4.2 Variable-Assist SBW 2WS Conversion Mechatronic Control Systems

4.2.1 Essentials of SBW 2WS Conversion Mechatronic Control Systems

An automotive M-F-M FPS, E-M-F-M EFPS or E-M EPS SBW 2WS conversion enhances steering performance and betters the feel of the steering and power-saving efficiency. It does so with conversion mechatronic control mechanisms that decrease the steering effort. An automotive FPS, EFPS or EPS SBW 2WS conversion mechatronic control system is joined to the M-F-M, E-M-F-M or E-M booster actuator, respectively. The intention of FPS, EFPS and EPS SBW 2WS conversion mechatronic control systems was originally, to reduce the steering effort when driving at low values of vehicle velocity and to provide a feedback loop for the proper steering reaction force when driving at high value of vehicle velocity. To reach those objectives, automotive velometers or speedometers are employed as vehicle velocity sensors to measure vehicle velocity according to any variations in the steering assist rate under circumstances differing between certain limits from steering manoeuvres at zero value of vehicle velocity to those at high values of vehicle velocity. Nevertheless, as vehicles became supplied with E-M booster actuators and smart E-M EPS SBW 2WS conversion mechatronic control systems, the affirmation for these systems initiated the diminution in power demands and superior performance. The important normal actions needed for SBW 2WS conversion mechatronic-control systems are listed in Table 4.2 [SATO 1995].

Table 4.2 Requirements for SBW 2WS Conversion Mechatronic-Control System

Attenuation of driver's nuisance when turning the hand steering wheel and betterment in the steering feel	**Foolproof**
➢ Decrease in steering effort ➢ Ease of steering operation ➢ Feedback of correct reaction steering forces ➢ Decrease of kickback [SATO 1991] ➢ Betterment in convergence [NISSAN 1991] ➢ Energy saving ➢ Formation of other innovative functions	Sustaining of manual steering function in the case of any malfunctions

Single Axle SBW 2WS Conversion Mechanism Normally, the aim of the single axle SBW 2WS conversion mechatronic control system is simply that of making available a mechatronic means whereby the driver may locate the vehicle as exactly as possible where the driver wants it to be situated on on/off road, for the

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Intelligent Systems, Control and Automation: Science and Engineering 52,
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selection of the course needed to steer round corners, and so that the driver can avoid other on- and/or off-road users and obstacles.

On the other hand, it must also keep the automotive vehicle stably on course irrespective of deformities in the surface over which the vehicle is roving. For the achievement of these basic aims, the first requirement is that, when the vehicle is moving very slowly, all the wheels should roll correctly, that is, without any lateral slip.

In Figure 4.33, motion of the wheel along YY is rolling; along XX it is slipping [NEWTON ET AL. 1989].

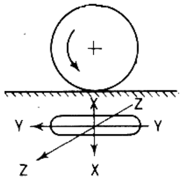


Fig. 4.33 Motion of the wheel [NEWTON ET AL. 1989].

In view of the fact that for all the wheels on a vehicle to roll in reality, they must all move in the same direction perpendicular to their lateral axes. These axes must all intersect at a common point.

If the vehicle is on a straight course, this point will be '*ad infinitum*', that is, the axes will be parallel. However, if the vehicle is turning a corner, this point will be, for all time, situated in the centre of the vehicle as the whole is turning, and the tighter the turn the closer it will be to the vehicle. If not both the front and rear wheels are to be steered --impractical on difficult terrain, except in particular conditions, for example on vehicles having more than eight wheels, where it may be practically unavoidable -- the common centre must be positioned everywhere along the lines of the axis created from the fixed rear axle. As may be seen from Figure 4.34 [NEWTON ET AL. 1989], this indicates that when the front wheels are steered, their axes must be turned through different angles and consequently the point $P(x_0, y_0)$ of their intersection is created each time on that axis.

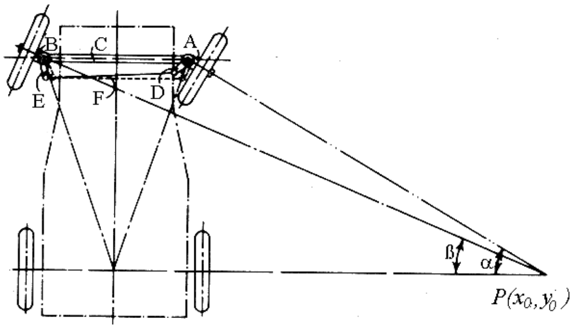


Fig. 4.34 A double-track full vehicle physical model of the coordinated *Ackerman* SBW 2WS principle [NEWTON ET AL. 1989].

A beam axle pivoting the whole axle assembly about a vertical axis midway between its ends can do this. On the other hand, such an arrangement is impractical for all but very slow vehicles. Normally, the wheels are carried on stub axles A and B in Figure 4.35 [NEWTON ET AL. 1989]. Except with autonomous suspension, these stub axles are pivoted on the ends of the axle beam C that, since it is linked by the road springs to the chassis frame, continues in reality parallel to the rear axle, as displayed in the illustration.

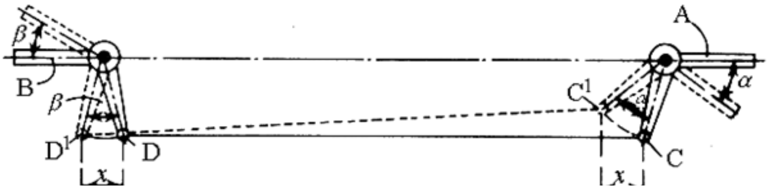


Fig. 4.35 Stub axles steered differentially by *Ackerman* linkage [NEWTON ET AL. 1989].

With autonomous suspension, the rule continues in the same way, albeit the mechanism is completely different. The arms D and E together with their coupled stub axles form what amounts to bell crank levers pivoted on the kingpins and are used for coupling the two wheels so that they move together when they are steered. These arms are called the '*track arms*' and are interconnected by the '*track rod*'. The actual steering is generally caused by a connecting link, termed a '*drag link*', between the steering gear and either what is called the '*steering arm*' on the adjoining stub axle assembly or, in some instances, part of the track rod system.

Ackerman Linkage - From Figure 4.34 it may be seen that there is a difference between the angles α and β in that the wheels on the inside and outside, respectively, of the curvature have to be turned. In reality, this difference is realised by setting the arms D and E at angles such that, in the straight ahead position, exposed dotted lines are drawn through the centres of the two pivots on each intersection near the centre of the rear axle. The precise position of this intersection points rely on the correlation between the wheelbase and track, and other factors.

From Figure 4.35 [NEWTON ET AL. 1989] it may be seen how the stub axles are steered differentially by this linkage, the full lines representing the straight ahead and the dotted lines a steered circumstance.

In the latter, the stub axle B has turned through an angle β and the end D of its track arm has moved to D^1, a distance x parallel to the axle beam. Ignoring the slight angle of inclination of the track rod, it follows that the end C of the other track arm must move the same distance x, parallel to the axle beam. This, on the other hand, entails movement of arm C through a greater angle than D, because the latter is swinging across the dead centre of the base, as depicted in the illustration, while the former is moving further from its related lowest point.

Even if, for realistic reasons, these arms may have to be curved, possibly to clear some other part of the wheel or brake assembly, the effective arm continues that of a straight line joining the centres of the kingpin and the pivot at the contrary end.

Figures 4.34 and 4.35 illustrate the track rod at the rear of the axle, but exceptionally it is in front, again with precisely inclined arms.

A feature of inserting it to the rear is the protection provided by the axle beam, but it is then loaded in compression and, as a result, must be of inflexible structure.

Conversely, when it is in front, complications is normally arise when giving clearance between its ball joints and the wheels.

With *Ackerman* SBW 2WS, the wheels really roll in no more than three positions – straight ahead or when turned through a particularly selected angle to the right and left. However, in the last two positions, rolling takes place only at low values of vehicle velocity. At all other angles, the axes of the front wheels do not intersect on that of the rear wheels, while at the higher values of vehicle velocity, the slip angles of the front and rear tyres normally alter and definitely those of the tyres on the outside may always alter from those of the inside of the curvature.

In all cases, the slip angle on both the front and rear wheels have the consequence of turning their real axes forward.

Linkages providing almost precise static steering geometry on all curls have been invented; they are complicated and in reality have not shown to be satisfactory because they cannot consider the difference in slip angle.

The *Ackerman* rule, derived from the best realistic compromise – as a rule slip angles are understood to be equal on all four wheels – is acceptable in reality, perhaps for the reason that flexing of the tyres contains the errors.

The Steering Hand-Wheel (HW) Angle--Torque Characteristics -- According to SHIMOMURA ET AL. [1991], in a mechanical steering system, the steering HW angle-torque (d_h - T_h) characteristic is clearly one of the most important items that influence the driving feeling. The d_h - T_h characteristic is influenced by the vehicle velocity, the wheel-tyre properties, the suspension parameters, and the on/off road surface, namely:

$$T_h = f(d_h, V, \text{Wheel-Tyre Properties, Suspension Geometry, On/Off Road Surface})$$

In a SBW 2WS conversion mechatronic control system, different steering feelings may be obtained by modifying the d_h - T_h characteristic (Fig. 4.36) [SHIMOMURA ET AL. 1991; DOMINGUEZ-GARCIA AND KASSAKIAN 2003].

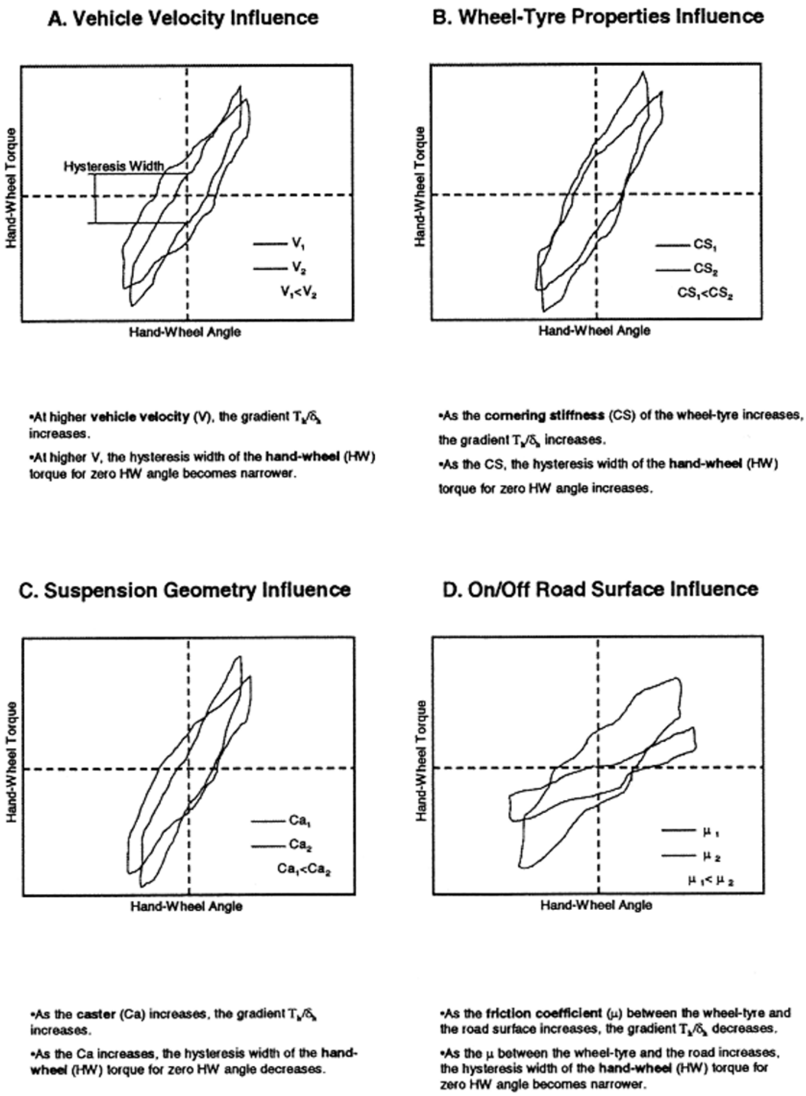


Fig. 4.36 The hand-wheel angle vs.torque characteristics:
vehicle velocity influence (A); wheel-tyre properties influence (B);
suspension geometry influence (C); on/off road surface influence (D).
[SHIMOMURA ET AL. 1991; DOMINGUEZ--GARCIA AND KASSAKIAN 2003].

4.2.2 Categories of the SBW 2WS Conversion Mechatronic Control Systems

FPS, EFPS and EPS SBW 2WS conversion mechatronic control systems that may be soon enter production may be arranged systematically, in order of their fundamental structure and principles, into four types: full M-F-M, E-M-F-M and E-M ones, as displayed in Table 4.3. Particular explanations of these SBW 2WS conversion mechatronic control systems are also given in the table [SATO 1995].

Table 4.3 Categories of SBW 2WS Conversion Mechatronic-Control Systems [SATO 1995].

Fundamental structure		M-F-M FPS SBW 2WS conversion mechatronic control system				E-M-F-M EFPS SBW 2WS conversion mechatronic control system	E-M EPS SBW 2WS conversion mechatronic control system	
Mechatronic control methods		Oily-fluid or air flow	Power F-M cylinder bypass	Fluidic valve characteristics	Fluidic reaction force mechatronic control	Oily-fluid or air flow	E-M motor voltage	E-M motor current
Mechatronic control objects		Oily-fluid or air flow supply to power F-M cylinder	Effective actuation oily-fluid or air pressure given to power F-M cylinder	Oily-fluid or air pressure generated at mechatronic control value	Oily-fluid or air pressure acting on the fluidic reaction force mechanism	Oily-fluid or air flow supply to power F-M cylinder	E-M motor power	E-M motor torque
Automotive vehicle sensors	Vehicle velocity	☺	☺	☺	☺	☺	☺	☺
	Angular velocity					☺	☺	
	Steering torque				☺		☺	☺
	Electric current	☺	☺	☺		☺	☺	☺
Actuator		Solenoid fluidic valve	Solenoid fluidic valve	Solenoid fluidic valve	Solenoid fluidic valve	Linear or rotary E-M motor	Linear or rotary E-M motor	Linear or rotary E-M motor
Major effects	Steering force responsive to vehicle velocity	☺	☺	☺	☺	☺	☺	☺
	Energy saving					☺	☺	☺

4.2.3 Description of SBW 2WS Conversion Mechatronic Control Systems

Current SBW options available include E-M, M-F-M or E-M-F-M actuation. Sensors may be required for steering position and velocity both at the steering HW and the road wheels.

Torque measurements may be required for the road wheels as well as for the steering HW if force feedback is required.

Feedback may not be required for early prototypes but would certainly be required in a production situation in order to give the driver meaningful information about what is happening at the road wheels.

Other sensors and information may also be required, such as wheel speeds, lateral acceleration, yaw rate, and so on for the system's self-calibration and other features.

Steering actuation may be achieved through several methods. An easy way is to replace the input from the steering column into the steering rack with that from an E-M motor (Fig. 4.37), whilst retaining the PS [JB 2004]. This may require a reduction through a gearbox to achieve the required torque and speed, but the E-M motor may be relatively small and run off the standard 12 V_{DC} power supply.

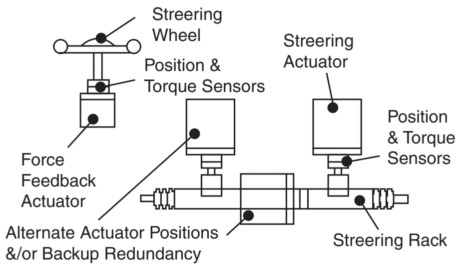


Fig. 4.37 Electro-mechano-fluido-mechanical (E-M-F-M) actuation [JB 2004].

This solution provides an easy method of modifying a current vehicle to SBW, provided there is space for the E-M motor, but still suffers from the package, mass, and fuel economy that the fluidics (hydraulics) of a PS system bring.

The fluidics only method makes use of the power assisted steering rack to provide the steering actuation with a series of fluidical valves to provide control over the rack position (Fig. 4.38) [JB 2004].

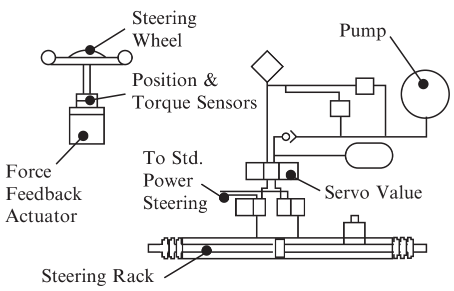


Fig. 4.38 Mechano-fluido-mechanical (M-F-M) actuation [JB 2004].

Again this solution provides an easy method of modifying a current automotive vehicle to SBW but still suffers from the package, mass, and fuel economy that the fluidics (hydraulics) of a PS system bring. The next step is to completely remove the M-F-M system and replace it with a direct drive from an E-M motor of sufficient power. This may be done with one E-M motor controlling both wheels through a steering rack or with one E-M motor per wheel providing independent control of each road wheel (Fig. 4.39) [JB 2004].

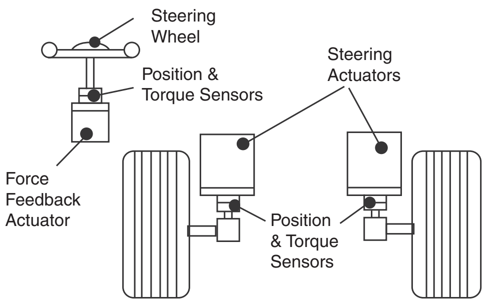


Fig. 4.39 Electro-mechanical (E-M) actuation [JB 2004].

With the need for redundancy, the ability to have twin actuation for the steering imposes additional restrictions on the above architectures.

The M-F-M only system, whilst acceptable for a prototype, becomes complicated for production implementation with the need for two M-F pumps, two racks or fluidical chambers within the rack, and two sets of control fluidical valves.

Packaging, cost, and complexity become a large issue. For the E-M-F-M system, the issue is compounded by the fact that the PS fluidics (hydraulics) and the E-M motor would be unnecessary.

If the PS was to fail in a standard vehicle, it is considered to be reasonable that the driver would still have sufficient energy to maintain a level of control over the vehicle. Here the E-M motor be designed to complement the PS and would therefore be insufficient to control the steering without assistance. The E-M motor could be sized to cope with this but then the system would be almost equivalent to the E-M implementation [JB 2004].

Mechatronic Control Architecture -- Once again the safety case dictates that the mechatronic control is fail safe and therefore must be somewhat unnecessary. As developed from the *Markov* model [Hammett et al. 2003], this could even be a dual-dual or triplex mechatronic control system (Fig. 4.40) [JB 2004]. An important factor in determining the mechatronic control system is not only the ability to detect failures, but also to determine what the failure is. For example if there are two position sensors in the system and if one fails, it could be obvious that they are different but how do you tell which one is correct?

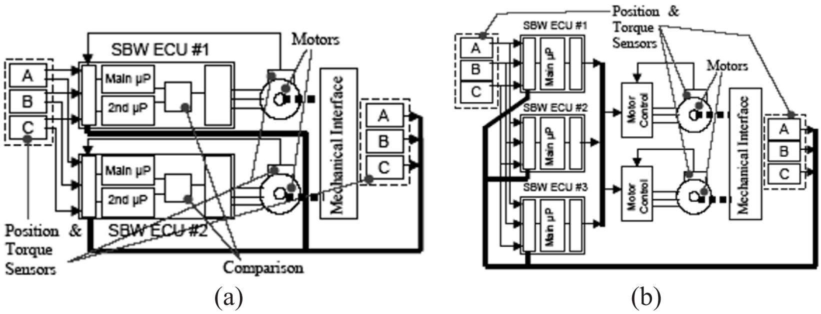


Fig. 4.40 Mechatronic control architecture: (a) -- dual-dual SBW 2WS conversion mechatronic control system; (b) -- triplex SBW 2WS conversion mechatronic control system [JB 2004].

Sensors -- The SBW 2WS conversion mechatronic control system requires measurements of angular position, angular velocity, and torque from both the steering wheel (that is, the driver's input) and the road wheels in order to provide suitable information to the controller for correct operation.

Other data such as yaw rate and lateral acceleration may allow additional features such as stability control and steering correction. These signals must be accurate and have good resolution to allow the system to perform well. In addition, for SBW at least one sensor at the steering HW and road wheels should be capable of measuring the absolute angle over the complete steering range.

These sensors must also be dependable (not affected by their age or environment), reliable, and conform to the usual package and cost considerations, and so on.

Suitable sensors are likely to be of the on-contact variety with optical and magnetoresistive sensors providing good performance and reliability.

The exact sensor and technology though is likely to rely on many factors dependent on the specific application [JB 2003].

Actuators -- The SBW 2WS conversion mechatronic control system requires the use of actuators for two purposes. The first is to provide the correct positioning and sufficient force to control the steering rack. The second is to provide meaningful feedback to the driver through the steering HW. Both require good performance in both power/torque and accuracy. This is currently best achieved through the use of brushless DC-AC macrocommutator IPM magneto-electrically-excited steering-actuator motors, likely to be of a higher voltage than the standard 12 V_{DC} for **energy-and-information networks** (E&IN) (e.g. 42 V_{DC}). Although this would not necessarily be required for feedback, it certainly would for the steering actuation. This could be achieved through a number of solutions including twin E-M motors connected via a gearbox or twin wound E-M motors sharing the same package. These E-M motors may need to be powerful enough to achieve sufficient steering force. Again, specific application may determine the exact requirements for the actuator [JB 2003].

Power Supply -- There are two main requirements for a SBW power supply: sufficient power for the steering actuators and redundancy. This may require dual power systems (two M-E generators, two storage batteries, two looms, and so on).

The main power system may have to be of a voltage higher than the standard 12 V_{DC} **electrical energy distribution** (EED) systems in order to provide the required performance (e.g. 24 V_{DC}, 42 V_{DC}, or higher).

With the need for a 12 V_{DC} for the main EED systems, this could then provide the required redundancy (albeit at a reduced level of performance).

The power wiring may have to be protected against single-point failure. This may require multiple wires from the power supplies to the critical components, wires routed separately, independent protection for the separate wires, and switching to the use of separate wires [JB 2004].

M-F-M FPS SBW 2WS Conversion Mechatronic Control System -- This mechatronic control system is composed of a linear electro-magneto-mechanically operated solenoid fluidical valve, a vehicle velocity sensor, and other automotive mechatronic devices situated in part of the fluidical circuit of the M-F-M FPS SBW 2WS conversion mechatronic control system (see Fig. 4.41) [HITACHI 2004].

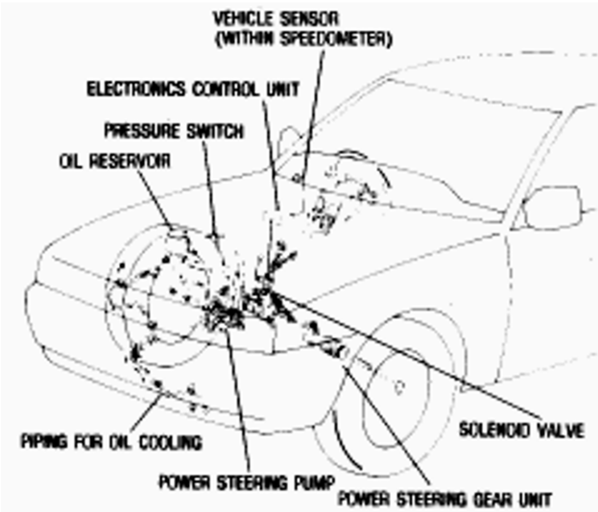


Fig. 4.41 Oily-fluid pressure M-F-M FPS SBW 2WS conversion mechatronic control system [Hitachi Co; HITACHI 2004].

The flow of oily fluid to the F-M cylinder is decreased when driving at high values of vehicle velocity, with the intention that for this mechatronic control system, the magnitude of the steering response rate and the steering reaction force are equal in value at the point of balance. FPS SBW 2WS conversion mechatronic control systems are capable of mechatronically adjusting the steering force according to vehicle velocity, and are used primarily in luxury vehicles.

For instance, a **vehicle-velocity responsive power steering** (VRPS) SBW AWS conversion mechatronic control system may be capable of adjusting steering force by controlling the oily-fluid pressure using fluidical valves according to the vehicle velocity (Fig. 4.42) [HITACHI 2004].

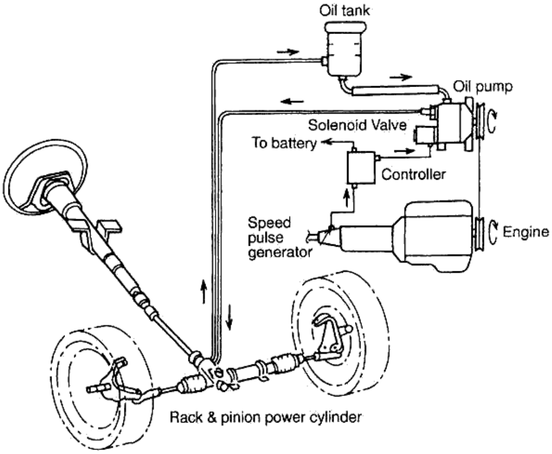


Fig. 4.42 Vehicle velocity-responsive M-F pump discharge oily-fluid–flow volume mechatronic control system [SATO 1991]

This, as shown in Fig. 4.43, requires a relatively simple fluidical valve structure and makes possible highly responsive steering because it converts the oily-fluid flow supplied by an M-F pump to a pressure that efficiently operates an F-M cylinder (a linear F-M motor) [HITACHI 2004].

Fig. 4.43 Fluidical power steering (FPS) – vehicle velocity responsive type [Hitachi Co.; HITACHI 2004].

Power F-M Cylinder Bypass M-F-M FPS SBW 2WS Conversion Mechatronic-Control System **--** In this mechatronic control system, a fluidical valve's solenoid and a bypass line are situated between both fluidical chambers of the power F-M cylinder [NISSAN 1991B]. The turning on of the fluidical valve's solenoid is expanded by the ECU in conformity with gains in vehicle velocity, thus weakening the pressure in the power F-M cylinder and increasing the steering effort. Similar to the oily-fluid flow mechatronic control system, this system may also try to reach the equilibrium point for the steering response rate and the steering reaction force [SATO 1995].

Rotary Fluidical Valve Characteristics M-M FPS SBW 2WS Conversion Mechatronic Control System **--** In this mechatronic control system, the oily-fluid-pressure control limitations of the rotary fluidical-valve mechanism that controls the volume and pressure of the oily-fluid provided to the power F-M cylinder, are separated into second and third parts. A fourth part, controlled by means of the vehicle-velocity signal, is supplied in the fluidical line between the second and third parts, fulfilling variable control of the fourth part to vary the assistance ratio controls of the steering effort. Since the structure is unsophisticated and the oily-fluid flow from the M-F pump to the power F-M cylinder is provided effectively without dissipation, this mechatronic control system demonstrates a satisfactory response rate. For example, when a value of the electric current is about 300 mA, the solenoid fluidical valve is fully turned on and this demonstrates the high value of vehicle-velocity driving [SATO 1995].

Fluidical Reaction-Force M-F-M FPS SBW 2WS Conversion Mechatronic-Control System -- In this mechatronic control system, the steering effort is controlled with the aid of a fluidical reaction-force mechanism that is situated at the control rotary fluidical valve. A control rotary fluidical valve increases the reaction oily-fluid pressure leading to the reaction force fluidical chamber in uniformity with intensities in vehicle velocity. The stringency of the fluidical reaction force mechanism (equivalent spring constant) is variably controlled to directly control the steering effort. This system requires a reactive-force mechanism that makes the structure of the control fluidical valve more sophisticated but radically increases the cost. On the other hand, because the stiffness of the reaction-force mechanism rises in conformity with escalations in vehicle velocity, there is no difference in the steering feel in the section around the basic steering position. Since this mechatronic control system gives the steering reaction force without regard to the volume of oily-fluid provided to the power F-M cylinder, the magnitude of the steering reaction force may be adjusted independently without requiring substitution any of the steering response rates [SATO 1995].

4.2.4 Hybrid E-M-F-M EPFS SBW 2WS Conversion Mechatronic Control System

For SBW 2WS conversion mechatronic control systems, the most likely approach may be to implement the E-M-F-M EFPS option (Fig. 4.44) [JB 2003]. In actual fact, the PS on the automotive vehicle is likely to be mechatronic so the implementation may follow the philosophy discussed for the E-M-F-M architecture but may in fact have no fluidics (as power assist is electrical). These options allow the implementation of SBW on the vehicle without the need for major modifications to the vehicle's current steering from the rack down. The lack of FPS on the vehicle also prevents an M-F-M-only solution.

An additional benefit of using the E-M-F-M approach for the SBW 2WS mechatronic control system is that it may have a failsafe option.

This approach also avoids the need to source expensive and/or hard to obtain parts such as high-power E-M motors for the steering, whilst proving the concept and developing a model for potential production.

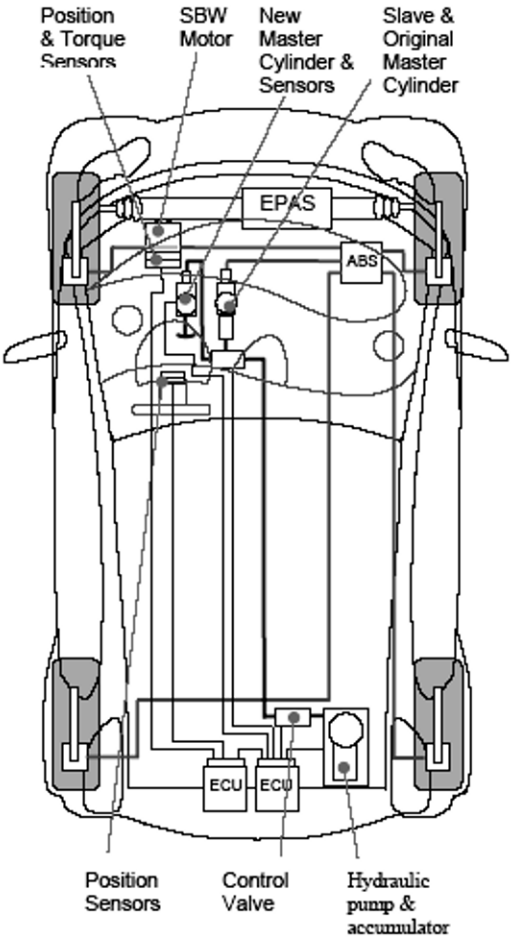


Fig. 4.44 Proposed Pininfarina *Autosicura* prototype implementation [JB 2003].

The SBW 2WS conversion mechatronic control system would consist of the M-F-M actuation shown in Figure 4.37 in the form of an E-M implementation (as the power assist may be electrical).

At least dual position sensors would be required for both pinion and steering HW angle although this would be confirmed by a safety case analysis. In addition, a torque sensor at the pinion or a rack force sensor would be required.

For the initial implementation it may not be necessary for force feedback of the steering, therefore not requiring an actuator or torque sensor at the driver interface. This functionality could be added at a later date though.

With the SBW 2WS conversion mechatronic control systems requiring a control ECU of some kind, there is the possibility of using each ECU as the other's backup, or one ECU as the master for SBW and the second as a safety monitor.

There are several suitable rapid prototype ECUs capable of performing this function, for example, PiTechnology's *Open* ECU [JB 2003].

The main power supply for the SBW 2WS conversion mechatronic control system would come from the vehicle's 12 V_{DC} supply.

As the steering main actuators would be F-M, there would be no need for a secondary power supply system; although a small secondary storage battery could be installed for the SBW ECUs using a split charge system with the vehicle's current AC-DC macrocommutator electromagnetically-excited generator. This again would be determined by safety and vehicle review.

Below (Fig. 4.45) is a high-level overview of the control strategies intended for the suggested SBW 2WS conversion mechatronic control systems [JB 2003].

This structural and functional block diagram is meant to give a basic understanding of the control strategy and therefore does not include safety monitors, diagnostics, fallback mechanisms, as well as redundancy and so on.

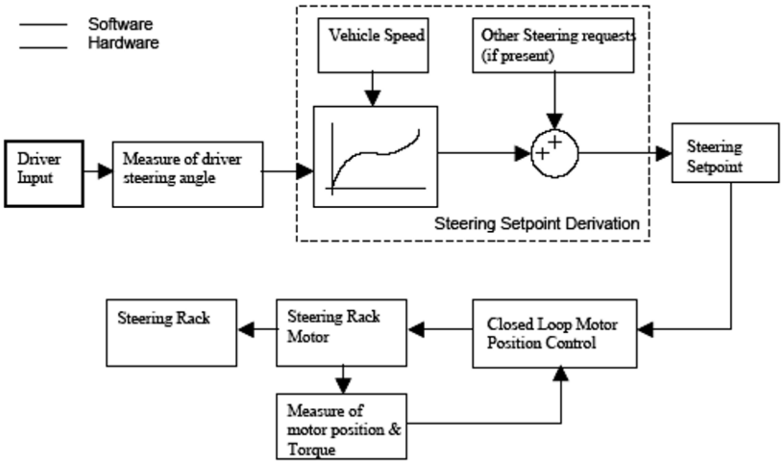


Fig. 4.45 Structural and functional block diagram of the SBW 2WS conversion mechatronic control system [JB 2003].

Hybrid E-M-F-M EFPS SBW 2WS conversion mechatronic control system for new passenger vehicles (Fig. 4.46) [TRW 2003] combines an electrically driven E-M-F pump with conventional R&P steering to give the most precise handling and steering assistance using minimal energy consumption. This mechatronic control system uses an oily-fluid-flow control method in which the power steering E-M-F pump is driven by an E-M motor. The steering effort is controlled by regulation of the angular velocity of the E-M-F pump's rotor, that is, the discharge.

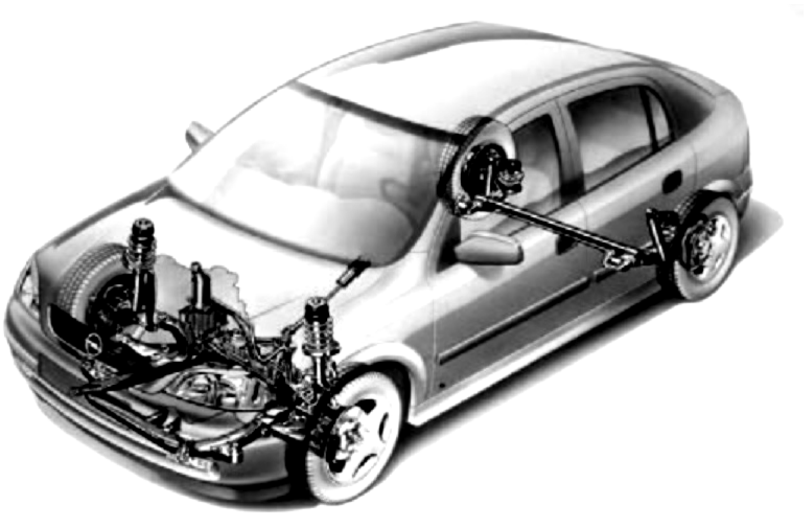


Fig. 4.46 Hybrid E-M-F-M EPFS SBW 2WS conversion mechatronic control system for the new Opel *Astra* [TRW 2003].

The driving efficiency of the M-E generator and E-M motor are related to that of the M-F pump which is driven by the vehicle's ECE or ICE and/or F-M, P-M or E-M motor(s).

Nevertheless, because any residual flow is not discharged, the power loss is lower than that of the ECE or ICE M-F pump when driving at high velocities.

For the reason that the vehicle's ECE or ICE and/or F-M, P-M or E-M motor(s) does not drive the E-M-F pump, there is also a great degree of freedom in the choice of mounting places for the E-M-F pump.

Driving Mode Responsive Hybrid EFPS SBW 2WS Conversion Mechatronic Control System -- In this mechatronic control system, it is composed of a vehicle-velocity sensor, steering-angular-velocity sensor, an ECU, and an E-M motor driven E-M-F pump, as illustrated in Figure 4.47 [IGA ET AL. 1988].

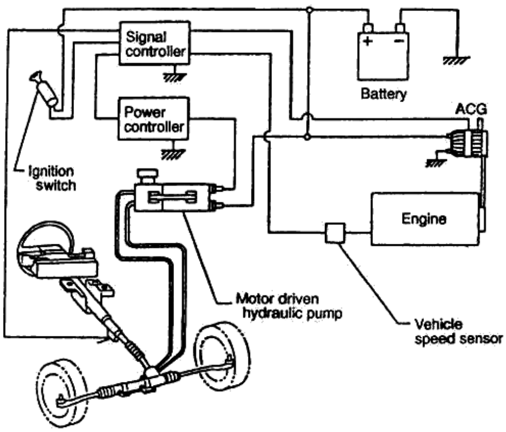


Fig. 4.47 Driving mode-responsive hybrid EPFS SBW 2WS conversion mechatronic control system [IGA ET AL. 1988]

Driving situations; such as driving in urban areas, country areas, winding regions, or highways; are instinctively deduced, and the E-M-F pump flow rate is controlled uniformly in order to provide proper steering effort for driving situations. Sensitive control adjustments are achieved with the aid of this mechatronic control system when related to the previously mentioned vehicle-velocity responses [SATO 1995].

Steering Wheel Angular-Velocity Responsive EFPS SBW 2WS Conversion Mechatronic Control System -- This system contains component parts such as vehicle-velocity sensor, steering wheel angular-velocity sensor, an ECU, and an E-M motor-driven E-F-M pump, as illustrated in Figure 4.48 [HONDA 1991].

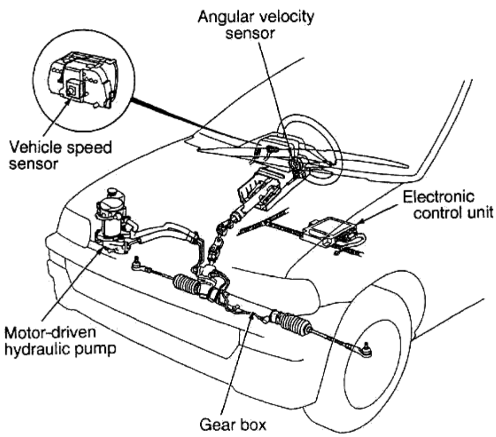


Fig. 4.48 Steering velocity-responsive hybrid EPFS SBW 2WS conversion mechatronic control system [HONDA 1991].

As mentioned above, the discharge flow volume of the E-M-F pump decreases and the steering response decreases when the vehicle is driven at high velocity. Consequently, in this mechatronic control system, the angular velocity of the E-M motor's rotor becomes more uniform with the sensed angular velocity of the steering HW according to the increasing discharge flow volume.

Correspondingly, power loss resulting from the dispersion of residual oily-fluid flow within the system are maintained to a minimum satisfactory level, and the magnitude of the reaction force may be controlled independently without neglecting any of the steering response ratios [SATO 1995].

4.2.5 E-M EPS SBW 2WS Conversion Mechatronic Control System

During the last few years, the automotive industry has focused efforts on the development of E-M EPS SBW 2WS conversion mechatronic control systems. Among the main advantages of such a system, the most important are the enhancement of passive safety systems and the introduction of lateral active safety systems.

An E-M EPS SBW 2WS conversion mechatronic control system is the key to vehicle performance and safety. Problems with existing F-M FPS SBW 2WS conversion mechatronic control systems [CHEN 2006]:

- Complex – high cost;
- *'On'* all the time and powered by ECE- or ICE-low fuel economy and safety concern;
- Hard to integrate advanced technologies.

Supplementary advantages with E-M EPS SBW 2WS conversion mechatronic control systems [CHEN 2006]:

- Reduce maintenance and recycling cost;
- Reduced assembly time (up to 4 min);
- Up to 4% improvement in fuel economy;
- Enhanced safety (still operate even if ECE or ICE is stalled);
- Active tuning, chassis mechatronic control integration.

One of the objectives in the development of such control systems is to equip the driver with tactile feedback from the on/off road surface.

The importance of force feedback or *'road feeling'* has been well understood in both the automotive field and in telemanipulator systems.

Force feedback is one of the most valuable parameters in providing the driver with accurate control of the vehicle.

In this context, it is very important to provide a tuneable realistic steering feel that ensures comfortable driving.

The next generation of E-M EPS SBW 2WS conversion mechatronic control systems [CHEN 2006]:

- ❖ Further cost reduction for design, testing, manufacturing/assembly, and warrantee service;
- ❖ Advanced functions to enhance reliability and safety: fault-detection and tolerant, parts erosion compensation, and so on;
- ❖ Higher torque generation and optimised power flow management.

Current R&D ought to be focusing on [CHEN 2006]:

- ❖ Low cost motor with high torque yield, for example, a brushed motor with an easy drive and performance control set-up (in contrast to brushless motors) with the aim of applying to bigger vehicles;
- ❖ Optimised torque/energy distribution control with robustness to improve the driver's steering feeling, attenuate undesired disturbance and noise from both tyres and rough road surfaces;
- ❖ On-board diagnostics, tolerance and compensation of non-critical faults with fault-tolerant control strategies to extend the life of parts or components.

The principle layout of a column-mounted E-M EPS SBW 2WS conversion mechatronic control system's module is shown in Figure 4.49 [CHEN 2006].

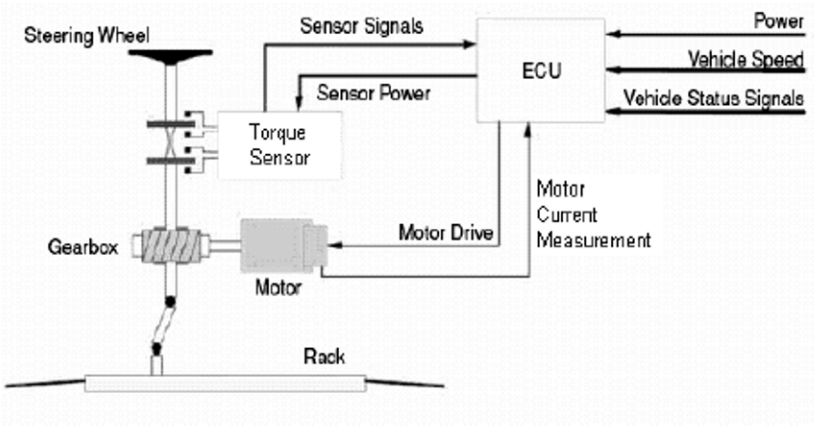


Fig. 4.49 The principle layout of a column mounted E-M EPS SBW 2WS conversion mechatronic control system's module [CHEN 2006].

Figure 4.50 shows a structural and functional block diagram of a column-mounted E-M EPS SBW 2WS conversion mechatronic control system's module for analysis and design [CHEN 2006].

A structural and functional block diagram of an E-M EPS SBW 2WS conversion mechatronic control system's module with road/surface dynamics using *CAR SIM*^{TM} is shown in Figure 4.51 CHEN 2006].

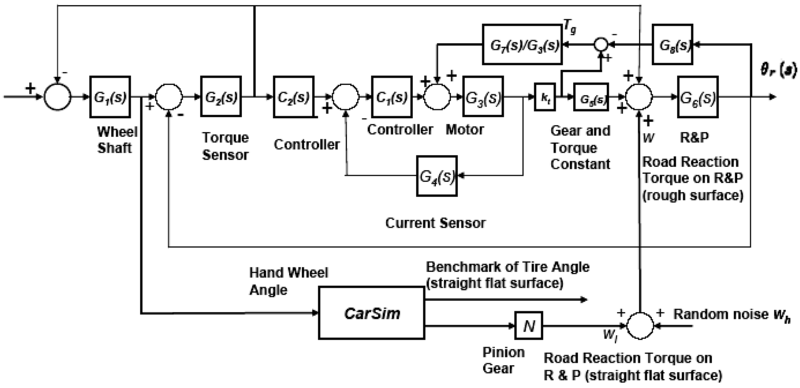


Fig. 4.50 Structural and functional block diagram of a column-mounted E-M EPS SBW 2WS conversion mechatronic control system's module [CHEN 2006].

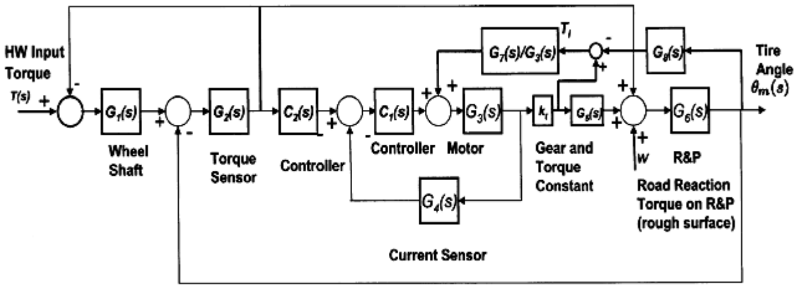


Fig. 4.51 Structural and functional block diagram of an E-M EPS SBW 2WS conversion mechatronic control system's module with road/surface dynamics using *CARSIM*™ [CHEN 2006].

A generic description of an E-M SBW 2WS conversion mechatronic control system [DOMINGUEZ-GARCIA AND KASSAKIAN 2003]:

- ❖ No longer a mechanical connection between the driver and the steering system;
- ❖ Significant similarities with telemanipulator systems;
- ❖ The control of both the steering wheel and steering system rely on a unique controller.

An E-M EPS SBW 2WS conversion mechatronic control system replaces conventional M-M linkage between the steering HW and the road-wheel actuator (e.g. an R&P steering) with an electronic connection (see Fig. 4.52) [GÜVENC 2005]. This allows flexibility in the packaging and modularity of the design. Since it removes the direct kinematics relationship between the steering and road wheels, it enables control algorithms to help enhance driver input.

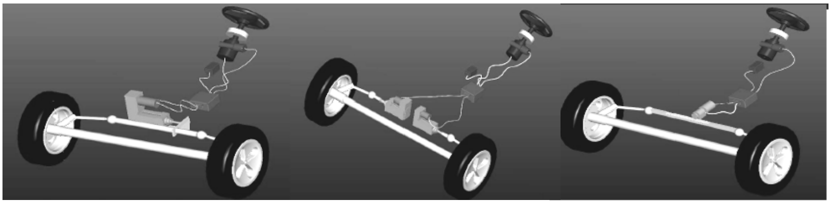


Fig. 4.52 E-M EPS SBW 2WS conversion concepts [GÜVENC 2005].

Figure 4.53 shows a principle layout for the E-M EPS SBW 2WS conversion mechatronic control system's conceptual design [AMBERKAR ET AL. 2003]. It may be subdivided into three major parts: an ECU system (Controller), a steering **hand-wheel** (HW) system, and a road-wheel system. The steering HW system contains sensors to provide information about driver steering input. This information is sent to the ECU hyposystem (Controller) that employs knowledge of the vehicle's current state to command the desired road wheel angle.

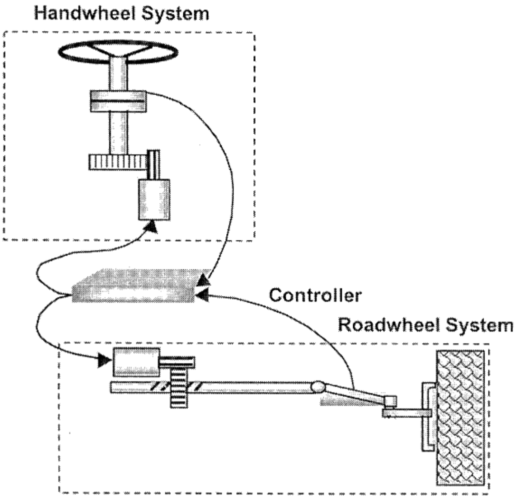


Fig. 4.53 Principle layout of the E-M EPS SBW 2WS conversion conceptual design [AMBERKAR ET AL. 2003].

The road-wheel system contains actuators to position the wheels. An actuator in the steering HW system provides road feedback to the driver. This also is commanded by the ECU system and based on information provided by the sensors in the road-wheel system. A place where the mechanical-to-electrical transformation is taking place, albeit slowly, is in the vehicle's PS.

Some smaller vehicles appeared with EPS back in 1998, with volumes increasing steadily as vehicle manufacturers adapted very advanced technology. By using an E-M motor to replace the conventional combination of M-F pump, oily-fluid, hoses, and oily-fluid reservoirs, drivers have a SBW 2WS conversion mechatronic control system that, while not significantly less expensive to produce, is smaller and lighter.

Summing up, the M-F-M SBW 2WS conversion mechatronic control system of recent automotive vehicles is equipped with a PS that reduces the steering effort of the driver, while allowing for manual steering in the case of a decrease in the oily fluid pressure.

However, it requires the use of fluidics (hydraulics) and large amounts of energy for driving the boost M-F pump, especially at low velocity [TREVETT 2002].

When a vehicle is idling or running at a low velocity, the rotary vane M-F pump must provide sufficient flow fluid to facilitate the turning of the wheel. Low velocities usually occur when turning takes place, so a good M-F-M SBW 2WS conversion mechatronic control system must operate well at these velocities. As a direct result of this, the M-F pump moves a much larger amount of oily fluid than is needed when the ECE or ICE speeds up [LUKIC AND EMADI 2003]. However, at high velocities, the steering wheel is barely turned at all. Therefore, there are huge losses involved with the current FPS. Also, the steering column that is used to couple the steering wheel with the drivetrain is a major source of injury in front-end collisions [TREVETT 2002]. In addition, the steering assembly places constraints on the design of the vehicle. The discovery of the E-M SBW 2WS conversion mechatronic control system opens the way to creating a steering system that is safer, cheaper, and more efficient.

In the M-F-M SBW 2WS conversion mechatronic control system, as shown in Figure 4.54, the steering column may be eliminated completely [LUKIC AND EMADI 2003]. As a replacement, there would be a purely mechatronic control system. This form of steering would contain sensors that would send signals to the actuators that make the wheels turn in the desired direction. It is even possible for the driver to know what the vehicle is experiencing.

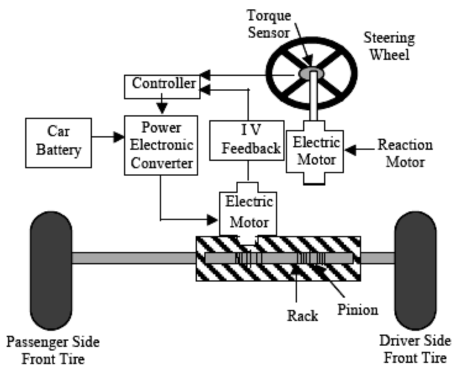


Fig. 4.54 E-M SBW 2WS conversion mechatronic control system [LUKIC AND EMADI 2003].

Energy may be consumed only when the steering wheel is being turned, leading to huge energy savings [LUKIC AND EMADI 2003].

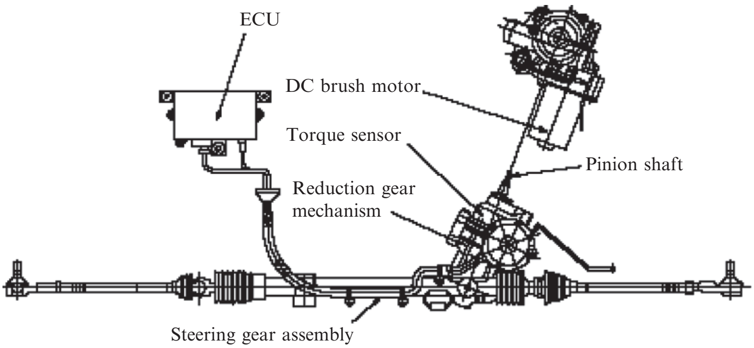
The major issue with the E-M SBW 2WS conversion mechatronic control system is safety. If the FPS fails, there is a mechanical backup provided by the steering column. When the system is used, there is no physical connection between the steering shaft and the steering wheel; so there is no opportunity for mechanical backup. However, there are advances in mechatronic control that make the SBW failsafe [LEONI AND HEFFERMAN 2002].

The pinion assist type EPS SBW 2WS conversion mechatronic control systems consist of [UEKI ET AL. 2004]:

- ❖ A torque sensor that detects steering force;
- ❖ An electronic control unit (ECU) that calculates signals from the torque sensor and supplies the necessary electrical energy to the E-M motor;
- ❖ An E-M motor that conveys an assist force to a pinion shaft through a reduction gear mechanism;
- ❖ A rack and pinion (R&P) type steering gear.

The ECU controls vehicle-velocity sensitive PS SBW AWS conversion mechatronic control systems by processing signals indicating the vehicle velocity and the rotation of the ECE or ICE.

In addition, the torque limiter is positioned between the plastic gear in the reduction gear mechanism and the pinion shaft, and protects the plastic gear from on/off road surface pressure (Figs 4.55 and 4.56) [UEKI ET AL. 2004; HAGHIGHAT-GOO AND ESFANDYARI 2005; COSC/PSYCH 2006].



ECU: electronic control unit

Fig. 4.55 Electric power steering (EPS) [UEKI ET AL. 2004].

Of particular interest to complex embedded mechatronic control systems such as SBW 2WS conversion, are software-implemented hazard mechatronic controls. These tasks monitor the state of the system for signs of hazards and take the necessary action.

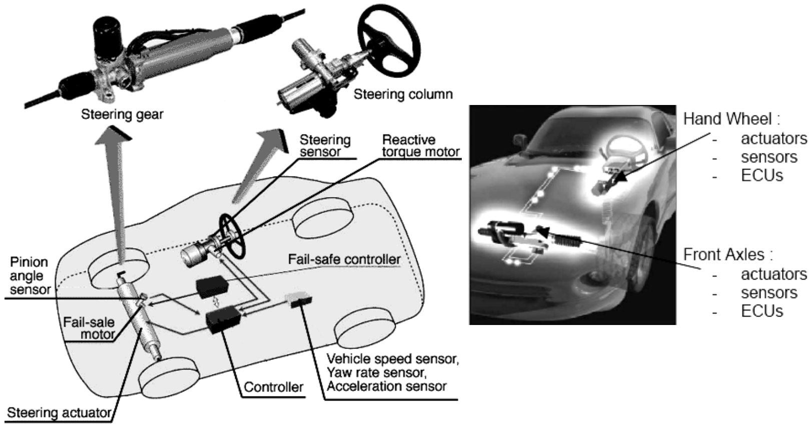


Fig. 4.56 Electric power steering (EPS) [COSC/PSYCH 2006 – Left image; HAGHIGHATGOO AND ESFANDYARI 2005 -- Right picture taken from: www.delphi.com].

Some potential hazards in mechatronic control systems, such as SBW 2WS conversion, may require fault tolerance because of inherent system limitations. This implies that some wiring, and/or ECUs (Controllers), and/or actuators, and so on may be unnecessary. Starting with the simple fault tree of Figure 4.57 [BERTRAM ET AL. 1999; AMBERKAR ET AL. 2003], but introducing the impact of hazard mechatronic controls for reducing risk, it is now possible to demonstrate improvements in the safety of the AE E-M EPS SBW 2WS conversion mechatronic control system. The same likelihood of occurrence is assumed for each event in the fault tree. By introducing hazard mechatronic controls into the tree, the likelihood that certain branches of the tree may lead to the top event can be reduced, thus reducing the risk of the hazard. For instance, if a redundant ECU (Controller) is added, it may take over for the primary ECU if it fails. The addition of the ECU (Controller) reduces the likelihood that the system may fail due to an ECU (Controller) failure (Fig. 4.58), since ECU 1 (Controller 1) and ECU 2 (Controller 2) must now both fail [BERTRAM ET AL. 1999; AMBERKAR ET AL. 2003].

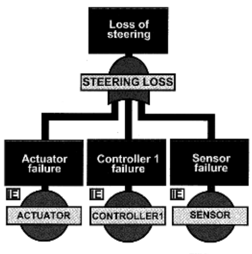


Fig. 4.57 Principle layout of the fault tree [AMBERKER ET AL. 2003].

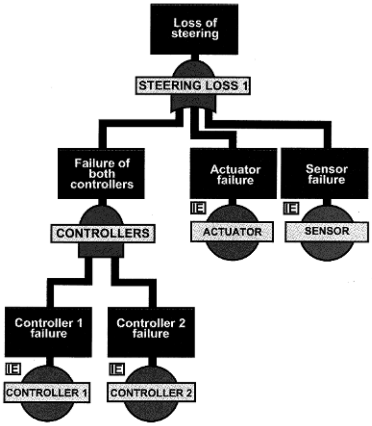


Fig. 4.58 Principle layout of the modified fault tree [AMBERKAR ET AL. 2003].

From a design perspective, it is important to know how this additional hazard mechatronic control should be added to the system so that it can take over when necessary, for example, warm standby, system voting, and so on.

Since hazard mechatronic controls may be added at a high level, as just illustrated in Figure 4.58, or at lower hyposystem or component levels, the hazard mechatronic controls are being implemented, where they are being implemented, and how many exist.

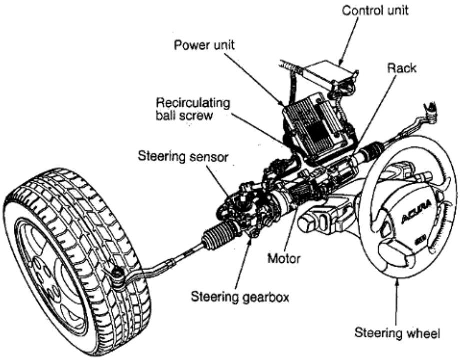


Fig. 4.59 Structure of E-M EPS SBW 2WS conversion mechatronic control system (rack assist-type ball screw drive) [ACURA 1991]

An AE E-M EPS SBW 2WS conversion mechatronic-control system, as illustrated in Figure 4.59 [ACURA 1991], is one that weakens the quantity of steering effort by basically using the output value of the mechanical energy from an E-M motor to it. This mechatronic control system contains of vehicle-velocity sensors, steering-wheel angular velocity and torque sensors, an ECU, a drive unit, and an E-M motor.

Signal outputs from each sensor are input to the ECU, where the essential steering assistance is computed and used by the drive unit to control the operation of the E-M motor. Since the motor's output value of a power is mechatronically controlled in this mechatronic control system, the adjusting range for the steering effort is great. In addition, because it is able to provide only the quantity of output power that is essential when the steering wheel is turned, great attenuation in output power needs may be efficiently fulfilled with no power losses. This shows when a contrast is made to M-F-M FPS SBW 2WS conversion mechatronic control systems that it is not essential for the M-F pump to maintain operating continuously when the steering wheel is not being turned.

In R&P steering mechanisms, the E-M EPS SBW 2WS conversion mechatronic control system uses the E-M motor's mechanical energy to the pinion gear shaft or to the rack shaft. Individual reduction gears are incorporated to amplify the torque of the motor. This system may be arranged systematically according to the drive method, as given in Table 4.4 and Figures 4.60 and 4.61.

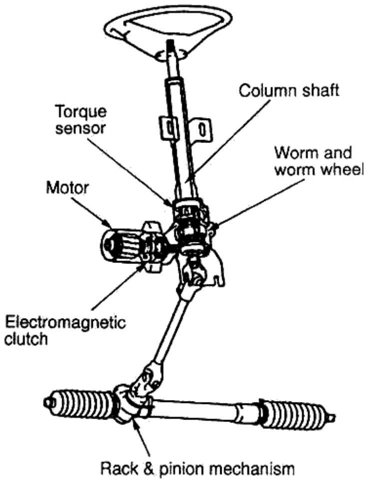


Fig. 4.60 Structure of E-M EPS SBW 2WS conversion mechatronic control system (column shaft drive) [SATO 1991].

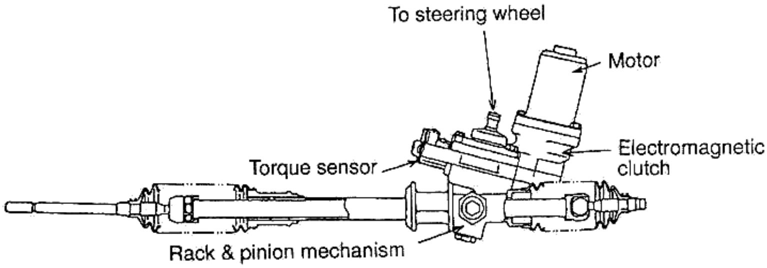


Fig. 4.61 Structure of E-M EPS SBW 2WS conversion mechatronic control system (pinion shaft drive) [SATO 1991].

The maximum amount of assistance, the softness of the steering feel, and the level of noise present during steering are, as a rule, specified by the power transmission systems in Table 4.4 [SATO 1995].

Table 4.4 Classification of EM Motor Mechanism Drive in EPS SBW 2WS Conversion Mechatronic Control

Method		Rack assist	Pinion assist	Figure
E-M motor drive mechanism		Another shaft pinion drive.	E-M motor → planetary gear train → another shaft pinion → rack shaft.	
		Ball screw drive.	E-M motor → ball screw → rack shaft.	0.10
Power transmission mechanism		Column shaft drive.	E-M motor→worm gear → column shaft → pinion shaft.	0.11
		Pinion shaft drive.	E-M motor → gear train → pinion shaft.	0.12

In most cases, it is able to acquire a greater amount of assistance from the rack assist method than from the pinion assist method which is optimal for vehicles in which the FWD load is high. Particulars of the individual sensors, controls, and the results fulfilled thereby are thus set under informal headings [SATO 1995].

Summing up, an AE E-M EPS SBW 2WS conversion mechatronic control system is designed to use an E-M motor to provide directional control to the driver. Most E-M EPS SBW 2WS conversion mechatronic control systems have variable assist that allows for more assistance as the vehicle velocity decreases and less assistance from the mechatronic control system during high-velocity situations. This functionality requires a delicate balance of power and control that has only been available to vehicle manufacturers in recent years.

The E-M EPS SBW 2WS conversion mechatronic control system is replacing the M-F-M FPS SBW 2WS conversion mechatronic control system and is destined to soon become a mainstream among vehicle manufacturers. E-M EPS SBW 2WS conversion mechatronic control systems do not require ECE or ICE power to operate. Thus, a vehicle equipped with an E-M EPS SBW 2WS conversion mechatronic control system may achieve an estimated 3% greater fuel economy than the same vehicle with conventional M-F-M FPS SBW 2WS conversion mechatronic control systems. As an added benefit, more of the ECE’s or ICE's power is transmitted to its intended location -- the wheels.

Sensors -- The E-M EPS SBW 2WS conversion mechatronic control system applies a diversity of sensors to control the E-M motor. These sensors contain a torque sensor that measures the steering effort of the steering wheel; a steering wheel angular-velocity sensor that measures the angular velocity of the steering wheel; a DC CH-E/E-CH storage-battery sensor that measures the storage-battery voltage; an electrical-current sensor that measures the motor’s armature current and the storage-battery current; and a vehicle-velocity sensor [SATO 1995]. Of these sensors, the torque sensor and the steering wheel angular-velocity sensor, that constitute the essential part of the SBW 2WS conversion mechatronic control system, are represented as follows.

<u>Torque Sensor</u> -- The pinion shaft in the R&P steering mechanism is separated into two parts -- the input shaft and pinion gear. The torque sensor includes a torsion bar that joins the two parts: a slider with a movable soft-iron core, a cam mechanism that changes the twist torque of both parts of the shaft into an axial direction displacement, and a differential transformer that changes the axial direction displacement of the slider into an electrical signal. For example, the torque sensor detects the magnitude and sense of direction of the slider displacement. The main signal is the output signal of torque and others are output signals for fault diagnosis instrumentality. The differential transformer-type torque transducer has a dual electrical structure to supply differential output signals so that a high sensing accuracy and satisfactory temperature characteristics can be acquired and detection of faults can be correctly made.
<u>Angular Velocity Sensor</u> -- The angular-velocity sensor is made up of a gear train that is situated around the input shaft and an AC-DC macrocommutator generator that is driven by the gear train to enhance the angular velocity. The right or left sense of the turning direction and the angular velocity of the steering wheel are measured by the right or left sense of the turning direction and the angular velocity of this AC-DC macrocommutator generator, respectively. An output signal shows the signal from the steering HW angular-velocity sensor.
Electronic Control Unit (ECU) -- The ECU is made up of an interface circuit that equals in importance the signals from the different sensors, an **analog-to-digital** (A/D) converter and **pulse-width-modulation** (PWM) unit that are all built into a 32- or 64 bit single-chip microprocessor, a **watch-dog timer** (WDT) circuit that checks the operation of this microprocessor, and a PWM drive ASIM macrocommutator matrixer that drives the previously mentioned electric power unit. The ECU allows a search for data according to a table lookup method used as the basis for the signals input from each sensor and fulfils a necessary computation employing the data to acquire the assistance force. Also, fault diagnosis for the sensors and the single-chip microprocessor is fulfilled. When a difficulty is discovered, electrical energy to the E-M motor is turned off, an indicator lamp lights up, and the difficulty circumstance memorised, then this difficulty mode appears instantly on a display [SATO 1995].
Power Unit -- The electric power unit comprises a power **metal oxide semiconductor field effect transistor** (MOSFET) DC-DC matrixer that drives the E-M motor in a forward or reverse sense of direction, a drive circuit that controls the respective power MOSFET of this power MOSFET DC-DC matrixer, an electrical current sensor, and a relay that turns the motor's armature current '*ON*' and '*OFF*'. The motor is driven based on instructions from the ECU. The electrical current at this time is monitored by the ECU, and the electrical energy supplied to the motor is turned off in the case of no uniformity. Relying on the magnitude of the motor's armature current, certain mechatronic control systems are furnished with an integrated ECU and electric power unit, while other systems include each part separately [SATO 1995].

E-M Motor Mechatronic Control Systems -- In the physical model (equivalent circuit) of the E-M motor, the relationship between the terminal armature voltage u_a, the armature self-inductance L_a, the armature resistance R_a, and the induced armature voltage constant k , the rotor angular velocity ω, the armature current i_a, and the time t , is represented by the subsequent mathematical model [SATO 1995]:

$$u_a = L_a\,(\mathrm{d}i_a/\mathrm{d}t) + R_a\, i_a + k\,\omega, \tag{4.12}$$

$$\approx R_a\, i_a + k\,\omega. \tag{4.13}$$

Moreover, it is recognised that the motor's armature current i_a is proportional to its assistance torque T_M. As can be comprehended from Eq. (4.12), there are two mechatronic control systems. In the motor's armature-current mechatronic control system, the reference (desired) value of a motor's armature current that is proportional to the value of the motor's assistance torque T_M , is resolved from i_a^* the signal output T_M from the torque sensor. Moreover, control is achieved so that there is no difference between the reference value of an armature current i_a^* and the actual value of an armature current i_a measured through a feedback loop from the armature-current sensor.

In a motor's armature voltage mechatronic control system, the reference value of an armature voltage component ($u_{a1}^* = R_a\, i_a = k_T\, T_M$; k_T is a proportional constant) that is equal to the value of the motor's assist torque as computed from the output signal T_M from the torque sensor, and the reference value of the motor's armature voltage component ($u_{a2}^* = k\,\omega$) that is equal to the motor's rotor angular velocity as computed from the output signal θ_s from the steering wheel angular-velocity sensor. These two voltage components are, in that case, added and output [SATO 1995].

<u>*Armature Current Mechatronic Control System*</u> -- In this mechatronic control system, the reference value of the motor's armature current that is equal to the motor's assistance torque, is adjusted so that it corresponds to the vehicle velocity response type received from the signal of the vehicle-velocity sensor.

<u>*Armature Voltage Mechatronic Control System*</u> -- In this mechatronic control system, both the E-M motor torque and the motor's rotor angular velocity can be controlled by the output signals from the torque sensor and the steering wheel's angular velocity sensor. When the vehicle is cruising at low velocity, '*normal mechatronic control*' is performed. With this mechatronic control system, the expression $R_a\, i_a + k\,\omega$ in Eq. (4.13) is output to the motor to obtain a good steering response rate (E-M motor response rate) and thus provide a comfortable steering performance. When the vehicle is travelling at high velocity, it is possible to perform two forms of mechatronic control systems. In the first one, '*return mechatronic control*', the value for $k\,\omega$ is made smaller so that a damping torque that is proportional to the motor's rotor angular velocity generates.

In the second one, '*damper mechatronic control*', the motor's torque generates in the opposite sense of the motor rotation with u_a = 0 when the steering wheel is released in turning.

Normal Mechatronic Control System --This is a mechatronic control system of drive control for steering with poor steering effort and an excellent steering response rate. As is displayed in Table 4.5 [ACURA 1991], when the steering wheel is turned to the right, MOSFET electrical valve Q1 is '*ON*' at the same time that MOSFET electrical valve Q4 is performing PWM-driver ASIM macrocomutator and armature-current flows to the MOSFET DC-DC macrocommutator, as shown in Figure 4.62 [KIFUKU AND WADA 1997], uses as a basis for the value of u_a in Eq. (4.13). If the angular velocity of the steering wheel increases, the PWM function also increases.

Table 4.5 DC-AC Commutator Motor Drive During Normal Mechatronic Control [ACURA 1991]

Steering condition	Steering to right	Straight ahead	Steering to left
Q1	ON	OFF	OFF
Q3	OFF	OFF	ON
Q4	PWM	OFF	OFF
Q2	OFF	OFF	PWM
DC-AC commutator E-M motor operation	Operates in a right sense of steering direction	Stops	Operates in a left sense of steering direction

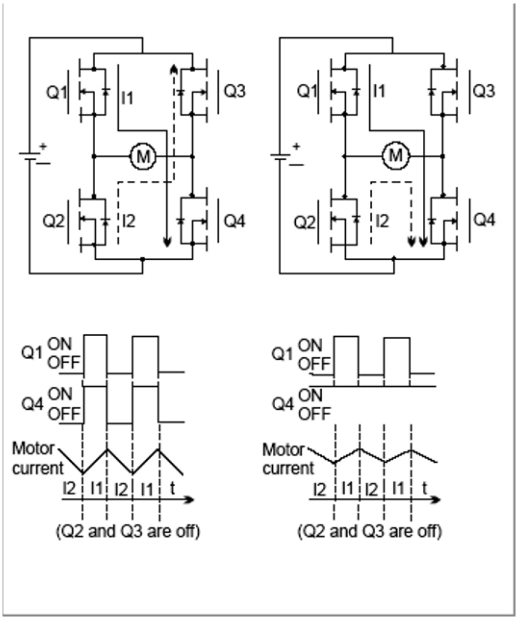


Fig. 4.62 PWM driven DC-DC macrocommutator [KIFUKU AND WADA 1997].

Return Mechatronic Control System -- This mechatronic control system of drive control is for altering the steering wheel return characteristics. When the driver is returning the steering wheel to the neutral position at low-velocity driving, the E-M motor's armature current is instantaneously and uniformly weakened to cause the motor to operate in the reverse sense of the motor's rotor rotation to the torque originating senses of motion direction.

As a result, a satisfactory returnability of the steering wheel should be gained. At high-velocity driving, the motor's armature current is slowly and uniformly decreased to suppress returnability and gain more stable steering characteristics.

Table 4.6 DC-AC Commutator E-M Motor Drive during Return Mechatronic Control [Source: ACURA 1991]

Steering condition	Return from right steering to straight ahead	Return from left steering to straight ahead
Q1	PWM	OFF
Q3	OFF	PWM
Q4	PWM	OFF
Q2	OFF	PWM

As represented in Table 4.6 [ACURA 1991], when the steering wheel returns to the basic position after being turned to the right, MOSFET electrical valve Q1 performs PWM-driver ASIM macrocommutator used as a basis for the signals from the steering wheel angular-velocity sensor and, at the same time, MOSFET electrical valve Q4 also performs PWM-driver ASIM macrocommutator used as a basis for the signals from the torque sensor.

Damper Mechatronic Control System -- This mechatronic system of drive control is for enhancing the convergence of the steering wheel when the vehicle is cruising at high velocity and for suppressing wandering of the steering wheel supplied by the wheel-tyre inputs. When the motor's armature terminals are short-circuited, it is able to generate torque in the reverse sense of direction in proportion to the angular velocity of the motor's rotor and this characteristic is used for mechatronic control.

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