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Academy of Sciences of the Czech Republic
Institute of Information Theory and Automation

RESEARCH REPORT

E. Suzdaleva, I. Nagy

Experiments with PID controller for fuel consumption optimization

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ÚTIA AV ČR, P.O.Box 18, 182 08 Prague, Czech Republic
Tel: (+420)266052422, Fax: (+420)286890378, Url: http://www.utia.cas.cz, E-mail: utia@utia.cas.cz

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1 Introduction

This research report describes experiments performed with a Matlab simulator of a vehicle, controlled by a PID controller.

A simple vehicle simulator is provided by Škoda auto a.s. (www.skoda-auto.com) for testing. The simulator generates responses to control variables fed to it. The control variables are

- pressing the gas pedal,
- pressing the braking pedal,
- selected gear of transmission.

The most important variables generated by this simulator are the fuel consumption, the speed, the engine speed and the engine torque.

The PID controller should be set so that:

- the vehicle speed will follow the recommended speed as close as possible;
- at the same time, the fuel consumption will be as close as possible to zero.

It means that there are two set-points for the system “driver-vehicle”: the recommended speed and the zero set-point for the fuel consumption.

The recommended speed used for experiments is chosen from measurements of the most economical driving in the given route, i.e., with the lowest fuel consumption. This speed was preprocessed in order not to exceed the speed restrictions existing in the given road. It means that when the speed values meet the restrictions, they remain to be equal the allowed speed, and excesses are cut off.

1.1 Aims of experiments

The aims of experiments are

- to try to control a simulated vehicle by a PID controller and ensure safe driving (i.e., non-exceeding the limits);
- to find the most suitable settings of the PID controller from the viewpoint of safety and the minimal fuel consumption (simultaneously);
- to test the PID controller with logical fuel-saving conditions (that will be explained later)
- to compare indicatively the resulting reduced fuel consumption with various real consumptions in the given route.

2 Description of Matlab code

M-file is available in http://utia.cas.cz:1800/svn/jikin/_Zenja/KfaSimPidLog.zip

2.1 Preparatory settings

Both the recommended and the maximal allowed speed courses are loaded as the separate mat-file. The same file also contains the information about a road gradient in the given route in %. It is loaded as

```
load __terrain_rychlosti
```

Another mat-file to be loaded contains the information about real (both average and immediate) fuel consumptions from 7 rides in the given route, i.e.,

```
load spo7dat
```

Number of data items practically for the whole route is defined as:

```
nd=11500;
```

Initialization of the vehicle simulator is:

```
global Simul;
variables;
skoda_sim_init_v20;
```

Default (recommended) settings for the vehicle simulator are as follows. Default gas pedal pressing:

```
plyn = 30;
```

Default braking pedal pressing:

```
brzda=0;
```

Default gear:

```
kvalt = 6;
```

Assignment of variables from the loaded mat-file __terrain_rychlosti;

```
ref=doporucena_rychlost;
maxry=maximalni_rychlost;
skl=sklon_vozovky;
```

where `skl` is a road gradient, positive uphill and negative downhill.

Definition of a constant for conversion of fuel consumption from $[\mu L/0.2s]$ to $[L/100km]$:

```
k=100*((5*3600)/1000000);
```

2.2 Logical block initialization

Before the time cycle it is necessary to define whether the logical fuel-saving conditions should be used. These conditions should be understood as series of logical statements, which check the current driving from the viewpoint whether a situation is suitable for fuel saving or not (depending on downhill or uphill, etc.). The logical fuel-saving conditions are based on general recommendations from experts for lower fuel consumption [1, 2].

The logical block is called as function `logCond`. It is turned ON or OFF in the following way:

```
logc=1; % 1 =  with or 0 = without log.conditions
```

The fuel-saving conditions in this logical block are mostly connected with (i) fuel economy when driving downhill and in a flat road; (ii) prohibition to exceed the speed; (iii) check of speed and braking (if needed) before approaching speed limits; (iv) prohibition of simultaneous pressing the gas and the brake pedals, etc.

Another group of logical conditions with auxiliary recommendation for manual gear selection is turned ON or OFF by:

```
kv=1; % 1 = with  0 = without
```

In detail, implementation of logical fuel-saving conditions is described in Section 2.5.

2.3 Vehicle simulation

During the time cycle the vehicle simulator generates the fuel consumption, the speed, the engine speed and the engine torque, etc (a sequence of variables can be shown, using command `vars`).

```
Auto(i,:)=skoda_sim_simul_v20([plyn,brzda,kvalt]);
rych = Auto(i,2); % saving the speed
```

As a default the generates variables respond to the default values of the gas pedal pressing, brake and gear.

At each time instant the fuel consumption is converted into [L\100km] with the help of the constant defined above: `spot(i) = k*(Auto(i,1)/Auto(i,2));`

A vehicle position in the given route is defined via a special kilometer counter, which starts at the certain known place of the route and calculates a position of a vehicle in meters in relation to the start location.

```
km(i)=Auto(i,13);
```

This kilometer counter replaces the GPS information about the given route for this experiment. Its index is used to determine the corresponding recommended and the maximal allowed speeds and the road gradient in the certain location.

```
j=round(km(i)*1000);  if j==0, j=1; end
ist=j;
refr(i)=ref(j);
maxr(i)=maxry(j);
```

2.4 PID controller

Proportional, integral and derivative terms of the PID controller are defined as follows:

```
erych = rych - refr(i);
drych = rych1 - rych2;
srych = srych + erych;

plyn1=Auto(i-1,4);
plyn2=Auto(i-2,4);
dplyn=plyn2-plyn1;
espot=(spot(i)-0); % here to zero set-point
```

The PID controller can be switched between using the set-points both for consumption and speed (`reg=1`) and using set-point only for speed (`reg=2`). The second case gives almost precise tracking the recommended speed, but higher fuel consumption. The first – more free speed (non-exceeding the limits), but lower consumption. The PID controller is as follows:

```
reg=1;
 switch reg
     case 1 % control to consumption and speed
         plyn = -(1.6*espot + 2.9*erych + 2*drych  + 0.6*dplyn);
     case 2 % control only to speed
         plyn = -( 50*erych + 0.4*drych + 0.01*srych + 0.02*dplyn);
 end
 pd=plyn;
```

where tuning parameters (proportional, integral and derivative gains) are obtained (so far) empirically. *pd* is used for saving.

2.5 Logical block

For experiments, the following logical fuel-saving conditions are proved themselves. They are placed inside of function `logCond`.

1. So far the acceleration downhill along with prohibition of exceeding the maximal allowed speed is solved as follows:

```
% a bit downhill
 if and((skl(j)<-1.3),(abs(Auto(i,2)-refr(i))<=2))
     plyn=0.5*pd;
 elseif and((skl(j)<-1.3),(abs(Auto(i,2)-refr(i))<=8))
     plyn=0;
     % more downhill with exceeding the maximal allowed speed
 elseif and((skl(j)<-1.5),(Auto(i,2)-maxr(i))>3)
     plyn=0;
     kvalt=0;
     brzda=6;
     % returning the zero braking and smooth starting
 else brzda=0;
     plyn=0.5*pd;
```

```
     kvalt=6;
 end
```

The considered route is characterized mostly by presence of slight hills. For these situations `skl`, approaching the values from -1% to -1.5%, indicates a slight descent. A minimal gradient of the given route is -3.417%. In the same time, a difference between the controlled speed and the recommended speed in the given location is also important. Values of these differences are obtained empirically in km/h.

2. Prohibition of exceeding the maximal allowed speed when driving in a flat road, i.e., usual driving, is implemented as

```
% exceeding the maximal allowed speed in a flat road
 if and((skl(j)>-0.1),(Auto(i,2)-maxr(i))>2)
     plyn=0;
 % exceeding the maximal allowed speed in a flat road
 % with already zero gas pressing
 elseif and((and((skl(j)>-0.1),(Auto(i,2)-maxr(i))>2)),(plyn==0))
     brzda=10;
 else
     % returning the zero braking and smooth starting
     brzda=0;
     plyn=0.5*pd;
 end
```

3. Auxiliary recommendation for manual gear selection (still must be tested)

```
ot=Auto(i,8); % engine speed
if kv
    if (1550<=ot<=1800) & (3<rych<15) & (kvalt==1)
        kvalt=2;
    elseif (1450<=ot<1550) & (15<=rych<25) & (kvalt==2)
        kvalt=3;
    elseif (1350<=ot<1450) & (25<=rych<35) & (kvalt==3)
        kvalt=4;
    elseif (1150<=ot<1350) & (35<=rych<45) & (kvalt==4)
        kvalt=4;
    elseif (1000<=ot<1150) & (45<=rych<50) & (kvalt==4)
        kvalt=5;
    end

    % recommendations
    if (1000<ot<=1850) & (rych>rych2) & (kvalt~=6)
        kvalt=kvalt+1;
    end
    if (rych2>rych) & (ot<=1000) & (kvalt~=0)
        kvalt=kvalt-1;
    end

end
```

4. Approaching speed restrictions

```
%km counter values before the limits start
bodOmez=[5805; 13000; 15773; 17593; 18540; 20168; 27420; 29574; 30651; 33110; 34998;...
    35107; 35244; 36452; 37523];
% check of speed before area with speed limits and braking by engine if needed
for l=1:size(bodOmez,1)
```

```
    if and((abs(ist-bodOmez(l))<0.0001),(rych>maxry(ist)))
        plyn=0;
    end
end
```

5. The speed check and braking in sharp turns with a low speed

```
bodf=ist+1;
   if  and((ref(bodf)<50),(rych>ref(bodf)))
       plyn=0;
       brzda=7*(rych-ref(bodf));
   end
```

6. Prohibition of the simultaneous press of the gas and brake pedals:

```
if brzda>0.8, % minimal press in brake system
     plyn=0;
 end
```

   Minimal value of press in the brake system is 0.8, maximal – 25.

The logical conditions for approaching the road turns must also be implemented here.

2.6 Route specification

The considered road is of a altitude, whose course as well as the gradient are shown in Figure 1 (left). The used kilometer counter is shown in Figure 1 (right). Such a view is useful to see where the driving takes place each time instant in relation to the altitude and some "key" identification road points in the ordinate axis of the kilometer counter.

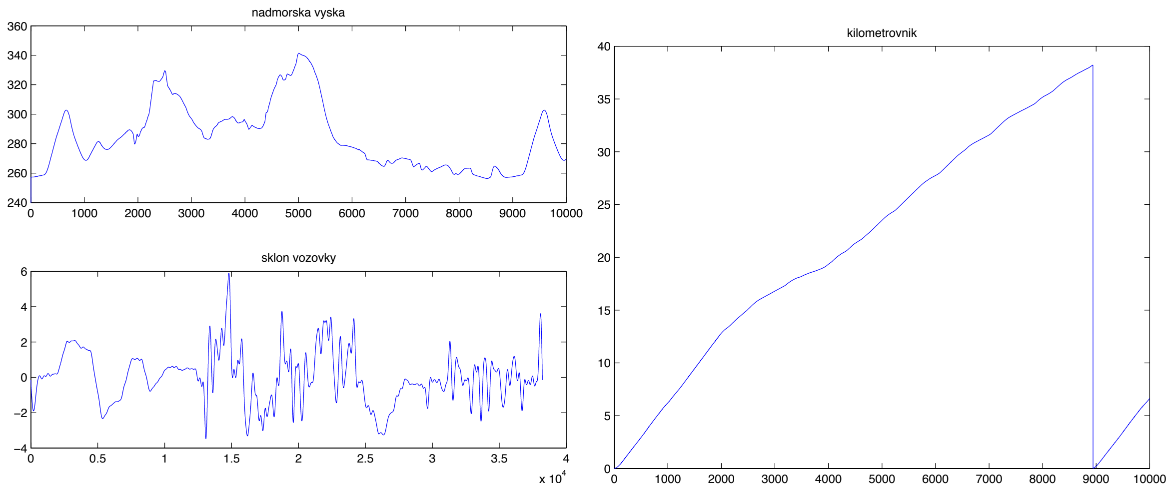

Figure 1: The altitude, road gradient and the kilometer counter.

3 Results of experiments

3.1 PID controller using set-point only to recommended speed

The following results are obtained using the PID controller, which controls only to the recommended speed (`reg=2`). The logical blocks are used. The obtained fuel consumption is 5.6844 $L/100km$ with average speed 83.6804 km/h.

Figure 2 demonstrates courses of the fuel consumption and the controlled speed, which follows the recommended speed.

Figure 3 shows courses of pressing the gas and the brake pedals and of gear selection.

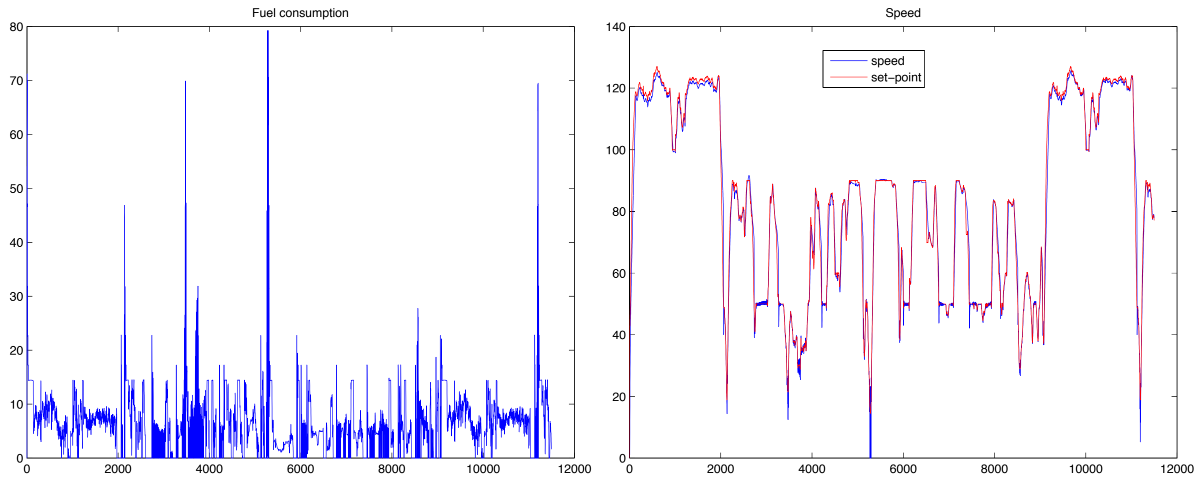

Figure 2: The fuel consumption (left) and the speed tracking (right) for PID controller using set-point only to speed. The average fuel consumption – 5.6844 $L/100km$. Notice that the controlled speed follows the recommended very well.

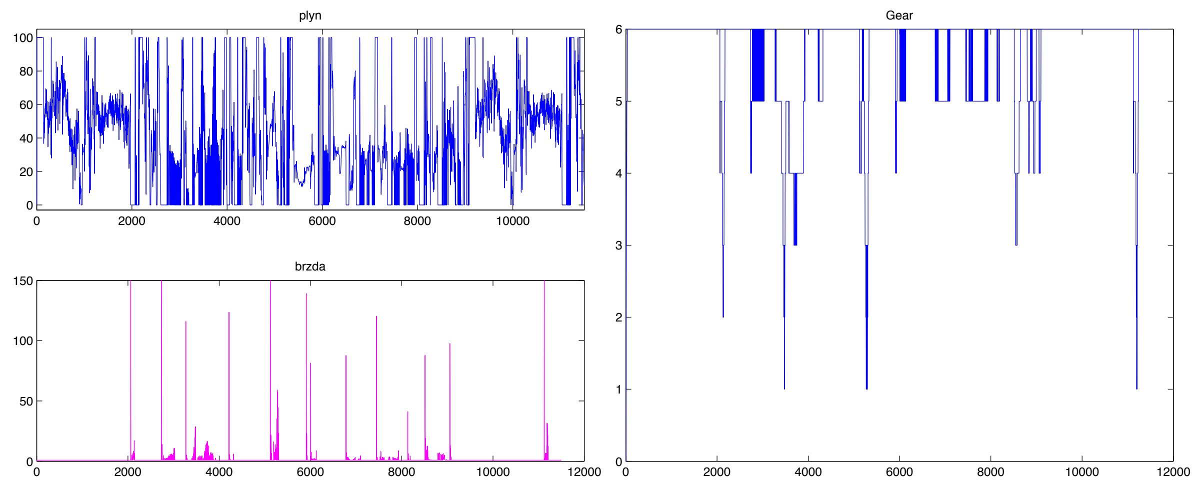

Figure 3: The gas and the brake pedal press (left) and the gear (right) for PID controller using set-point only to speed. Notice that the gas pedal pressing jumps very often to 100%. The braking is used only in sharp turns with low speed.

3.2 PID controller using set-points both to fuel consumption and speed

This section provides results obtained with PID controller using set-points both to fuel consumption and speed (`reg=2`). The logical blocks are used.

The fuel consumption is reduced to 4.3597 $L/100km$ with average speed 59.3114 km/h. See the obtained results in the following figures.

Figure 4 demonstrates courses of fuel consumption and speed.

3.3 Results of "Pure" PID controller without logical block

The results of the PID controller without usage of logical block were worse and unstable.

3.4 Indicative comparison with real fuel consumptions from given route

The average fuel consumption is evaluated as follows.

```
disp('---------------------------------------')
```

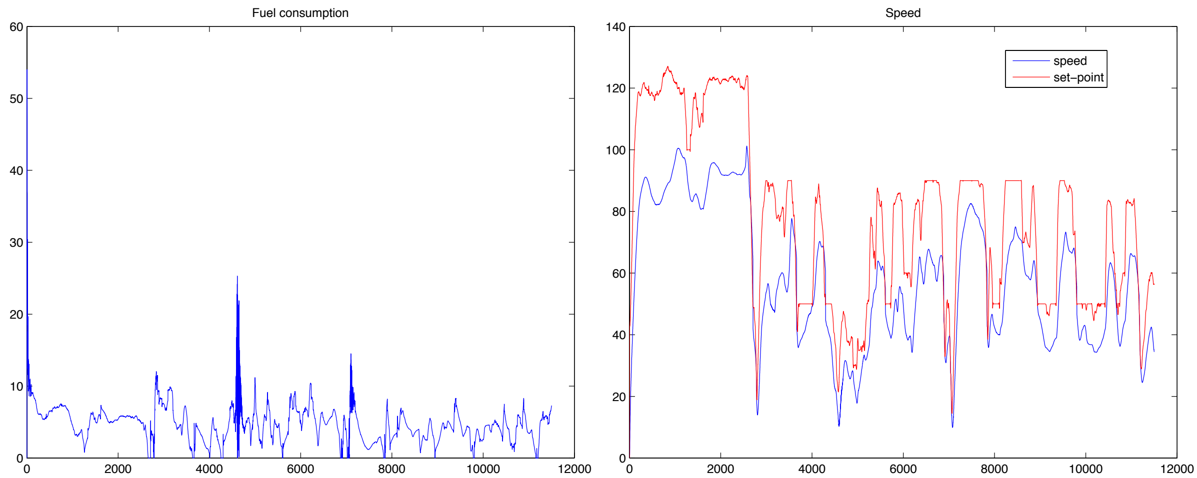

Figure 4: The fuel consumption (left) and the recommended speed tracking (right) for PID controller using set-points both to fuel consumption and speed. The average fuel consumption – 4.3597 $L/100km$. Notice that the speed is not so close to the recommended as in Figure 2. However, it is still in safe interval even for out-of-town road. The fuel consumption is reduced in comparison with that in Figure 2. More specific settings of PID tuning parameters can help.

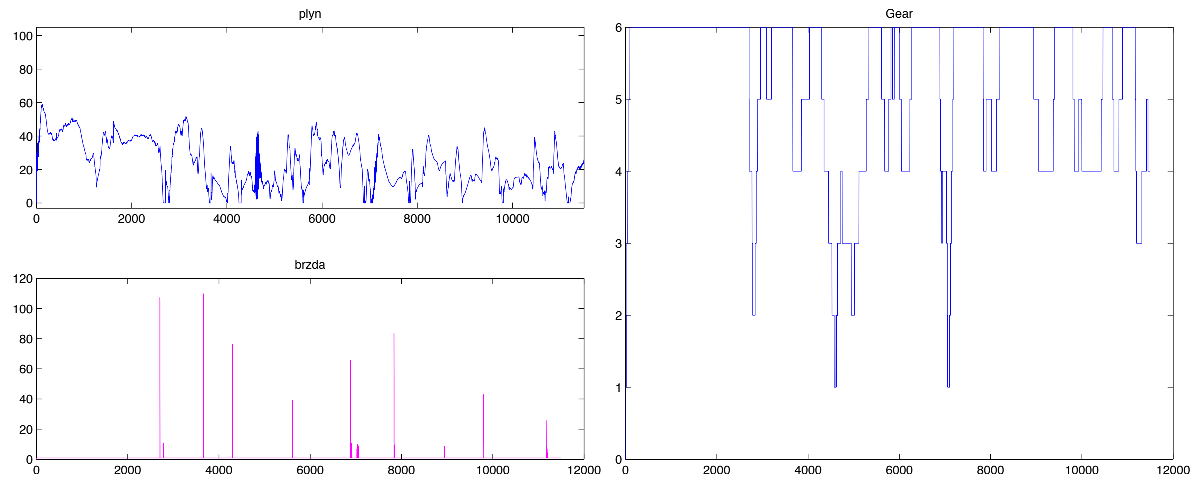

Figure 5: The gas and the brake pedal press (left) and the gear (right) for PID controller using set-points both to fuel consumption and speed. Notice that the gas pedal pressing is much smoother in comparison with that in Figure 3. The braking again is used only in sharp turns with low speed.

```
disp('Average consumption and average speed- with PID')
avercon=sum(Auto(:,1)/1000000)/ (sum(Auto(:,11))/1000) * 100;
averspee=mean(Auto(:,2));
[avercon averspee]
```

where $Auto(:, 11)$ is a distance travelled.

Average real fuel consumptions and average real speeds used for indicative comparison are loaded as follows:

```
disp('--------------------------------------')
disp('Average consumption and average speed - real from 7 rides')
prspo=[prumspo{1};prumspo{2};
    prumspo{3};
    prumspo{4};
    prumspo{5};prumspo{6};prumspo{7}];
```

```
pruryc=[mean(ryc{1});mean(ryc{2});mean(ryc{3});mean(ryc{4});
mean(ryc{5});mean(ryc{6});mean(ryc{7})];
spot_ryc=[prspo pruryc]
```

The average fuel consumptions and the average speeds from 7 rides for indicative comparison are as follows:

6.3557	78.5883
5.3661	72.6437
5.2353	72.7957
4.7087	66.0269
4.7146	68.4693
5.3620	73.7642
4.9381	69.2354

The lowest (so far) experimental fuel consumption 4.3597 with average speed 59.3114.

4 Conclusion

The experiments performed demonstrate optimistic results. They are surely worth continuing and improving.

References

[1] E. Suzdaleva, I. Nagy, and L. Pavelková. Fuel consumption optimization: Early experiments. In *Preprints of the 16th IFAC Symposium on System Identification Sysid 2012*, pages 751–756, Brussels, Belgium, July 11 – 13 2012.

[2] E. Suzdaleva, I. Nagy, L. Pavelková, and T. Mlynářová. Servo problem within fuel consumption optimization. In *Proceedings of IASTED International Conference on Engineering and Applied Science (EAS 2012)*, Colombo, Sri Lanka, December 27-29 2012. accepted.