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Theoretical Study of Steering Effort
- using Autosim -

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The steering effort is an important characteristic of vehicles because it influences driver comfort directly. Steering effort and steering feel are of interest in this report. This report used AutoSim to model the vehicle and to prepare simulation code. FORTRAN was used to analyse the non-linear behaviour of vehicle and was also used for tire modeling using the Magic Formula. A parametric study of these parameters is carried out to get their effects on the steering effort. The influences of design parameters and driving conditions were computed.

Keywords: Steering Effort

INTRODUCTION

Steering feel, a driver's perception of steering characteristics, has become an important issue in recent years. Steering effort according to the vehicle speed and steer speed is directly affecting the steering feel and driving comfort. Steering effort can be conveniently divided into parking manoeuvre and driving manoeuvre categories. The driving manoeuvre class can be further broken down into on-centre and off-centre sections. Steering effort on parking and on driving manoeuvre is generated by different procedures. In a parking manoeuvre, steering effort is developed due to the elastic deformation of the tire tread due to the friction between tire surface and ground. Self-aligning moment, couple due to side force and pneumatic trail, is the main parameter in a driving manoeuvre. So, in a driving manoeuvre the slip angle concept is an essential factor in analysing steering effort. This report concerns the use of AutoSim to model the vehicle and to prepare FORTRAN code. AutoSim is a computer language designed for an efficient simulation for mechanical systems composed of multiple rigid bodies. FORTRAN is used to analyse the non-linear behaviour of a vehicle and is used for tire modelling using Magic Formula.

STEERING EFFORT AND STEERING FEEL

In order to quantify drivers 'feel', several methods have been utilised. Norman(1984) used four plots to analyse the handling of cars. Each plot has three or four parameters to characterise itself as following. Jaksch(1983) used the plot of inverse lateral acceleration gain versus lateral acceleration response time in order to determine the controllability and stability of the driver/vehicle system.

Steering wheel Torque vs. Angle Characteristics Two parameters are used to characterise this plot as shown in Figure 1. These are the steering wheel torque at 0 degree and steering torque gradient at 0 degree, commonly referred to as "steering stiffness" which shows whether the steering system requires precise handling.

Steering wheel Angle vs. Lateral acceleration Characteristics This plot has three parameters, steering sensitivity, minimum steering sensitivity and steering hysteresis. Steering sensitivity describes the change of lateral acceleration with the steering input. High steering sensitivity means that the vehicle moves sensitively according to the steering input. Steering hysteresis is related to the lag of yaw rate with steer input, since the greater the phase lag, the greater the hysteresis.

Steering wheel Torque vs. Lateral acceleration Characteristics This plot is characterised by five parameters as shown in Figure 2. Lateral acceleration at 0 Nm, steering wheel torque at 0 g, steering torque gradient at 0 g, steering wheel torque at 0.1 g and steering torque at 0.1 g. Lateral acceleration at 0 torque is strongly related to the returnability. Steering wheel torque at 0 g is an indication of Coulomb friction in the steering system. Steering torque gradient at 0 g is related to the "road feel" and "directional sense". It is greatly influenced by kingpin axis torque gradient and overall steering ratio. Steering wheel torque at 0.1 g is a measure of steering effort.

Also Steering work gradient versus lateral acceleration characteristics, lateral acceleration gain versus lateral acceleration response time (Jaksch, 1983) has been used to analyse the relations steering angle and torque with vehicle

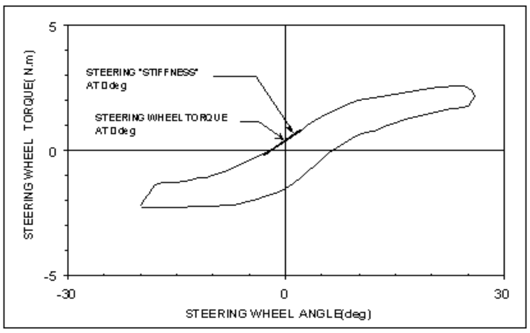

Figure 1- Steering Wheel Torque vs. Angle

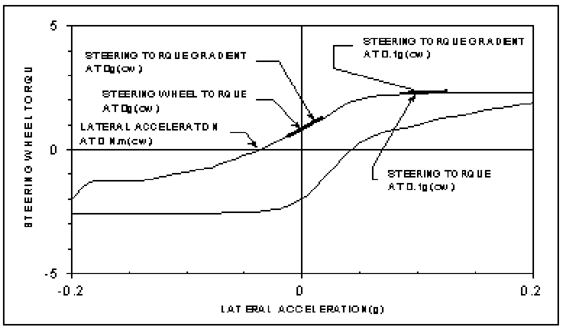

Figure 2 –Torque vs. Lateral Acceleration

response.

This report used steering wheel torque versus steering wheel angle characteristic plot mainly in order to investigate how the steering torque varied with each parameter.

DESIGN FACTORS

The model used in this report can be characterised by the following descriptions;

- Longitudinal, lateral movement and yaw vehicle itself.
- Roll freedom for the sprung mass.
- Steer degree of freedom for the front wheels

VEHICLE BODY The vehicle body affects steering effort by its weight and the position of centre of mass. Heavier vehicles will require much steering effort, so large and luxury cars and commercial vehicles have power steering as standard. Heavier vehicles also increase the tire loading, which changes the tire cornering stiffness. The side force varies as a function of side slip angle. The varied side force affects steering effort strongly. Higher yaw moment of inertia of vehicle body causes slow turning of vehicle, since it works as inertia. The position of centre of mass determines the characteristics of over-steer or under-steer.

STEERING PARAMETERS *Power Steering*. In situations where excessive steering effort is anticipated, the vehicle designer considers adopting power steering if there is no other way to reduce the steering effort. Nowadays most cars employ power steering as standard equipment or optional. Power steering consists of hydraulic pump, connecting hoses and tubes, valve and steering gear. An engine driven hydraulic pump delivers fluid to a valve that controls this fluid. The valve of steering gear is controlled using torsion bar. A stiff torsion bar produces a heavy feel to the driver. The structure of the valve and the shape of the port also affect the power assistance characteristic. In this report, the steering effort is investigated to see how it varies with the different stiffness of the torsion bar and the characteristic of the power steering.

Steer characteristic. The concept used to describe under-steer quantitatively is static margin. Jaksch used d(steer)/d(slip) instead of static margin. When the behaviour of the vehicle as sensed by the driver is of interest, d(steer) can be changed to d(steer-wheel). Vehicles that have the under-steer characteristic require much steer effort from drivers due to the lowered steering response.

SUSPENSION PARAMETERS *Roll steer*. For an ideal steering system the tie-rod linkage is designed such that the arc described by its ball joint to the steering arm exactly follows the arc of the steering arm as the wheel moves into jounce or rebound. This means that there is no steer action result regardless of suspension motion. In practice, it is not always possible to achieve this ideal and the steering geometry error causes toe change and roll steer during suspension motion. The location of inboard joint, either above or below the ideal center, determines how roll steer produces under-steer effect or over-steer effect. The roll steer is defined as the change of the road wheel steer angle when the sprung mass rolls relative to the suspension and can be described by using the roll steer coefficient as follows.

$$\delta_{rs} = (\partial\delta_f / \partial\phi) \times \phi \qquad (1)$$

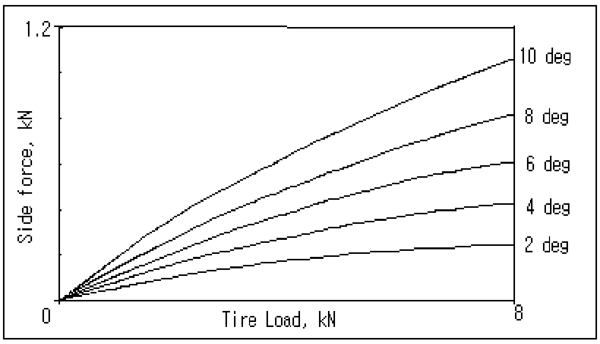

Figure 3 – Camber effect to Tire Side Force

Camber effect. When the vehicle is running straight and the tire load on port and starboard sides are the same, these camber thrusts cancel each other. A load transfer from inside to outside wheel due to the roll during cornering cause more camber thrust on the more heavily laden outer wheels. The resultant camber thrust will effectively reduce the cornering stiffness and contribute an under-steer effect if the wheels have positive camber in the front. Figure 3 shows the relation of tire side force and camber angle as well as the tire load. In this report, the camber is defined by using the coefficient of camber to roll as shown in equation (2). The camber thrust is determined using the camber angle and the camber stiffness as following equation (3). The camber stiffness is the slope of the curve between the lateral force and the camber angle for a given load.

$$\gamma = (d\gamma / d\phi) \times \phi \qquad (2)$$

$$F_{Y\gamma} = C_\gamma \times \gamma \qquad (3)$$

Load Transfer. In a straight line, the camber thrust and toe in or toe out effect will cancel each other, left and right wheel, as the forces will oppose one another. However, if the load transfer occurs in cornering, the outside wheel will be more heavily loaded and provide a greater side force due to the tire load change. This increased side force on the outside wheel can not supplement the reduced side force on inside wheel. Hence the load transfer reduces the total side force after all. The load transfer is determined by the roll stiffness. The higher roll stiffness, the more load transfer occurs so the roll stiffness in front and rear suspension determines the magnitude of the load transfer for each end. The relation of the load transfer between front and rear wheels will affect the steer characteristic

Tire. Side forces and aligning moments directly affect vehicle response and also affect the steering effort strongly. The side forces are generated by the elastic properties of tire. The tire tread is deformed laterally due to the side slipping and this deformed tire tread generates shear force. The integration of the forces over the contact patch yields the net lateral force. Aligning moments occur from this asymmetry of the side force position known as the pneumatic trail. The lateral force is a maximum when sliding expands over the whole contact region. The aligning moment will be very small when side force reaches the peak because the maximum of aligning moment occurs when the side slip is 1/3 of the peak of side force as shown figure 4. Tire load and the friction between the tire and ground affect cornering stiffness as well as tire size, structure and inflation pressure.

MODELLING

The simulation model was constructed mainly for the analysis of steering effort associated with steering wheel input to find out the effects of each parameter.

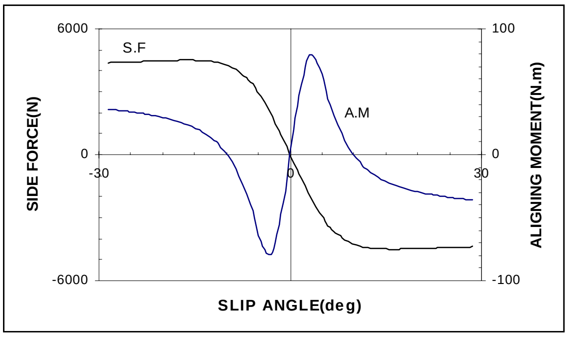

Figure 4 – Side Force and Aligning Moment

VEHICLE BODY The body has longitudinal and lateral movement, yaw and roll motion as shown figure 5. The front wheels have yaw motion and each wheel has spin motion. The steering has two degrees of freedom, one is for the hand wheel input and the other is the displacement of the pinion. The degree of the freedom of the steering wheel is constrained with the front road wheels by rigid linkage to each other. Vehicle body is added to the AutoSim written program using add-body function. The hub carriers and the road wheels of the front and the rear are added to the model also using add-body

```
(add-body u :name "reference frame" :parent n
   :translate (x y) :mass 0 :inertia-matrix (0 0 iuz)
   :body-rotation-axes z    :parent-rotation-axis z
   :reference-axis x)
(add-body s :name "sprung mass" :parent u
   :joint-coordinates (0 0 -@hrp) :mass @ms
   :cm-coordinates (0 0 "@hrp-h")
   :inertia-matrix (isx 0 0)
   :body-rotation-axes x
   :parent-rotation-axis "pos(frc, rrc)"
   :reference-axis y
   :small-angles t)
```

STEERING SYSTEM The steering wheel and the rack were mounted to the sprung body so they influenced by the behaviour of the sprung body. The pinion can represent a distortion on steering column. In a power steering system, it will work as the torsion bar.

```
(add-body pinion :name "pinion"
   :parent stwhl :mass 0 :inertia-matrix 0
   :body-rotation-axes x
   :parent-rotation-axis x
   :reference-axis y)
```

Steering Input The driver's usual steering can be expressed as sinusoidal in a slow lane change as 0.25 radian. In order to get clear results 0.3 radian is used as steering wheel input amplitude in this report. This steering wheel input amplitude is larger than the angles that are normally employed while driving in high speed. The input frequency is 0.5Hz and 0.25 Hz is also used to investigate the effects of inertia and friction.

```
(motion    "rq(stwhl)"    "amp*sin(2*@pi*freq*t)")
```

Steering Column stiffness. The steering stiffness includes not only the steering column unit itself but also the entire steering system from the steering wheel to the front road wheels. In a power steering system, the stiffness of the torsion bar replaces the steering column stiffness.

Power steering. Power assist pressure varies with steering wheel torque that is obtained from the angular distortion. Power steering characteristics are added to the AutoSim model using a table function. The simplified mathematical model for a power assisted rack and pinion steering gear is shown in Figure 6.

```
(install-table pstq    "pressure vs torque"
   :table-function spline :npts 300
   :xunits f*l      :yunits f/l**2
   :values ((-6 -5000000) (-4 -1000000) (0 0) (4 1000000)
            (6 5000000)))
```

The resulting torque from the power steering force is added to the front road wheel as a moment. The power assist pressure is transferred to a force by multiplication the hydraulic pressure area of the power steering gear. The steer arm and the mechanical trail are multiplied to this force.

```
(add-moment boostl
   :name "power steering assistant moment"
   :direction [uz]    :body1 fhcl    :body2 u
   :magnitude    "pstq(@sctq)*(arm+mtr)*area")
```

Friction. The coulomb friction in the steering system exists between connecting joints and support members. The connecting joints include ball joints and Hooke's joint, and support members contain a bearing at the steering column, pinion support bearing and rack support bush. All the friction in steering system is supposed to work in the rack movement and approximated by the following equation

$$F_{CF} = -|\mu F_n| \times \tanh(\text{rate} \times \text{rack velocity}) \qquad (4)$$

```
(add-line-force frack :name "force in the rack"
   :point1 rack0    :point2 s0 :direction [racky]
   :magnitude "-dstr*tanh(rate1*tu(rack))")
```

SUSPENSION AND TIRE In low input amplitude of the steering wheel simulation, as for the straight driving, we do not require a specific description of the vehicles'

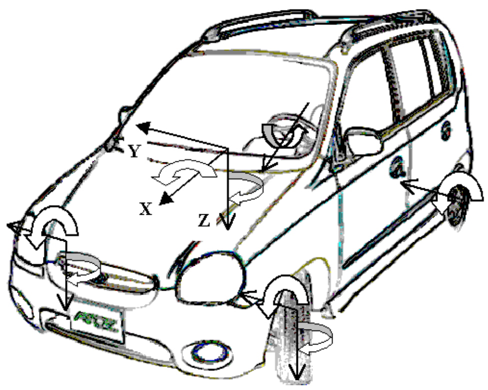

Figure 5 –Body Model

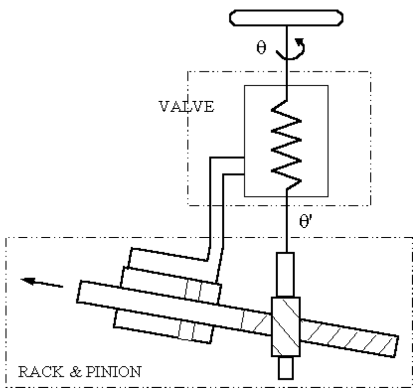

Figure 6 - Power Steering

suspension. This work uses simply the roll steer coefficient, the camber to body roll derivative and the roll stiffness front and rear in order to simulate the roll steer, the camber thrust and the load transfer. Describing the vertical, the lateral and the longitudinal forces and the corresponding moments, generated by a rolling pneumatic tire, plays an important role in vehicle dynamics studies. For a non-linear tire model, this work uses the Magic Formula (Bakker, 1987). The Magic formula is a non-linear function of the longitudinal slip, the side slip angle, the camber angle and the normal load on tire. FORTRAN codes for the Magic Formula are imported into the AutoSim written program by an add-subroutine command.

```
(add-subroutine difeqn tirexyma
    "@kappafl"   "@alphafl"   "-fm(fwzl)"
    "@gamf"    fwhlyl   mfwhlzl))
```

Magic formula tire model is a semi-empirical model that can describe tire behaviour quite accurately. Bakker et al (1987) developed equation (5)

$$y(x) = D\sin(C\tan^{-1}\{B_x - E(B_x - \tan^{-1}(B_x))\}) \qquad (5)$$

$$\text{where} \quad Y(X) = y(x) + S_v$$

$$x = X + S_h$$

Y(x) stands for either side force, self-aligning torque or brake force. The input X may represent slip angle (α) or longitudinal slip the Magic formula parameters have a physical meaning, which enables the user to change the tire characteristics in a convenient way. Cornering Stiffness affects on vehicle response and steering effort more than other characteristics. Equation (6) and figure 7 shows Cornering Stiffness.

$$BCD = a_3 \sin(2\tan^{-1}(F_z/a_4))(1 - a_5|\gamma|) \qquad (6)$$

a_3=maximum cornering stiffness at $\gamma = 0$
a_4=load at maximum cornering stiffness
a_5=camber sensitivity of cornering stiffness

VEHICLE MODEL VALIDATION

Simple checks were performed to ensure the validity of the model. The road wheel steer angle multiplied by the gear ratio is also less than the hand wheel input due to the twist of the pinion. Figure 8 shows roll and lateral acceleration.. roll has opposite direction of rotation to the steering input because it is caused by the centrifugal force during cornering.

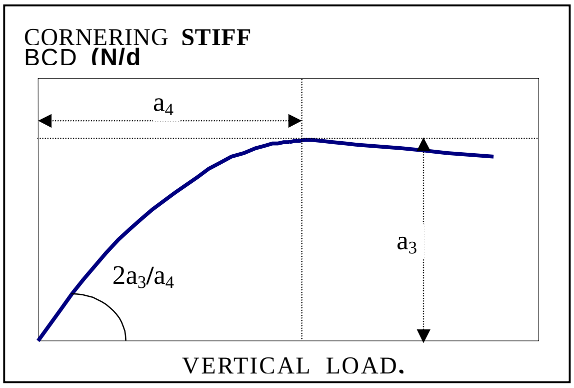

Figure 7 - Cornering Stiffness

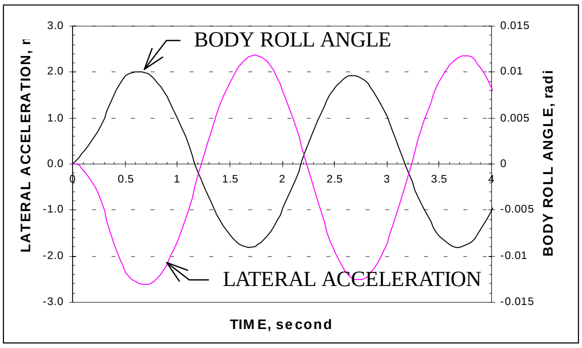

Figure 8 – Lateral Acceleration and Body Roll

RESULTS

Next the influences of the seventeen parameters were analysed to investigate how the each parameter influences the steering effort. Vehicle speed and power steering has affected largely to the steering effort.

VEHICLE SPEED. This report investigated the vehicle speed from 40 km/h to 160 km/h. Figure 9 shows the relation of vehicle speed and steering torque for the steering wheel input. The steering wheel torque with vehicle speed is illustrated in figure 10. The steering wheel torque increases with increasing of vehicle speed. This is because higher driving speed generated the bigger lateral acceleration and the side slip angle. Hence, the tire aligning moment increased and it enlarged the steering wheel torque.

POWER STEERING. Power steering does have a significant effect on the steering effort. In order to investigate the effect of the torsion bar stiffness, it was modified to 60 Nm/rad. The results are illustrated in figure 11. The power steering that used the stiff torsion bar increased the steering torque. The distortion of the torsion bar was decreased with the stiff torsion bar; hence a less amount of pressure oil would be supplied to the power steering cylinder. This is responsible for the higher steering torque. This can give a stable feeling to the driver in a high speed driving but it may give heavier feeling in a low speed

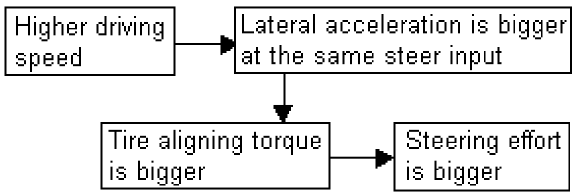

Figure 9 - Hand wheel Torque and Vehicle Speed

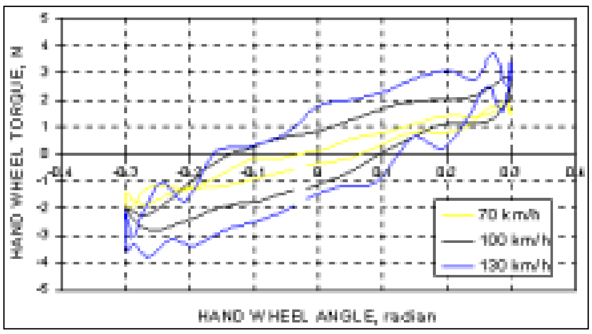

Figure 10 - Steering Torque and Vehicle Speed

driving in a normal valve system

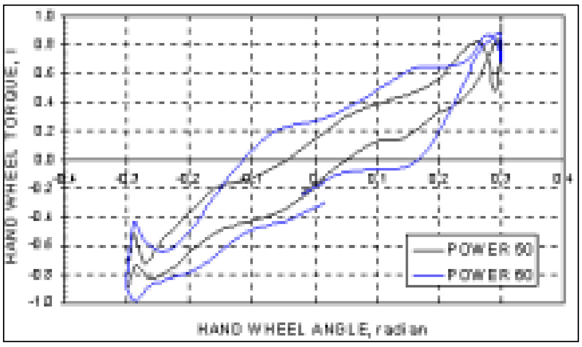

Figure 11 – Torsion Bar Stiffness Effects

STEERING INPUT FREQUENCY In order to find out the effect of the input frequencies on the steering torque, lower frequency input, 0.25 Hz, was applied to the hand wheel The steering torque is greater for the higher steering input frequency and increases especially in neutral position as can be seen in figure 12. Above the 0.1g, the steering torque on 0.25 Hz exceeded that of 0.5 Hz. The bigger side slip angle caused this result The time delay occurred more than 0.1 second for arriving to the peak values of the lateral acceleration and the side slip angle in a 0.5 Hz manoeuvre

TIRE LOAD All things being equal, heavier cars require more effort from the driver to steer them because heavier load on the tires increases the cornering force for a given steering input. The aligning moments increased in proportion to the tire load due to the side slip angle increasing. Figure 13 shows the relation of the steering torque to the tire load change when tire load increased 20 %.

FRICTION COEFFICIENTS ON GROUND The friction between the tire and the ground changed the steering torque widely. On the friction coefficient 0.8, the steering torque curve changed only insignificantly. The steering torque decreased significantly when the friction coefficient 0.6 was used as shown figure 14. Of course the side forces and the aligning moments decreased definitely for the friction coefficient below 0.6.

This report also checked following factors how they affect steering effort.

- Steering gear ratio
- Steering column stiffness
- Steering wheel’s and Road wheel’s inertia
- Steering’s and Suspension’s friction
- Mechanical trail
- Steer arm length etc.

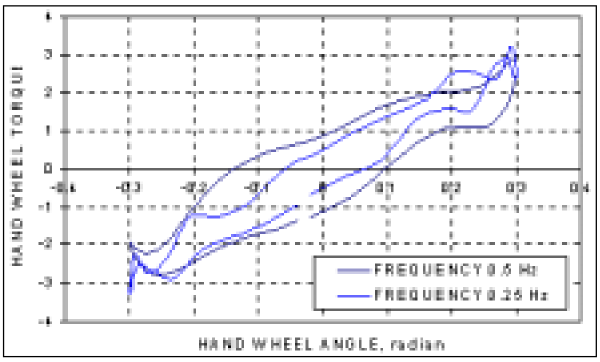

Figure 12 – Input Frequency Effects

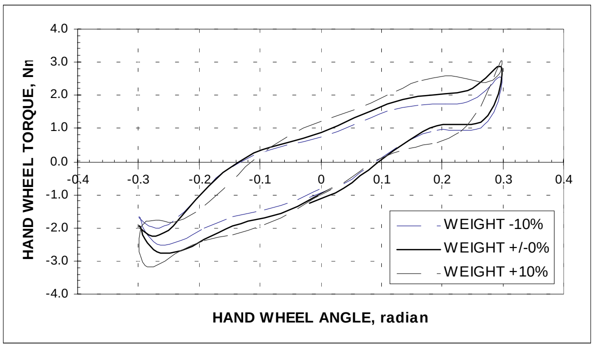

Figure 13 - Tire Load and Steering Torque

CONCLUSIONS

For an optimum steering torque under all condition, it is required to know how the steering torque varies with the driving condition. In this report, a method for investigation of the factors influencing the steering effort was developed using the parametric study. The driving speed, the power steering, the steering gear ratio, the friction on the ground and the mass centre position affected the steering effort largely. The method used in this report can anticipate the steering effort before the production of the prototype car and by using the steering torque, the characteristic plot of the power steering can be modified to get a satisfactory steering effort.

This report did not perform the test. Hence to prove the result of this modelling the real test should be done above all.

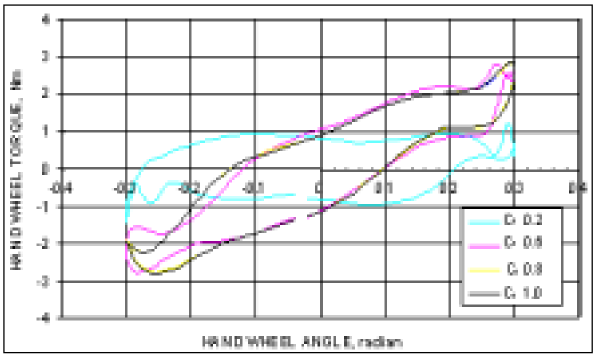

Figure 14 – The Effects of Road Friction

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