considerations can also become important. For example free play in steering and wheel suspension can be the cause of increased tyre wear, so that even repairs which do not have importance for traffic safety can be worthwhile as they may reduce the total running cost for the car owner.

The judgement of free play at the mandatory periodic vehicle inspection in Sweden is based mainly on the above criterion, and therefore, very small amounts of play are accepted in ball joints. Greater free play can be tolerated in parts where no risk of failure exists, especially so in older cars which have a short expected life left. In such cases, the change of expensive parts, if not necessary for traffic safety reasons, cannot be justified on economic grounds for either the owner or for society. The current study supports these criterion.
It is essential to point out that the degradations discussed in the current study, simulated the results of normal wear, i.e. free play in ball joints up to a few millimeters, free play in bushings up to a centimeter and free play in the steering up to about 15 - 20° at the steering wheel. Free play greater than this is normally the result of some component failure and this can immediately be considered as unsafe in traffic, partly because the information from the vehicle and the road that is normally transmitted to the driver through the steering wheel decreases significantly.

The current study has been carried out as a complement to the previous American studies in the same field. Only a very limited number of vehicles has been tested with modifications to only a few of the components which, because of wear, could affect handling. The effects of combinations of several components with free play or combinations of free play components and other factors, such as defective shock absorbers, oversteering due to heavy load etc, have not been studied. However, the results of the performed tests are similar to the results reported in the American studies.

For safety reasons, the test drives were carried out at relatively low speeds (60 - 70 km/h). It is known that changes in the vehicle's driving dynamics often become more evident at high speeds, and thus it would be desirable to test the effect of for example, steering free play at high speed. Practical driving tests are, however, risky and therefore difficult to conduct with subjects, but such investigations could possibly be conducted to advantage in a driving simulator.

In conclusion, with the exception of the bushings for rear axles, the results do not give any reason for changing the principles that are used today when judging free play in steering and wheel suspension at the periodic technical inspection of passenger cars in Sweden.

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LITERATURE REFERENCES


