AUTOMOBILE STOP-AND-GO CRUISE CONTROL SYSTEM TUNED BY GENETIC ALGORITHMS

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Abstract: This paper is concerned with "stop-and-go" cruise control systems. Using published data of previous papers, a realistic model of a vehicle dynamic is obtained. A control system is then developed, using state-of-the art industrial procedures. Genetic Algorithm is used for tuning of some control loops. The paper reproduces some results of other researchers, pointing out some mistakes and proposing enhancements in the control action. New results are also presented and analyzed.

Keywords: Intelligent cruise control, genetic algorithms, comfort, safety, stop-and-go system

1. Introduction

The first generation of cruise control systems was only designed to keep a desired speed of a vehicle. It was not concerned with other vehicles or obstacles ahead in the runaway. Such cruise systems are no longer useful in a crowd metropolis or in its neighborhood. Due to the huge number of vehicles, a driver has to slow down frequently, acting on the breaks and deactivating the control cruise system. The whole speed up process must then be restarted to reach the desired speed, when the cruise control can be turned on again. To solve this problem, car manufactures developed a new cruise control concept: the stop-and-go cruise control systems [Shaout, 97].

A stop-and-go system is equipped with a radar to detect targets ahead. It can actuate the breaks or the throttle, automatically controlling the speed of the vehicle. The fatiguing work of accelerating and breaking constantly is dramatically reduced.

Stop-and-go systems are on the brink of the technological frontier and still present several problems and limitations. Though these systems can guarantee faster responses then human drivers, they are not able, for example, to impose a change of road lanes. If the driver trusts too much his cruise system, a case where a change of lane could save his life will be discarded.

This paper is concerned with the use of alternative control laws for cruise systems. To guarantee an optimal behavior, an optimization procedure based on Genetic Algorithm (GA) is employed.

2. Mathematical Models

The vehicle dynamics is modeled by simple expressions. Applying Newton's second law to the vehicle, it follows:

$$M_V a_{des} = F_t - F_r \tag{1}$$

where:

$$F_t \approx \frac{1}{r}\left(T_{shaft} - T_{break}\right)$$

$$F_r = F_{weight} + F_{drag} = M_V g \sin\theta + F_{drag}$$

a_{des}	Controlled vehicle's desired acceleration	F_{drag}	Drag force
M_v	Vehicle mass	g	Gravitational acceleration
r	Effective tire radius	θ	Road inclination angle
T_{shaft}	Torque at the axle shaft	F_t	Friction force
T_{break}	Torque imposed by the break system	F_r	Resistance force

Applying Newton's law to the motor, one has:

$$J_e \frac{d\omega_e}{dt} = \Delta T_{engine} \quad (2)$$

ω_e	Angular speed of the engine
T_{engine}	Torque of the engine
J_e	Motor moment of inertia

The torque applied on the driving shaft, is calculated as follows:

$$F_t . r = T_{shaft} \quad (3)$$

$$T_{shaft} = r \cdot \left(M_V g \sin\theta + F_{drag} + M_V a_{des} \right) \quad (4)$$

Using the reduction ratio of the gearbox, R_{trans}, the engine torque is given by:

$$T_{engine} = \frac{1}{R_{trans}} \cdot r \cdot \left(M_V g \sin\theta + F_{drag} + M_V a_{des} \right) \quad (5)$$

To complete Eq. (4), the drag force must be determined. This force is significant to speeds over 48 km/h, considering the vehicle used. The drag coefficient was estimated as C_D=0.33 [Munson, 97]. The engine torque is then given by:

$$T_{engine} = \frac{1}{R_{trans}} \cdot r \cdot \left(M_V g \sin\theta + 0.424 (v_{cc})^2 + M_V a_{des} \right) \quad (6)$$

The break action is modeled as follows:

$$T_{break} = -r\left(M_V a_{des} + F_r\right) + T_{shaft} \quad (7)$$

The maximum break torque must be limited, since torques over a certain limit will cause the slipping of the vehicle. A reasonable limit may be defined as follows:

$$T_{break} - T_{shaft} = \mu M_V g \cos\theta \quad (8)$$

The friction coefficient μ is actually a function of road conditions, but for simplicity, it was supposed constant and equal to 0.5.

The torque on the shaft necessary to keep the vehicle moving with the desired speed is finally calculated by the following expression:

$$T_{nec} = r\left(M_V a_{des} + F_{drag} + M_V g \sin\theta\right) \quad (9)$$

3. Control Scheme

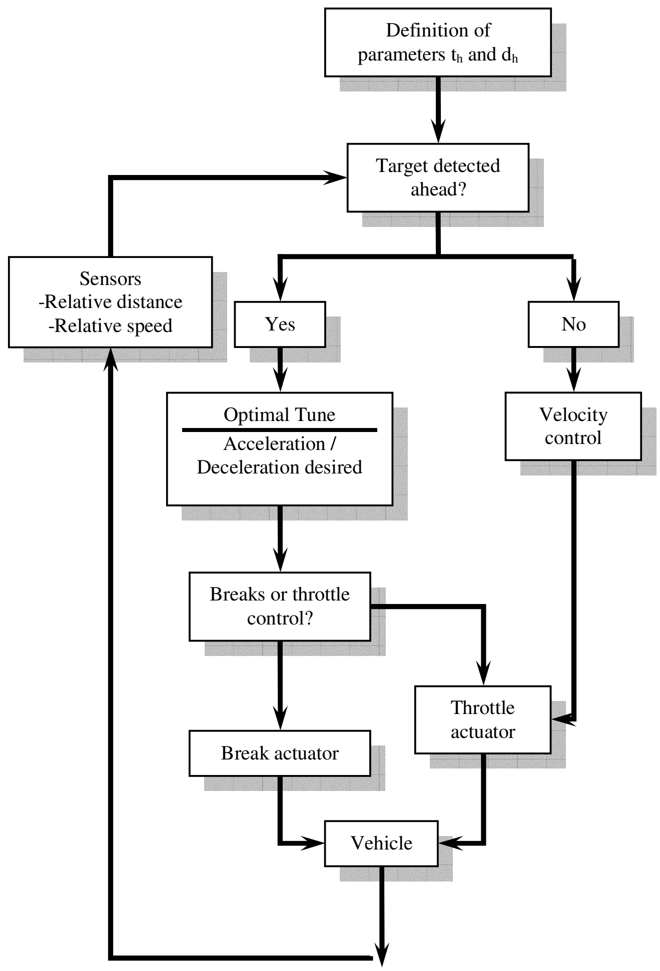

Figure 1. Control Algorithm

Figure 1 presents a block diagram of the control system algorithm used to simulate a stop-and-go cruise system. To start the control algorithm two parameters must be first defined:

a) The headway time, the time that the controlled vehicle will take to reach the target ahead, if it is stationed. This parameter was set as 1.5 seconds, based on vehicular dynamics and human reaction time [Touran, 99].
b) The desired distance between the controlled vehicle and the target forward, given by:

$$d_h = v_{cc} \cdot t_h \tag{10}$$

v_{cc} Controlled vehicle's velocity
d_h Headway distance
t_h Headway time

After that, the system verifies if there is any target ahead. If no target is detected, the system proceeds to the velocity control. Otherwise it proceeds to the optimal tune path.

Velocity control has two important functions:

a) To guarantee passenger's comfort, it limits the acceleration between -2 m/s^2 and 1 m/s^2
b) To determine the speed changes in very small intervals (Δt) according to:

$$\Delta v = a_{cc} \Delta t \tag{11}$$

a_{cc} Controlled vehicle's acceleration

Equation (11) shows that a proportional controller is sufficient for speed control.

Established a speed change, a signal is then sent to the throttle actuator. The throttle dynamics is modeled using a look-up table, a usual procedure in the automobile industry. Due to the lack of information, in this work this table was constructed using data of a fictitious vehicle. Furthermore, when the throttle actuator is on, the break torque is zero and if the driver activates the breaks, the cruise control is switched-off.

Due to throttle actuation, the vehicle dynamics is changed. The vehicle speed is calculated as in the previous section. When a target is detected ahead, the optimal tune block defines the desired acceleration or deceleration. The logic underlying the optimal tune block is presented in the next section. For now, only the block function is elucidated. The next two blocks in this path actually perform several functions, as may be clearer in Fig. (2).

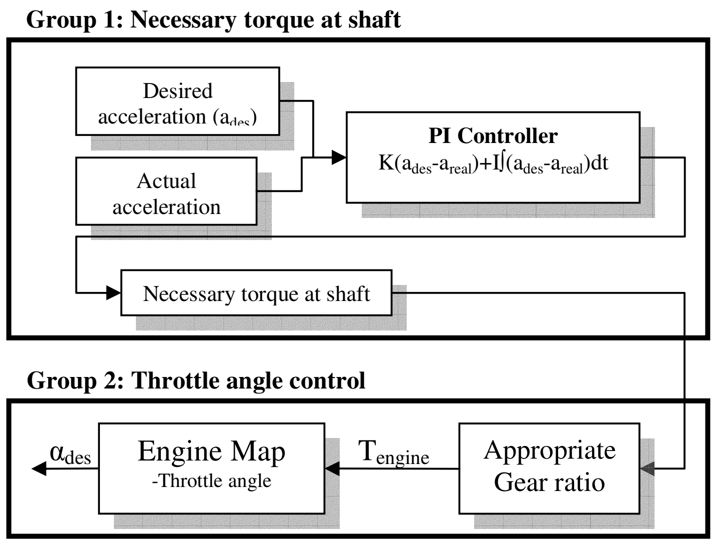

Figure 2. Acceleration control

In the first group, the desired acceleration is compared to the actual acceleration and an error signal is issued and sent to a PI controller, which determines the necessary torque at the shaft to decelerate the vehicle.

In the following group, it is defined whether to activate the breaks, to change the gear ratio or just to reduce the throttle angle, based on Eq. (9). If $T_{nec} < 0$, breaks are also activated, besides the throttle angle is set to zero (fully closed position), otherwise the gear ratio is verified and, if necessary, the throttle angle is changed.

At last, vehicle information are measured using proper sensors, such accelerometers and inclinometers. In this work, it was supposed that these devices have a much faster dynamics then the plant, allowing therefore their dynamics to be neglected.

4. Vehicle behavior control law

In this section, the definition of the control law used in the block Optimal Tune is presented.

Optimal control laws with quadratic performance indices have been frequently used in this stage [Yi, 00].

Yi, Lee and Kwon [Yi, 00] suggest the following performance index and state space equation for this problem:

$$J = \int_0^\infty \left(e_d^{\ 2} + \delta \cdot e_v^{\ 2} + \varepsilon u^2\right) dt \qquad (12)$$

Where:

$$e_d = d_h - \left(x_p - x_{cc}\right) = x_3 t_h - x_1 \qquad (13)$$

$$e_v = v_p - v_{cc} = x_2 \qquad (14)$$

e_d	Distance error
e_v	Velocity error
J	Performance index
v_p	Target velocity
x_p-x_{cc}	Distance between target and controlled vehicle

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix} u + \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} w \tag{15}$$

where u is the desired vehicle acceleration and w is the target acceleration. The state vector is given by:

$$x = \begin{bmatrix} x_p - x_{cc} \\ v_p - v_{cc} \\ v_{cc} \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \tag{16}$$

Although a not completely controllable system rises using the suggested state vector, as can be easily seem from the rank of the controllability matrix, it was decided to use the same state representation for comparisons purposes.

Notice that the vehicle behavior is defined using the acceleration of the vehicle, the relative speed between the target and the vehicle, and the distance between the target and the vehicle and these are the variables weighted in the performance index. The target acceleration, obviously, is modeled as an exogenous input signal.

The performance index can be rewritten in its usual form as follows:

$$J = \int_0^\infty \left(x^T Q x + u^T R u \right) dt \tag{17}$$

where:

$$x^T Q x = e_d^{\,2} + \delta \cdot e_v^{\,2} \tag{18}$$

$$Q = \begin{bmatrix} 1 & 0 & -t_h \\ 0 & \delta & 0 \\ -t_h & 0 & t_h^{\,2} \end{bmatrix} \tag{19}$$

$$u^T R u = \varepsilon \cdot u^2 \tag{20}$$

Q State weighting matrix
R Input weighting matrix

The parameters to select for optimization are ε and δ, when an trade-off between safety, comfort and energy use is the main objective.

The control solution comes from the well-known Riccati equation solution, supposing full state measurement:

$$u = -Kx = -R^{-1} B^T X x \tag{21}$$

X Riccati equation solution

5. Control system tuning

As shown in Fig. (1), there are two controllers in stop-and-go procedure presented here: a PI controller to take account of the throttle and a Linear Quadratic Regulator (LQR) to control the vehicle dynamics itself. The PI controller was optimized using a Genetic Algorithm, specially designed for this purpose.

The PI controller actually was started with a three terms controller (PID) [Aström, 88], but the optimization discarded the derivative term, showing that the usual assumption of a PI controller for this task is indeed correct. GA parameters in this case were as follows:

- Population size: 10 individuals per generation;
- Maximum number of generations: 20;
- Crossover probability: 0.70;
- Crossover points: one;
- Mutation probability: 0.15;
- Binary population;
- Elitism selection.

Typical gains obtained by GA were:

K (Proportional gain) = 1.0
I (Integrative gain) = 4.6
D (Derivative gain) = 0.0

Due to uncontrollable states, verified by the controllability matrix rank: rank (Mc) = 2, it was impossible to apply a similar procedure to tune the LQR controller. Parameter values suggested by Yi, Lee and Kwon [04] for the definition of performance index shown in Eq. (12) and the use of the mathematical model developed in this work leaded to an unstable system. To solve the LQR control problem and reproduce results by Yi, Lee and Kwon [04], an exhaustive search was carried out, when ε=50 in Eq. (12) was found.

$$Mc = \begin{bmatrix} 0 & -1 & 0 \\ -1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \tag{22}$$

6. Results

To illustrate results three different cases are presented next.

6.1 Case 1: Comfortable system

It is supposed that a target is detected right ahead of the vehicle, moving with a velocity of 25.0 m/s (90 km/h), the cruise controlled vehicle is moving at 30.5 m/s (110 km/h) and that the distance between the target and the vehicle is initially 40 m.

Results of this simulation are presented in Fig. (3), which shows that the speed reaches the desired value very quickly, and the minimum distance between the target and the vehicle is 29 m at 4s. The headway distance converges as expected. In this case, the maximum deceleration reaches smoothly -2 m/s^2 for a very short time interval, indicating that comfort is being guaranteed.

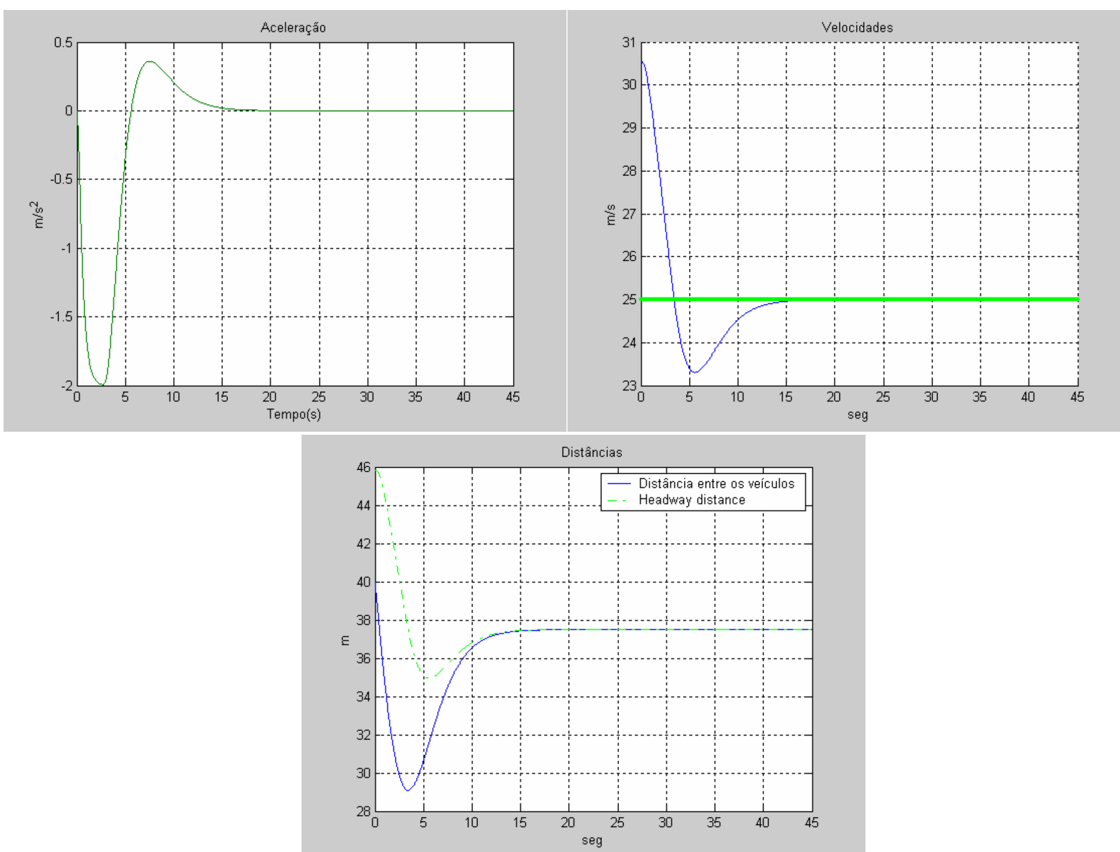

Figure 3. Case 1: Comfortable System results

6.2 Case 2: Safe system

In this simulation the same conditions of case 1 were used, but the saturation limits, which were removed to ensure a maximum safety level in detriment of comfort. Figure (4) shows that the maximum deceleration reaches now 2.5 m/s. As expected, there is a considerable improvement in the distance between the vehicle and the target, which reaches now a minimum of 33 m. It is important to point-out that nowadays a lower limit to acceleration is still subject of research. Actually, this value should be dynamically changed by the on-board computer, which would remove saturation limits to avoid collision in dangerous situations. However, for simplicity, this work and the work by Yi, Lee and Kwon [01] do not use this enhancement.

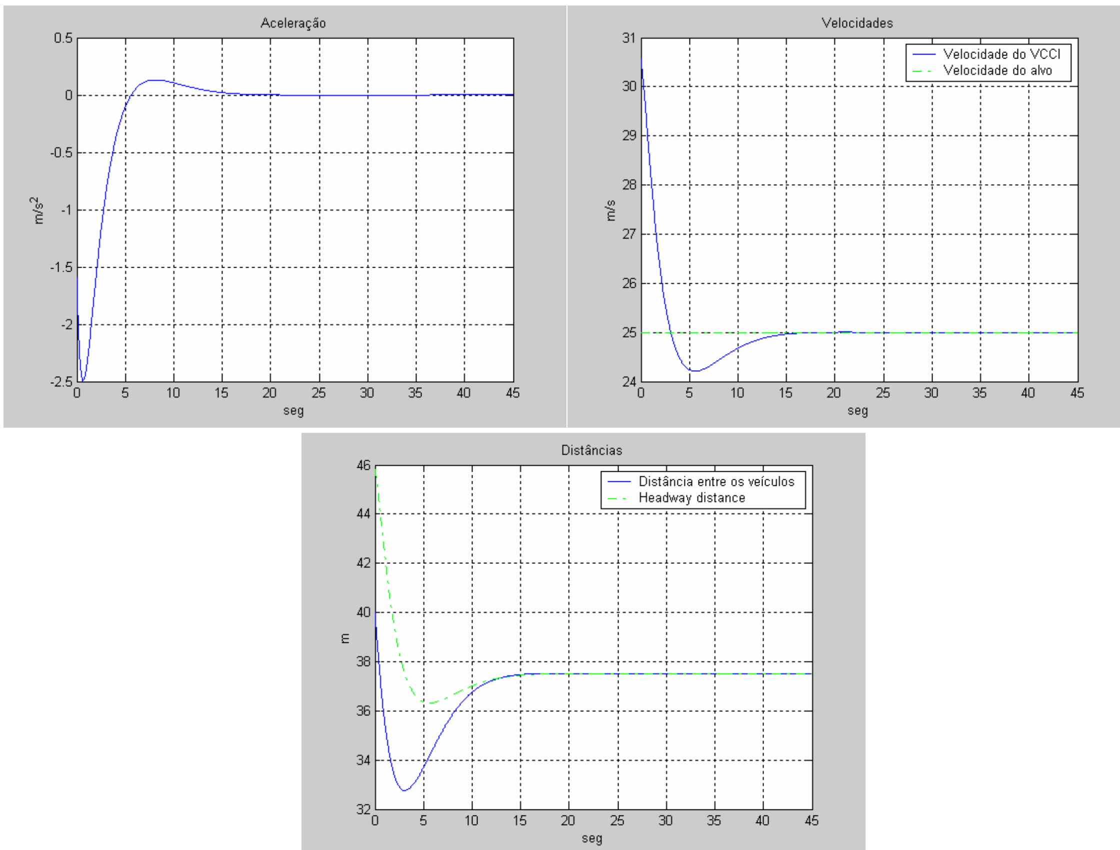

Figure 4. Case 2: Safe system results

6.3 Case 3: Target switch

This case simulates a cutout vehicle situation, when a target detected ahead disappears from the radar and a new one is immediately detected far ahead. The conditions simulated in this case are: new target speed 8.33 m/s (30 km/h); initial vehicle speed 5.55 m/s (20 km/h) and initial distance to new target is 10 m. Figure (5) shows that the vehicle acceleration to cope with the new situation. As expected, the vehicle will first accelerate till the new target velocity (8.33 m/s). The headway distance, the overshoot, the settling and raise times indicate a very satisfactory performance.

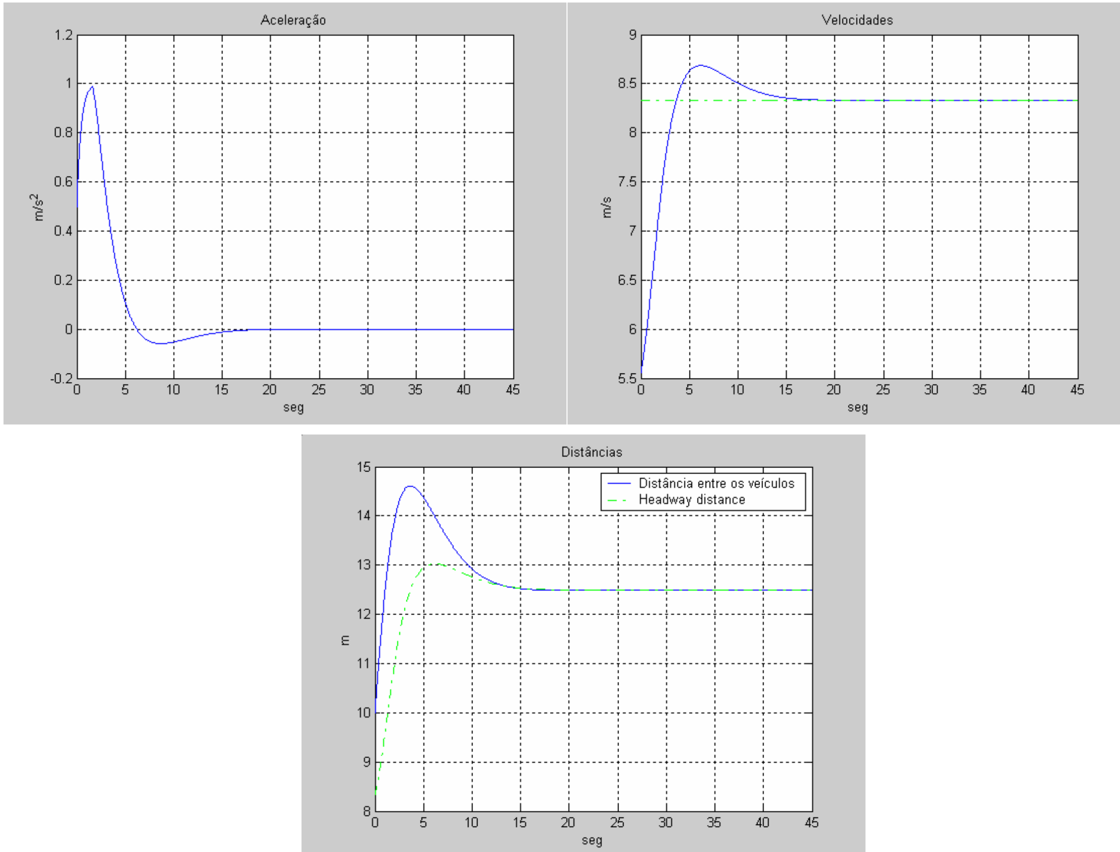

Figure 5. Case 3 – Target switch results

7. Conclusions

Though difficulties found to establish engine and break system maps due to industry sigil, a generic stop-and-go cruise control was designed and tested by simulations. Tools developed in this work can be used to simulate any type of vehicle with small adjustments. The next step in this research will be the definition of a new state space vector, which can guarantee complete controllability and allow the application of an optimal tuning method by GAs. New approaches to improve driving safety and comfort must also be taken in consideration.

8. References

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