

# Development of a 4WD System for SUVs

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## ABSTRACT

Surveys of sports utility vehicle (SUV) use in the United States, where they are extremely popular, show that they are mostly driven on streets in urban areas. However, most SUVs are based on a truck chassis, and performance under adverse conditions is regarded as more important than on-road controllability and efficiency. Therefore, this system was created using an FF passenger car chassis with functions integrated in the rear final drive unit, clutch units installed on the axle for the left and right rear wheels, electronically controlled torque control, torque limit control, and so on. The result combines the rough road performance required for an SUV with the controllability of a passenger car, and achieves these goals in a system weighing only 97 kg, making it the lightest in its class.

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## 1. Introduction

Sales of vehicles in the Sport Utility Vehicle category (SUV below) have shown a recent trend towards yearly increase in the US. Surveys have yielded various reasons for choosing an SUV, including the feeling of security from the greater visibility due to height and the ease of use for leisure activities.

In actual terms, SUVs are used almost exclusively for town driving and only rarely for off-road use. However, many present SUVs are based on a truck chassis, and many of them emphasize performance under adverse conditions over on-road controllability. This situation made it necessary to develop a 4WD system which corresponded to the pattern of actual use of SUVs.

or to tow a boat up a slope is sufficient for practical use, while it is also possible to provide users with easy-to-use SUVs which feature controllability performance equivalent to passenger vehicles on paved roads. On this basis, we established our developmental aim as ‘a balance between the necessary sufficient drivability as an SUV and controllability performance as a passenger vehicle’.

To ensure drivability, it is necessary to provide optimum control of driving force to the front and rear left and right wheels in response to vehicle conditions, while chassis performance equivalent to that of a passenger vehicle and weight savings are important to ensuring controllability performance. These were the considerations behind the development of the 4WD system introduced in this paper, Variable Torque Management-4 (VTM-4).

## 2. Developmental Aim

Given the purpose of their use, various driving conditions are projected for SUVs. As a result of surveys on mode of use, we realized that in terms of drivability, ensuring traction to drive up gravel or snow-covered slopes

## 3. 4WD Systems

As a result of examination of the functions considered necessary to achieving SUV drivability and passenger vehicle controllability performance, we realized the importance of the following items (Fig. 1).

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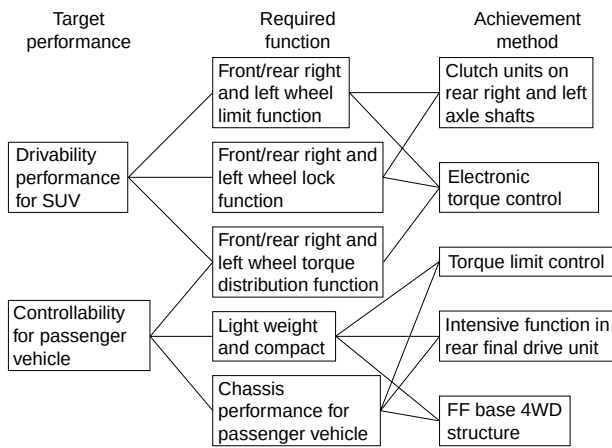


Fig. 1 Target performance and achievement method

There are various configurations among 4WD systems, including the full-time, direct type and center clutch type (Table 1).<sup>(1) (2)</sup> For the new development we examined methods of achieving weight savings and compactness by minimizing the number of elements involved in the necessary functions, and decided on the 4WD basic system shown below (Fig. 2).

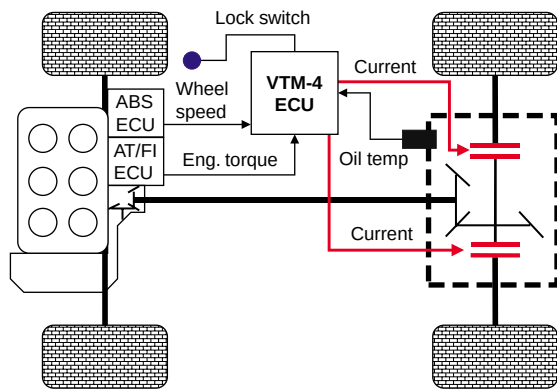


Fig. 2 VTM-4 system

### 3.1 Power Take Off (PTO)

Because of the adaptability of PTO, which receives traction from an automatic transmission (AT), to the engine room in an FF base, we were able to adopt a configuration in which hypoid gears change the direction of driving force after speed has been increased by helical gears on the differential. This has allowed us to lower the position of the section receiving driving force and to achieve weight savings. Fig. 3 shows a cross-section of PTO.

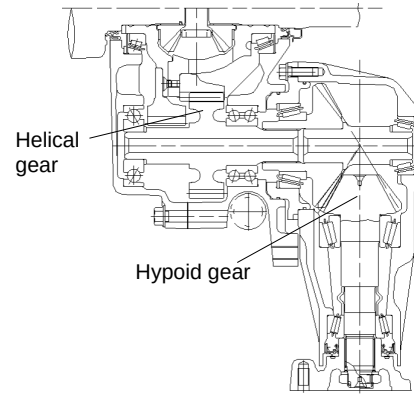


Fig. 3 PTO cross section

### 3.2 Propeller Shaft

Given the goal of weight savings, we adopted a two-piece type propeller shaft (Fig. 4). By regulating revolutions by means of PTO and the rear final drive unit gear ratio, we optimized joint size and pipe ratio. To suppress rotational vibration from the propeller shaft, we have maintained the rotational weight balance of the shaft below a fixed value, and adjusted it to be in locked phase with the rear final drive unit input flange. This has reduced noise and vibration during driving.<sup>(3)</sup>

Table 1 Respective functions of 4WD types and the number of elements

|          |                                                       | VTM-4 | Competitor A | Competitor B | Competitor C |
|----------|-------------------------------------------------------|-------|--------------|--------------|--------------|
| Function | Driving force distribute Function (front to rear)     | ○     | ○            | ○            | ○            |
|          | Driving force distribute Function (rear left & right) | ○     | ×            | ○            | ×            |
|          | Front and rear rock function                          | ○     | ○            | ×            | ×            |
|          | Rear left and right lock function                     | ○     | ×            | ×            | ×            |
| Element  | Differential                                          | 1     | 2            | 3            | 2            |
|          | Clutch                                                | 2     | 1            | 1            | 1            |

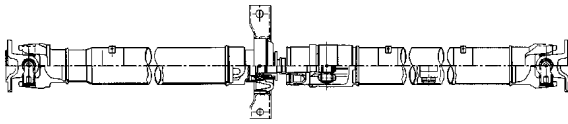


Fig. 4 Propeller shaft cross section

### 3.3 Rear Final Drive Unit

Given the goals of achieving weight savings and fitting the system in an FF base vehicle, we concentrated torque control functions in the rear final drive unit. We examined hydraulic, electromagnetic and other methods of torque control, but to achieve the target performance set for the new development, it was important to ensure controllability when rotational difference between the front and rear wheels is low. Hydraulic control of the clutch requires a separate oil pressure source, and the system becomes overly complex. Adoption of an electromagnetic coil-type clutch for torque control in the VTM-4 has ensured sufficient controllability with a simple structure.

The direction of torque input from the propeller shaft to the rear final drive unit is changed by the hypoid gears and transmitted to independently positioned electromagnetic coil-type clutches on the right and left. Fig. 5 shows a cross section of the rear final drive unit.

The electromagnetic coil-type clutches consist of a pilot clutch and a main clutch. When current flows to the electromagnetic coil, the armature is pressed against the rotor, producing friction torque. Friction torque is converted into thrust force by a ball cam inside the unit, and this becomes main clutch thrust force. Fig. 6 shows a cross section of the electromagnetic coil-type clutch.

The torque controlled by the main clutch is independently transmitted to the right and left axle shafts by the output shaft. As a result of investigating the relative effect of the various elements of the right and left clutches on the dispersion of torque transmission, we realized that pilot clutch clearance has the greatest effect on the amount of torque transmission. Fig. 7 shows the relationship between pilot clutch clearance and amount of torque transmission. In this system we have ensured right and left

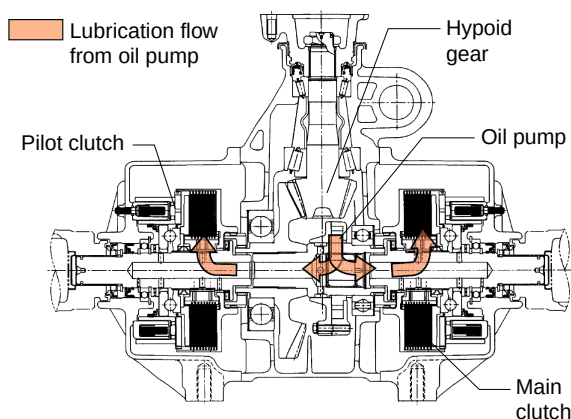


Fig. 5 Rear final drive unit cross section

torque differentials and controllability by optimizing clearance of the rubbing surfaces of the armature and the rotor.

Lubrication is provided to the clutches by an oil pump positioned on the same axle as the hypoid gear. The oil pump is positioned almost exactly between the right and left clutches, and provides uniform lubrication to both, with lubricating oil conveyed and provided to the clutches from within the shaft. The oil used is specifically designed to stabilize clutch friction characteristics.

In addition to ensuring the necessary driving force for drivability, lock mode does not feature mechanical linkages but constantly provides the maximum current to the electromagnetic clutches, suppressing excess driving force and achieving weight savings.

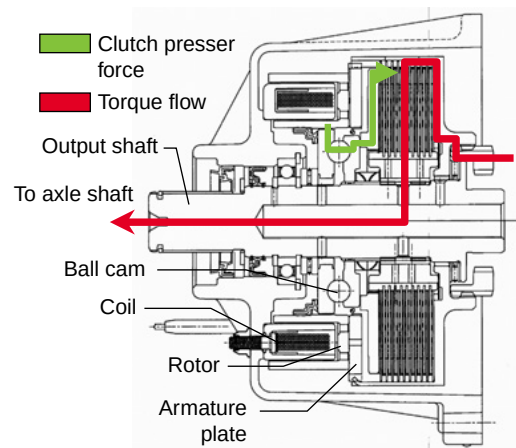


Fig. 6 Clutch unit Cross section

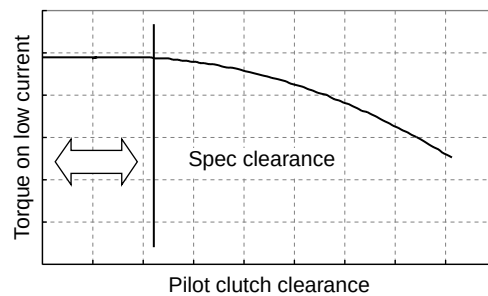


Fig. 7 Clearance and torque

## 4. System Control

The functions demanded of control to achieve the targets for the 4WD system were as follows:

- (1) Allocate the optimum driving force to the rear wheels as necessary to improve both drivability and controllability.
- (2) Do not transmit driving force when unnecessary, to achieve weight savings, compactness and fuel economy improvements.

We broadly set auto mode and lock mode to achieve these aims. Auto mode combines acceleration control, wheel speed control and hill climb control. Fig. 8 shows an outline of forms of control and their flow.

#### 4.1 Auto Mode

##### 1) Acceleration Control

The vehicle requires a large driving force during acceleration rather than when driving at a constant speed. We have therefore ensured drivability and controllability by optimal allocation of driving force to the rear wheels in response to acceleration. By not transmitting driving force to the rear wheels other than during acceleration, we have been able to make the system lighter, in addition to suppressing the tight corner braking phenomenon and

improving fuel economy. This system calculates vehicle acceleration from engine torque, torque converter characteristics, vehicle speed, gear position, etc., and decides the amount of driving force to be allocated to the rear wheels. Fig. 9 shows the amount of driving force allocated against vehicle acceleration.

##### 2) Differential Wheel Speed Control

Sometimes a large driving force must be provided from the rear wheels to ensure drivability on slippery road surfaces, such as found on bad or snow-covered roads. In addition to its utilization of acceleration control, this system ensures drivability by increasing rear wheel driving force in response to the front to rear wheel speed ratio. Fig. 10 shows rear wheel driving force against front to rear wheel slip ratio.

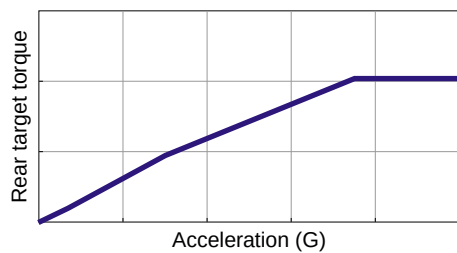


Fig. 9 Vehicle acceleration vs. rear wheel torque

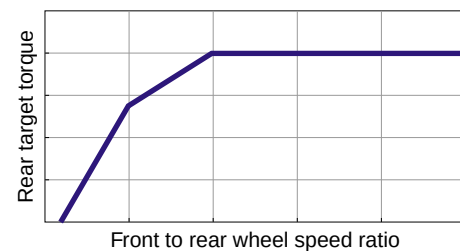


Fig. 10 Wheel speed ratio vs. rear wheel torque

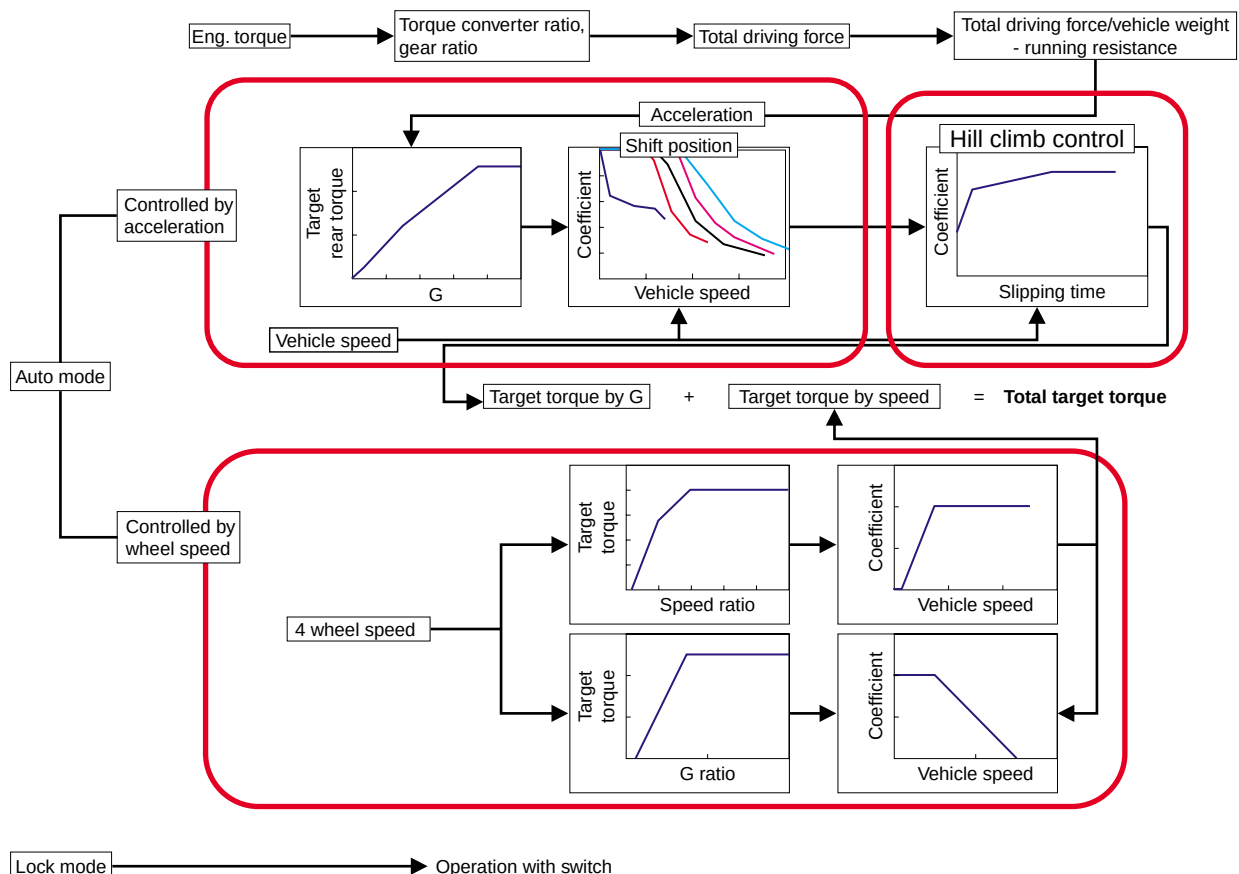


Fig. 8 Outline of control modes and flow

### 3) Hill Climb Control

When climbing extremely low  $\mu$  gradients, there are cases in which the vehicle does not accelerate and front to rear wheel speed ratio does not greatly increase. To ensure drivability in such situations, when slight front wheel racing continues for a certain period, control is conducted to increase allocation of driving force to the rear wheels depending on the length of the period. Fig. 11 shows wheel racing time against the coefficient of increase of driving force.

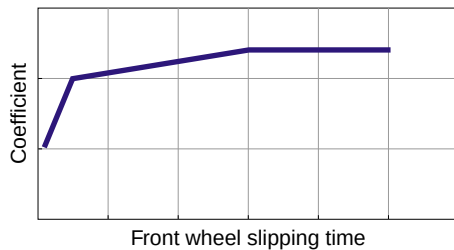


Fig. 11 Hill climb control

### 4.2 Lock Mode

When the vehicle is stuck or climbing a limit slope, it is possible to achieve greater drivability when the front and rear wheels and the rear right and left wheels are directly linked. However, this limits the differential between wheels, leading to strong braking when cornering, etc., and causing the vehicle to become unstable easily, and also puts more load on the drive system, increasing system weight. Because this type of drivability performance is required only at low vehicle speeds, this system gradually engages auto mode as vehicle speed increases, and limits use of lock mode to the low, 2<sup>nd</sup> and reverse positions on the AT shift lever. Fig. 12 shows vehicle speed against rear wheel torque.

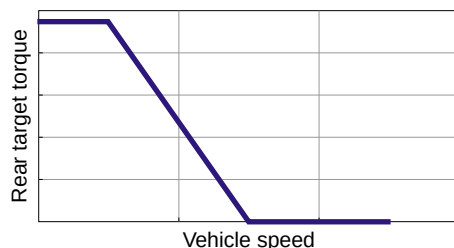


Fig. 12 Vehicle speed vs. rear wheel torque

## 5. System Weight

Fig. 13 shows a comparison between the weight of the VTM-4 used in the 2001 Acura MDX and the weights of the systems used in other models.

We have achieved the lowest system weight in the class (97 kg) through concentration of functions, the torque limit function, acceleration control, etc.

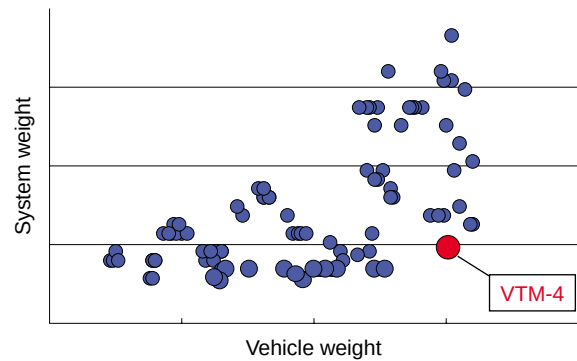


Fig. 13 System weight

## 6. Actual Vehicle Performance

The range of meanings covered by the term 'actual SUV performance' is broad and difficult to express quantitatively. Drivability and controllability performance must be evaluated with consideration of mode of use, road surface conditions, loading, etc. It has been normal to conduct relative evaluations of performance, utilizing subjective responses. For this paper, we have conducted a quantitative evaluation of basic performance in terms of drivability and controllability performance.

### 6.1 Drivability Performance

If the performance required to ensure drivability in a 4WD system is broadly divided, it is possible to generate the following broad categories:

- Absolute 4W driving force performance
  - Front and rear driving force allocation performance
  - Right and left driving force allocation performance
- (1) Absolute 4W driving force is the necessary driving force for absolute hill climbing performance, hill climbing when towing a trailer, etc. It is one indicator in determining the absolute amount of maximum torque to be allocated to the rear wheels in front wheel drive based 4WD systems like the VTM-4. The torque must be transmitted with appropriate timing, before the rate of front wheel slip becomes excessive. We judged from market surveys that if the following two points were satisfied, the MDX would be able to ensure absolute driving force performance at a level which would be competitive in its target market.
- Acceleration uphill on dirt roads
  - Acceleration uphill while towing a boat on a paved road

Results of measurements of necessary rear driving force under these conditions are shown in Figs. 14 and 15.

We have been able to achieve our target of necessary and sufficient hill climbing driving force and hill climbing performance. As can be seen from the rear wheel torque production characteristics, in auto mode it is possible to ensure the necessary sufficient hill climbing performance, while there is a moderate feeling of slip in the front wheels and road surface conditions are accurately transmitted to the user. In lock mode, the necessary driving force for hill climbing is instantaneously produced, and it is possible to show excellent hill climbing performance with a greater feeling of stability.

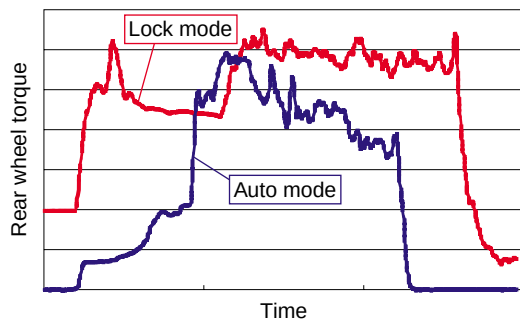


Fig. 14 Rear torque at hill climb on dirt

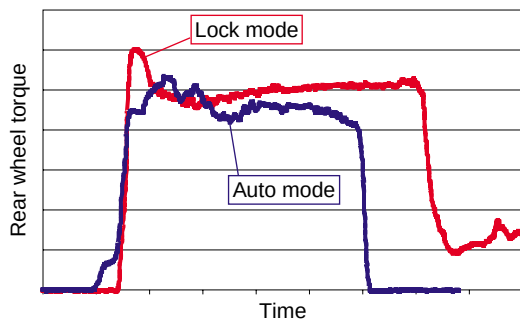


Fig. 15 Slope towing a boat on paved hill

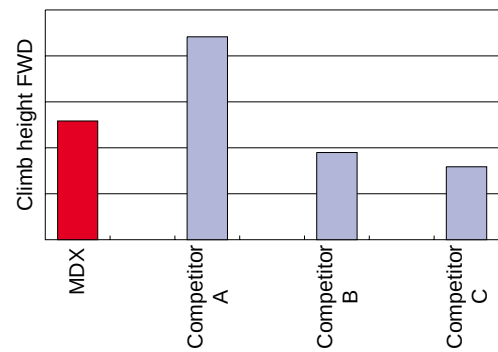


Fig. 17 Height difference for roller drive-over (Forward climb)

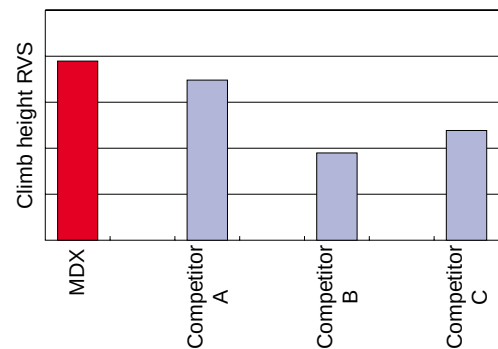


Fig. 18 Height difference for roller drive-over (Reverse climb)

(2) Front and rear driving force allocation performance is an indicator of drivability performance during driving on ordinary roads when there is snow cover, when there is a great difference between front and rear  $\mu$  on the road surface, when traversing a difference in level, etc. To quantitatively evaluate this performance in an actual vehicle base, we conducted a test using a roller jig (Fig. 16) to determine the height up to which forward and reverse progress was possible. Comparative results from the same test for representative models using other systems are shown in Figs. 17 and 18.

These results indicate that we have achieved the target of necessary and sufficient driving performance in comparison with the other vehicles tested.

(3) Right and left driving force allocation performance is acceleration performance on an ordinary road in conditions such as occur on a sloping road with a split  $\mu$  (e.g. the road shoulder is frozen) or performance in controlling a wheel which has left the road. To quantitatively evaluate these conditions, we used the same roller jigs as used in the previous tests. The front and rear wheels on one side of the car were placed on these (Fig. 19) and the towing force at that time measured. Fig. 20 shows comparative results with representative vehicles.

Under these conditions the MD-X could generate almost twice as much towing force as a normal preset-type LSD (competitor A), and could ensure the necessary and sufficient right and left driving force allocation performance for actual use.

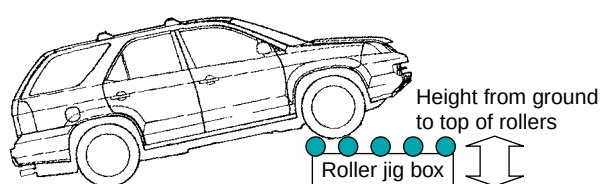


Fig. 16 The method for roller drive-over

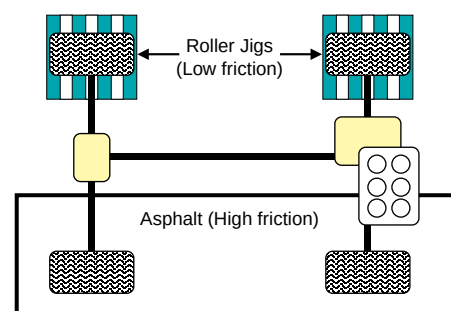


Fig. 19 The method for towing-strength measurement on split surface

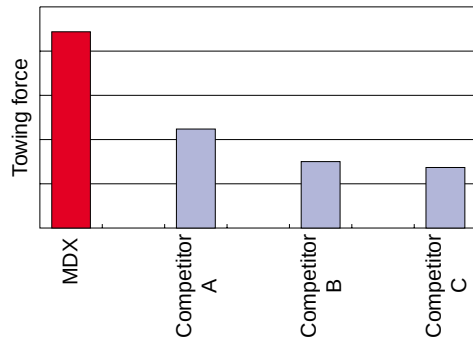


Fig. 20 Towing-strength measurement on split surface

## 6.2 Controllability Performance

Controllability performance is broadly divided into performance on wet and dry roads. Here, we conducted our evaluation by the standard method using circular acceleration characteristics.

We compared circular acceleration characteristics with those of representative passenger vehicles. As shown in Fig. 21, we have achieved controllability performance equivalent to that of a passenger vehicle, one of the targets set for this system.

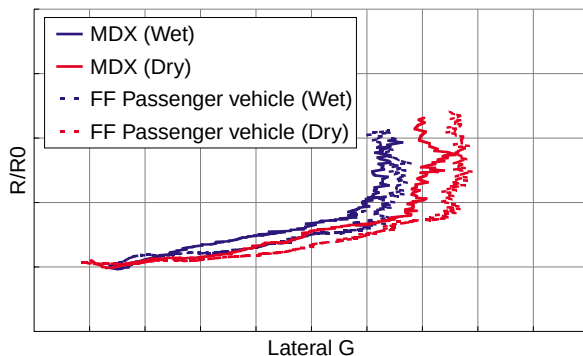


Fig. 21 US/OS Characteristics

## 7. Conclusion

These headings for comparative evaluation of 4WD drivability as an SUV and controllability as a passenger vehicle for the MDX and other vehicles are marked out as a radar chart in Fig. 22 below.

The target for this system was set as 'balancing necessary and sufficient drivability as an SUV with controllability as a passenger vehicle'. This target has been achieved at the lowest system weight in the class (97 kg), by the adoption of electronic torque control and a torque limit function, concentration of functions in the rear final drive unit, placement of clutch units on the right and left rear wheel axles and the use of a passenger vehicle chassis.

This system is being utilized in the 2001 Acura MDX, which has been well received by customers since being placed on the market in North America in September 2000.

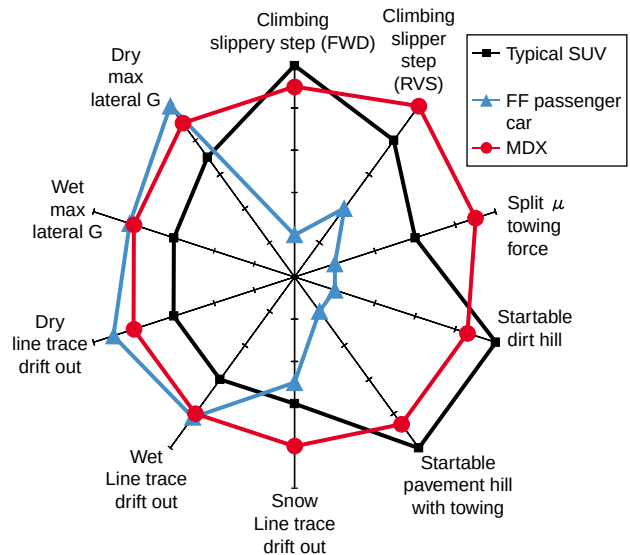


Fig. 22 Radar chart of 4WD performance

In conclusion, we wish to express our sincere gratitude to those at the R&D Center and elsewhere who provided significant support during the development of this system.

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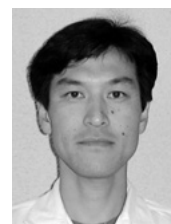
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