THE AUTOMATIC STEERING OF VEHICLES—AN EXPERIMENTAL SYSTEM FITTED TO A DS 19 CITROEN CAR

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1970
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THE AUTOMATIC STEERING OF VEHICLES – AN EXPERIMENTAL SYSTEM FITTED TO A CITROEN DS 19 CAR

ABSTRACT

The Road Research Laboratory has equipped a car with an experimental automatic steering system to study the feasibility of automatic vehicle control. The car, a Citroen DS.19 chosen for its high pressure hydraulic system, is capable of following a buried cable energized with a 5 kHz current. An electro-hydraulic servo mechanism has been installed to steer the front wheels.

Speeds of up to 130 km/h (80 miles/h) have been obtained on dry surfaces and 100 km/h (60 miles/h) on snow covered surfaces without loss of control.

Development work has been directed to preventing the car “hunting” over the cable and to improving vehicle lateral ride. The vehicle normally stays within ± 20 mm of the cable in straight running but on a curved path it is deflected to one side of the cable, by up to 130 mm or more depending on vehicle speed and radius of path curvature.

Details of the servo and sensing systems used are given with an account of the necessary mechanical and electrical modifications made to the vehicle. The course of future development work is outlined.

I. INTRODUCTION

Early experiments with the automatic steering of a car, using a buried cable to define the path, demonstrated the technical feasibility of such a method. The operation of the system, in general terms, was as follows:

A cable, buried below the surface of the Crowthorne research track, was energized with a 5 kHz current and the position of the resulting magnetic field was sensed by equipment installed in the test car. This generated a lateral position error signal which fed into an electro-hydraulic servo system operating the vehicle’s steering and enabled the vehicle to follow automatically the buried cable. Even with a very simple system the car could be controlled at indicated speeds of 80 km/h (50 miles/h) in straight running.
Two factors were evident as a result of these initial trials. Firstly, considerable development work would be required if acceptable lateral ride characteristics were to be obtained and, secondly, lateral control could not make an effective contribution to road safety unless a satisfactory and economical inter-vehicular anti-collision or headway control could be devised.

Over recent years there has been a gradual revival of interest in the automatic steering of vehicles in connection with possible future urban transport systems and, consequently, the original test car was prepared for further guidance study by rebuilding parts of its control system. This report gives some details of the modifications made to the Citroen DS.19 car and discusses the current performance of the car together with the direction that future work might take.

2. CHOICE OF A VEHICLE FOR GUIDANCE STUDIES

A vehicle suitable for research into automatic steering requires good dynamic stability, reasonable maximum speed, adequate space for housing equipment and has to be fitted with some form of powered steering. One suitable form of powered steering is a hydraulic power-assisted steering. As the command signals from the guidance system are electrical, in this case an electro-hydraulic type of servo valve is needed to control the hydraulic system. These valves have to be supplied from a high pressure source of filtered fluid, and this cannot be provided by many car steering systems due to the way in which they are designed.

The engine driven pump used for conventional power steering systems has special performance characteristics. The pump discharge is kept constant and is largely independent of pump speed while the output pressure may be varied. When the car is running straight and steering forces are small, fluid passes through the steering control valve, which is of the open centre type, at a low pressure, typically about 400 kN/m$^2$ (60 lb/in$^2$). Pump pressure only rises when demands are made on the system which call for force amplification of the driver's steering input. These systems are also designed to run with minimal filtration or none at all.

An exception, however, does exist in the Citroen range of cars. In these vehicles a high pressure pump supplies accumulators with fluid at a controlled pressure of between 12.4 to 16.5 MN/m$^2$ (1800 to 2400 lb/in$^2$). The fluid is used to feed various services on the car which include the high pressure power-assisted steering mechanism.

A particular make of servo valve was available which would work from the Citroen hydraulic system and which had a neutral leakage small enough not to overtax the limited output of the vehicle pump.

3. OPERATION OF THE CONTROL SYSTEM

The function of the principal elements in the steering control system, which has to maintain the position of the vehicle over the guidance cable, are shown in Fig. 1. When an excursion from the cable occurs the error sensing equipment at once indicates this by producing a positive or negative-going D.C. error signal proportional to the lateral displacement of the front of the vehicle from the cable, as shown in Block A. If the servo system simply made the front wheel steering angle
proportional to the position error signal, the car's lateral acceleration would tend to be proportional to its positional error, (since at a given speed the lateral acceleration is approximately proportional to the steering angle) and the car would perform a simple harmonic motion about the guidance cable. To provide a damped motion, the error signal is fed into stabilizing circuits, Block B, which add a signal proportional to rate of change of error. To this modified signal is added also a further stabilizing signal from a lateral accelerometer, Block E, mounted in the vehicle; the polarity of this signal is arranged to oppose the original error signal. The sum of these signals defines the front wheel angle required at any instant to correct the course of the car, and the servo system, Block C, angles the front wheels to cancel this demand signal. The vehicle, Block D, then responds to the side thrust of the front wheels until it is once again over the guidance cable, at which point the wheels should be set parallel with the cable.

At the present time, the control system sensitivity, measured under static conditions with the wheels on turn-tables, is fixed at a value of 1° of front wheel steering angle per 61.0 mm of lateral displacement (5° per foot) and has proved satisfactory for indicated speeds of up to 130 km/h (80 mile/h) this being the highest speed obtainable with the present vehicle. It should be noted that the radii of curves on the test track are relatively large (the smallest is 95 m (314 ft)) and consequently the wheel angles used are typically only a few degrees. In order to negotiate curves of small radii calling for maximum wheel lock (which would normally only be used at low speeds) the system sensitivity would have to be some seven times greater for these conditions than is now used. If this level of gain was used as a constant the vehicle would tend to become unstable at higher speeds. This can be simply resolved by modifying the system so that its sensitivity reduces automatically with increasing speed. More details of the servo system may be found in Appendix 1.

4. INSTRUMENTATION AND MEASUREMENT

Instrumentation used whilst running with automatic steering on the test track has been confined to measurements of the vehicle positional error, and the temperature and pressure of the hydraulic fluid. The vehicle positional error is recorded on an autographic chart recorder and this record is used as a check on changes in the vehicle lateral displacement. The hydraulic fluid temperature and pressure are monitored to ensure that the servo valve is running under correct conditions. The fluid temperature is measured at a point where the fluid enters the servo valve by means of a thermocouple connected to an indicating galvanometer. The fluid pressure is measured with a standard Bourdon tube pressure gauge mounted on the vehicle dash board.

5. THE EFFECTS OF INERTIA AND COMPLIANCE IN THE CITROEN STEERING MECHANISM

A number of points have arisen during the conversion of this vehicle to automatic steering caused by the inertia of various masses in the steering system and the back-lash and compliance in the mechanism that joins them together. Some of these may be peculiar to this particular conversion; others would apply generally to any future guided vehicle. The effects are most noticeable in two regions. Firstly, inertia of the steering wheel and compliance and back-lash between it and the steering box servo jack: secondly, compliance in the steering linkage connecting the servo jack to the front wheels. These will be considered separately.
5.1 Steering Wheel inertia

It was noted in the initial experiments that steering servo gain was limited by the 'flywheel effect' of the steering wheel, which oscillated at the end of the steering shaft due to 'wind up' and back-lash in the steering column and steering box. This caused instability to occur under automatic control. An hydraulically operated clutch was fitted in the steering column which automatically disconnected it from the steering when the vehicle automatic steering was working. The use of the clutch permitted an increase of system gain without instability, while giving completely normal steering on manual reversion. An additional benefit of disconnecting the steering wheel was that it also reduced the total steering mechanism inertia by a factor of twelve, because the inertia of the steering wheel when referred to the servo-jack through the steering box, increases as the square of the steering box ratio. The type of problems caused by inertia and compliance will reflect the sort of power source used to drive the steering. For instance, if the source is hydraulic, the likely actuator will be an hydraulic jack most conveniently connected to the steering links at a point between the steering box and front wheels. Here the jack must drive the steering wheel via the steering box with the attendant consequences noted on the Citroen. On the other hand, an electrical power source suggests the use of an electric motor driving, most conveniently, in the region of the steering wheel. In this case however, back-lash and compliance between the steering wheel and steering box must be added to that existing between the steering box and the front wheels. This, in turn, could affect the positional resolution of the front wheels. The total inertia of the steering system as a whole is, of course, the same for both types of actuator except where the steering wheel assembly is disconnected. It is noteworthy in this connection that the guided cars produced by the General Motors Corporation of America such as Firebird III and others have no steering wheels at all; when steered manually, a form of joystick control is used with an electrical output to the steering servo, removing the need for a steering wheel and column assembly and its attendant problems.

5.2 Compliance in the steering linkage between the servo jack and the front wheels

The command signal from the guidance and stabilizing circuits to the steering servo system defines the specific steering angle required by the front wheels to correct the path of the car at any time. The wheel angle has to be given by a D.C. signal from a pick-off attached at some point to the steering linkage of the car, and when the command and wheel angle signals agree, the correct wheel angle will have been obtained. For best servo performance the pick-off should be mounted actually at the front wheel hub where it can indicate steering angle most accurately. In the case of the Citroen, it has not been practical to do this because lack of space round the wheel hub and the shape and geometry of the suspension members prevent the use of a pick-off drive mechanism which respond only to steering movements of the wheels and not vertical wheel movement as well, i.e. it cross couples bump movements and steering movements of the road wheel. This is unacceptable for automatic steering control. To avoid this effect, the pick-off has been mounted on the sprung mass of the car connected directly to a point on the steering linkage partway between the road wheel hub and the steering servo jack. This removes the cross-coupling effects previously mentioned but introduces another problem, that of compliance in the car's steering linkage between the wheel hub and the position of the inboard pick-off. To investigate this problem, tests were carried out in which wheel angles were measured with a temporary, hub-mounted pick-off; the errors due to cross coupling and mechanical difficulties were acceptable for this particular experiment, although they would not be for normal use in the control system. These experiments showed clearly the extent to which compliance existed on the DS.19.
For a given positional command signal when the vehicle was in motion on a curved path, recorded wheel angles were not so great as when, for the same signal, the vehicle was stationary with the front wheels sitting on turn-tables. These differences of measured wheel angle between a moving and stationary vehicle are shown in Fig. 2 and indicate the reduction in actual wheel-steering angle as the lateral acceleration increases and also the irregular way in which it does so. The compliance, therefore, reduces the value of system sensitivity quoted in para. 3.0 i.e. it becomes something less than 1° of front wheel steering angle per 61.0 mm displacement from the guidance cable. The actual steering angle of the front wheels is thus determined by both the steering command signal and the lateral acceleration of the vehicle prevailing at the time. In the case where the vehicle is moving at constant speed along a road which consists of a number of curves of fixed radii joined by transition curves i.e. there are constant demands for changes in steering angle and lateral acceleration, then effects of compliance will influence the lateral ride. In general, the reduction of sensitivity or system gain will cause the car to move farther away from the guidance cable than if the steering linkage were mechanically stiff; and in particular, uniform changes of lateral acceleration will cause non-uniform and sudden changes of wheel angle, as indicated by the irregular shape of the curve in Fig. 2, giving rise to a disturbed lateral ride.

Thus in straight running, where lateral acceleration of ± 0.05 'g' are typical, the quality of steering control is unaffected by compliance. However, a constant speed run on the RRL track at 80 km/h (50 miles/h), requires lateral accelerations of 0.53 'g' on one curve and 0.33 'g' on three of the curves, which brings vehicle performance well within the region of steering compliance, resulting in a more disturbed ride in corners (bearing in mind that 0.53 'g' is greater than that acceptable for normal passenger comfort).

A possible cause of this compliance may lie in the basic configuration of the steering linkage used. The steering jack is placed some 228 mm (9 inches) above the front wheel axle height, within the engine compartment, steering motion being transferred from the jack to the lower level of the hubs by means of relay arms and vertical shafts, giving stress paths of unusual length. This together with the rubber bushes introduced by the manufacturer to reduce the effects of road shocks in the steering, may account for some of the flexibility in this particular steering system.

6. 'FAIL SAFE' PRECAUTIONS

Efforts to make the RRL Citroen as safe as possible, bearing in mind its experimental use, have been aimed at ensuring that, when in the automatic steering mode, it may quickly and easily be restored to manual control by the driver when he feels that the automatic system is going wrong.

The steering force on this particular experimental car is available only when high pressure fluid is admitted to the servo valve and steering clutch jack. This is done by the driver depressing a foot operated switch which energizes the two electric control valves allowing fluid under pressure into the system. Details of the control system are described in Appendix 3. A vehicle electric supply or hydraulic fluid failure will re-engage manual steering. An arrangement is included in which the output of the stabilized power supplies to the guidance and servo system amplifiers are monitored, any deviation of voltage from prescribed limits will likewise de-energize the control valves and re-engage the manual steering.
To offset the effects of either guidance cable or guidance amplifier malfunction, the steering wheel is fitted with an electrical pick-off, the output of which may be used to steer the front wheels via the servo system. Thus, a failure of the guidance command signal resulting in steering bias or absence of control may be overridden by using the steering wheel without switching off the hydraulic supply. This ability to steer the car with the steering wheel through an electrical signal results in purely positional steering devoid of those 'feel' or feedback forces normally present to centre the steering. To introduce some artificial feel a spring loading device attached to the steering column is used; this is described in Appendix 2.

A system for use in operational vehicles has not yet been properly studied; such a study would have to include factors such as, the effects of misuse, cost, redundancy etc as well as the factors previously discussed.

7. ROAD PERFORMANCE

Development running on the test track has been directed to improving vehicle lateral ride and to obtaining a consistent day to day performance. Trials have also been made on wet and snow covered track surfaces. Initially, the estimation of ride quality was fairly well reflected in measurements of vehicle path error, but the ride has reached the stage where it is acceptable to some passengers but not to others, so that the recording of path error may now be of lessening importance in assessing ride quality.

Two typical records of path error taken over the same length of track at the same speed of 64 km/h (40 miles/h) are shown in Fig. 3. One track shows the vehicle stabilized with two stages of phase advance of the error signal and the other shows the effect of additional stabilizing by means of a lateral accelerometer. The record taken with the accelerometer in use has a smoother appearance than the record taken without it, but the vehicle is caused to move away from the guidance cable by a greater amount in corners, because a signal is produced which is proportional to the lateral acceleration and in opposition to the guidance command signal.

Following the curves given in Fig. 3 the vehicle first passes over a point of intersection where two guidance cables cross at right angles; the small kink in the course is clearly indicated. Next, a transition curve giving an increasing curvature of path, which creates an increasing lateral acceleration, terminates in a fixed radius curve of 153.2 m (504 feet). This in turn is followed by a transition curve of decreasing path curvature leading into a fixed radius path of 317 m (1041 feet). The curve is turning to the right causing the vehicle to be displaced to the left of the cable.

There are four reasons for the displacement of the vehicle in a curve:-

(i) In order to turn a corner at all, the geometry of the car demands that the front wheels make a steering angle with the longitudinal axis of the chassis, and the steering servo will only do this when an error signal occurs due to vehicle displacement.

(ii) In order to produce a cornering force, a slip angle must occur at the tyre which causes the wheel to follow a wider radius of path than the actual wheel angle would dictate supposing the tyre had infinite stiffness.
Increasing lateral acceleration demanding increasing cornering force will, in turn, produce greater self aligning torques or centering forces at the front wheels and call for greater steering forces in the linkage to position the front wheels. This, as discussed in Section 5.2, will cause a loss of steering angle due to compliance of the linkage.

The vehicle has a pronounced forward biased weight distribution and consequently understeer handling characteristics. Understeer has been defined by Nordeen\textsuperscript{3} as follows: a vehicle will understeer when the change in steering angle per unit change in lateral acceleration is greater than the change in steering angle per unit change in lateral acceleration for a neutral steering vehicle. That is to say, on a path of constant radius increasing forward speed will demand increasing steering angle at the front wheels. This may only be obtained with the present automatic steering system by creating a greater displacement of the vehicle from the cable.

It follows, therefore, in the case of the relatively simple servo system used on the RRL Citroen, that it is not possible for the vehicle to negotiate a curve without displacement from the cable, and that the greater the forward speed the greater will be the displacement. In the straight running condition, however, the vehicle remains within $\pm 20$ mm ($\pm 0.8$ ins) of the cable; the small perturbations which occur, and which are most noticeable within the vehicle, have a frequency of 0.66 Hz. These may be due to limit cycle oscillations caused by non-linear flow characteristics of the servo valve around its centre position and future development may be expected to reduce the amplitude of these disturbances. The use of a more complex adaptive type of servo system would have the effect of removing the steady state course error in corners bringing the vehicle centre line back over the cable.

7.1 The effect of wet and snow covered surfaces

Whilst most test running has been done on dry road surfaces, wet and snow covered surfaces have also been used.

In dry test conditions indicated speeds of 130 km/h (80 miles/h) have been obtained successfully and although speeds in the wet have not greatly exceeded 100 km/h (60 miles/h) no degradation of ride performance or loss of stability has been noted.

On snow covered surfaces the higher speeds have not been attempted, being held to 55 km/h (35 miles/h) in corners and 100 km/h (60 miles/h) in straight running. However, efforts by a driver to emulate these speeds with manual steering have resulted in loss of control, and it would appear that where surface conditions are slippery, the automatic steering system is more effective in maintaining vehicle stability than a driver. A possible reason for this may be that a driver allows greater vehicle course errors to occur before taking corrective action and, in so doing, demands greater lateral acceleration from his steering inputs than the available tyre road adhesion will allow; thus he loses control of the car. The guidance system, in not permitting gross course errors to occur, is less likely to exceed the available tyre road adhesion, and is therefore, speed for speed, a more effective controlling medium. Plate 1 shows the vehicle running in snow. Frequent passes at various speeds have not greatly broadened the wheel tracks.
7.2 The effects of reinforced concrete

By far the greatest length of road on the research track is of bituminous construction, but on two short lengths reinforced concrete has been used: one is at a point where the road passes over a bridge and underground laboratory whilst the other is where the road curves with a 95 m (314 feet) radius at the foot of a concrete banking. The guidance cable was let into the road surface in a saw cut made after the pavement was laid, and lies under the road surface but above the steel reinforcing mats buried in the concrete.

The effects of the mats on the magnetic field round the cable is both to reduce its strength and to distort its shape in an asymmetrical way, from that of the correct circular form, and is examined in LN/7502. This report also shows the reduction of field strength to be greatest at the centre of a concrete slab and least at the joints. These changes in strength and symmetry of field are falsely interpreted by the car as changes of course error requiring steering corrections. This gives rise to many front wheel steering movements, unnecessary to the proper control of the car, which result in a disturbed ride. Evidence of this may be seen in Plate 2, which shows the wheel tracks made after a single passage of the vehicle at low speed over a snow covered reinforced concrete surface. The frequent changes of wheel angle that have been made are recorded by the edge of the wheel tracks. (The wheel tracks look unusually broad because the vehicle is crab tracked). Work is continuing on this problem and a number of possible solutions are being investigated. The use of a lateral accelerometer in negative feedback has produced some amelioration of the perturbations but cannot be regarded as completely effective in preventing their occurrence.

8. FUTURE DEVELOPMENT

A number of problems remain to be solved before a system of automatic steering may be considered fully developed. These lie broadly within three groups—firstly, work in the area of road installations; secondly, work in the field of vehicle-borne equipment and thirdly, work which involves both.

8.1 Work on road installations

A means must be found to render the magnetic field round the guidance cable as uniform as possible by reducing the effect of intersecting cables and ferrous masses in the proximity of the cable. This is needed to allow running on reinforced concrete surfaces together with an easy transition from such surfaces to bituminous surfaces, and where a cable laid in a bituminous surface, runs over a reinforced concrete or steel structured bridge.

8.2 Improvement in lateral ride and ‘Fail safe’ precautions

The quality of lateral ride may be improved by modifications to the servo valve and, finally, by use of some other vehicle that can offer a stiffer steering-linkage and a better placed front wheel position pick-off, the signal of which will represent more closely the true front wheel steering angle. Further improvements in ‘Fail safe’ precautions might limit the authority of the guidance system, thus preventing the accidental application of full steering lock under automatic control. A need exists also to control and limit vehicle speed, since excessive speed in a curve could demand forces exceeding the available tyre-road adhesion, even though the sensitivity of the guidance system was adequate to cope with such high values. The need to eliminate or reduce steering wheel
inertia also requires reconsideration. To have a vehicle in which the steering wheel is disconnected from the steering mechanism as a whole, may not be acceptable for psychological reasons, even if the problems of expense and reliability were overcome. The effects of torsional flexibility in the steering column might be reduced by using a steering wheel of lighter weight and a reduced steering box ratio, which would still allow permanent engagement of the steering wheel. The driver would have to accept a higher 'gain' steering, with the possible compulsory acceptance of power assistance to keep steering forces within reasonable bounds, when under manual control.

8.3 Work related to road installation and vehicle

A means of route switching will have to be devised enabling vehicles to switch safely from lane to lane and to merge with other traffic.

Although perhaps of less importance, a means may have to be found whereby a driver can 'lock onto' or leave a cable without the exercise of special skills or training, so that he may change from the guided to the manual mode of operation without difficulty. At the present time, a foot operated switch used in conjunction with a dial indicating the position of the vehicle relative to the guidance cable, has been found acceptable to the limited number of drivers who have driven the vehicle but operational systems will have to be developed.

9. CONCLUSIONS

Work with the automatically steered Citroen DS.19 car has confirmed that guidance of a vehicle by means of a buried cable in the road and sensor coils attached to the front of the vehicle is a practical proposition up to speeds of 130 km/h (80 miles/h). The chief problem is that of the quality of the vehicle ride, and the need to make it more acceptable to the passengers. The vehicle system in its present form has not succeeded completely in obviating vehicle yaw. One reason for this could be the non linear flow characteristics of the electro-hydraulic servo-valve over its centre position. In addition, the harshness of the ride experienced when running over surfaces of reinforced concrete construction have not been entirely eliminated and a number of possible solutions are to be investigated. Best results to date have been achieved by using phase advance of the position error signal together with a vehicle-mounted lateral accelerometer.

10. ACKNOWLEDGEMENTS

The author is indebted to the members of the Staff of the Laboratory who were responsible for various aspects of the project, particularly to Mr. J. A. Martin (Group Leader), Mr. S. Penoyre and Mr. J. R. Spindlow. This Report was prepared in the Driver Aids and Abilities Section of the Safety Division.

11. REFERENCES


12. APPENDIX I
DETAILS OF THE SERVO SYSTEM AND SPECIAL EQUIPMENT

A block diagram of the electrical circuits of the servo system is given in Fig. 4 and will be seen to be largely an amplification of Fig. 1 giving more details of Blocks A, B, C, and E in that figure. It is for the most part self explanatory but the following details of the equipment used may be of interest.

12.1 Electrical pick-offs

It will be seen that, whilst the servo system is essentially a D.C. system, with the exception of the accelerometer, all pick-offs are of the A.C. rotary variable transformer type. Earlier attempts to use D.C. potentiometers as pick-offs were abandoned because of their inability to withstand underbonnet environmental conditions. Their performance was badly effected by changes in temperature and humidity, giving rise to drift and noisy signals after only a few minutes running time. No trouble has been experienced with the A.C. type of pick-off.

12.2 Servo system amplifiers

The stabilizing, summing and recorder amplifiers are of the D.C. operational type having chopper stabilization and running from a +12, 0, −12 Volt stabilized D.C. supply. Their frequency response is flat from D.C. to about 1 kHz. The guidance amplifier for the 5 kHz signals is in reality two separate A.C. amplifiers the outputs of which are rectified and subtracted, each A.C. amplifier serving a single sensing coil. The two sensing coils are mounted in front of the car 1090.0 mm (43 in) ahead of the front wheel axle line, 1218.0 mm (48 in) apart and 457.0 mm (18 in) above the road surface. The servo valve torque motor amplifier is a D.C. amplifier having a long tailed pair configuration and running from a +12 Volt D.C. supply.

12.3 Electrical power supply

All electric power used on the vehicle is derived from three separate accumulator systems. These permit the vehicle to be run under guidance for periods of more than a working day without recharging, and have proved reliable in service. The systems are:-

(i) The normal vehicle 12 Volt battery which is used to power the hydraulic fluid supply control valves serving the servo valve and steering column clutch. See Fig. 5.

(ii) A +18, 0, −18 Volt battery, the output of which is stabilized to +12, 0, −12 Volts, and is used to drive summing, recorder, stabilizing and torque motor amplifiers.

(iii) Two 12 Volt batteries which, when used in series, supply a 115 Volt 400 Hz 3-phase DC/AC inverter, whose output is used to drive the AC pick-off amplifier demodulator units and the torque motor position pick-off circuits. The 50 Hz AC 250 Volt inverter used to drive the autographic recorder is run from one of these 12 Volt batteries.
The only servo valve found suitable for embodiment in the Citroen hydraulic system was that made by the Fairey Engineering Company. Basically this valve is of the balanced sleeve type where the edges formed by the ends of a short hollow cylindrical sleeve, sliding between parallel platens, cover and uncover ports machined in the platen surface. The position of the sleeve is controlled by a torque motor operating through a crank and link.

A version of this valve, which is of the four port type, was especially made having exceptionally small working clearances to give a reduced neutral leakage of 90 cm³/min. This called for 2½ micron filtration of the fluid supply.

The servo valve is shown in its hydraulic context in Fig. 6 details of which are self explanatory. It will be noticed, however, that the servo valve is supplied with fluid in parallel with other services on the car. The standard Citroen hydraulic system is protected only by a 47 micron nylon mesh filter and is remarkably tolerant of dirt in the fluid. To protect the servo valve it has been found necessary to use both a 5 micron and a 2.5 micron filter in series to prevent the valve seizing up due to contamination of the fluid. In an exclusive fluid supply less stringent filtration would be required, since the fluid, due to constant recirculation, would clean itself.
13. APPENDIX II

DETAILS OF THE MECHANICAL MODIFICATIONS TO THE STEERING MECHANISM

Modifications to the steering mechanism have been concerned with two items:-

(i) The design and insertion in the steering column of a clutch which may be depended upon always to engage when required; either automatically in an emergency or at will when desired by the driver, and

(ii) A device designed to apply a centering force to the steering wheel so that, when in the uncoupled state, the latter will position itself with the output of its electrical pick-off at zero to provide a means of aligning the system. This also ensures that when the driver transfers from a mechanical to an electrical steering input he shall know what output to expect from the steering wheel by virtue of its position and 'feel' forces.

13.1 Details of the steering column clutch and modification to the steering pinion assembly

The Citroen steering control valve and pinion were removed from the rack assembly, which contains the hydraulic jack, and were replaced by the directly coupled type of pinion used in the Citroen 1D model; the supply and return hydraulic fluid lines were connected to the electro-hydraulic servo valves.

A specially designed clutch was fitted into the steering column, details of which are shown in Fig. 7 and Plate 3. In this device a collar, sliding on the column, is used to lock eight 7.14 mm (9/32 in) diameter steel balls, located in the driving member, into 8 matching recesses in the driven member, by means of a ramp machined on the collar's inside diameter. The clutch is spring urged into engagement and is released by means of a small hydraulic jack which overrides the spring force.

Axial movement is imparted to the collar by means of a forked lever, but once the collar is driven over the balls, they are locked in position and the forked lever becomes redundant. A lack of fluid pressure at the jack, due either to supply failure or control operation, allows the spring to engage the clutch; the two parts of which need never rotate more than 1/16 of a turn relative to each other before the balls start to lock into the adjacent recesses. Thus the clutch will re-engage even though there is relative motion between driving and driven members.

13.2 Details of the steering wheel centering device

A degree of self centering action has been applied to the steering wheel by means of the steering column mounted device shown in Plate 4. Rotation of the steering wheel in either direction from centre, causes a steel wire to be wound onto a drum clamped to the steering column, having first passed between a pair of rollers mounted on a torque reaction member. The wire, which runs over pulleys to the front of the car, is tensioned by pre-stressed rubber cords. Because space was not available to house a steel spring of appropriately low load-extension characteristics, the rubber cords were used in conjunction with a correction pulley to give a force/deflection relationship in the steering wheel similar to that of a normal vehicle. A view of the spring and force correction cam may be seen in Plate 5.
14. APPENDIX III

14.1 Details of the operating controls and 'fail safe' systems of the Guided Vehicle

As was stated in paragraph 5.4 the electronic systems in the vehicle run continuously when the vehicle is to be used on automatic guidance. The selection of the mode of operation lies with the driver who permits high pressure fluid to enter the servo system for the automatic control mode by energizing two, two-way, normally closed, solenoid operated hydraulic valves marked A and B, shown in Figs. 5 and 6 in their electrical and hydraulic contexts respectively. Control valve A admits fluid to the servo valve, while control valve B admits fluid to the steering column clutch jack. The valves may be energized jointly or severally through switches S1 and S2 which operate relays RLA and RLB respectively through floor mounted switches S3 and S4 in series, the latter being provided so that either the passenger or the driver may 'kick out' the system. Current is fed to the valve solenoids via contacts A1 and B1 which are in series with contact C1. Relay RLC is held closed by a current supply from a special unit which monitors the output of the +12, 0, −12 Volt D.C. stabilized power supply to the amplifiers. Small changes in the correct value of 24 volts, due either to malfunction of the stabilizing units or lack of battery charge, causes relay RLC to open, closing valves A and B, and allowing the steering to revert to manual control. Furthermore, valves A and B and the relays are powered by the vehicle 12 Volt battery, therefore, a vehicle electrical failure will equally cause the control valves to revert the steering to manual control.

Fig. 6, showing the hydraulic circuit, is self evident but the use of hydraulically operated valve C will be noted. When the steering is in the manual mode, valve C short-circuits the two ends of the jack permitting a free flow of fluid between them and prevents the formation of a hydraulic lock. In the automatic mode admission of high pressure fluid to the servo valve closes this by-pass channel. In the event of an hydraulic supply failure valve C will re-open allowing the steering jack to move freely under manual control.
FIG. 1. BLOCK DIAGRAM SHOWING OPERATING PRINCIPLE OF STEERING CONTROL SYSTEM
Fig. 2. Steering angle position errors at the front wheels of a Citroen DS19, when cornering, due to compliance of the steering mechanism. Vehicle speed 48 km/h (30 mile/h)
Fig. 3 TYPICAL RECORDS SHOWING DISPLACEMENT OF THE GUIDED VEHICLE FROM THE GUIDANCE
VEHICLE SPEED 64km/h (40 mile/h)
FIG. 4. BLOCK DIAGRAM OF ELECTRONIC CONTROL CIRCUITS
**Fig. 5. ELECTRICAL CIRCUIT FOR HYDRAULIC CONTROL VALVES USED ON THE AUTOMATICALLY STEERED CAR**
Fig. 7. Details of Steering Column Clutch
PLATE 1

The Citroen DS 19 car running in a corner under automatic guidance control on a snow covered surface. The speed is 56 km/hour (35 mile/hr).
PLATE 2

Slow speed wheel tracks of the guided car made on a snow covered reinforced concrete surface
PLATE 3

The steering column clutch and actuator installed on the RRL Citroen DS 19 car.
(View with radiator removed)
The steering wheel centering force device fitted to the steering column of a Citroen DS 19 car.
PLATE 5

The rubber cord spring and force correction pulley used to control the steering wheel of the automatically steered car.

(1638) Dd635272 2,750 11/70 H.P. Ltd. G1915
PRINTED IN ENGLAND
ABSTRACT

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Crowthorne, 1970 (Road Research Laboratory). The Road Research Laboratory has
equipped a car with an experimental automatic steering system to study the feasibility of
automatic vehicle control. The car, a Citroen DS. 19 chosen for its high pressure hydraulic
system, is capable of following a buried cable energized with a 5 kHz current. An electro-
hydraulic servo mechanism has been installed to steer the front wheels.

Speeds of up to 130 km/h (80 miles/h) have been obtained on dry surfaces and 100
km/h (60 miles/h) on snow covered surfaces without loss of control.

Development work has been directed to preventing the car 'hunting' over the cable
and to improving vehicle lateral ride. The vehicle normally stays within ± 20 mm of the
cable in straight running but on a curved path it is deflected to one side of the cable,
by up to 130 mm or more depending on vehicle speed and radius of path curvature.

Details of the servo and sensing systems used are given with an account of the
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