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A novel integrated approach for path following and directional stability control of road vehicles after a tire blow-out

Fei Wang [a], Hong Chen [a,b,*], Konghui Guo [a], Dongpu Cao [c]

[a] State Key Laboratory of Automotive Simulation and Control, Jilin University (Campus NanLing), Renmin Str. 5988, 130025 Changchun, PR China
[b] Department of Control Science and Engineering, Jilin University, Changchun, China
[c] Center for Automotive Engineering, Cranfield University, UK

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ABSTRACT

The path following and directional stability are two crucial problems when a road vehicle experiences a tire blow-out or sudden tire failure. Considering the requirement of rapid road vehicle motion control during a tire blow-out, this article proposes a novel linearized decoupling control procedure with three design steps for a class of second order multi-input-multi-output non-affine system. The evaluating indicators for controller performance are presented and a performance related control parameter distribution map is obtained based on the stochastic algorithm which is an innovation for non-blind parameter adjustment in engineering implementation. The analysis on the robustness of the proposed integrated controller is also performed. The simulation studies for a range of driving conditions are conducted, to demonstrate the effectiveness of the proposed controller.

1. Introduction

A blow-out of a road vehicle tire is a sudden fast loss of pneumatic tire pressure yielding an explosion. Although blow-outs are rare, they happen very suddenly and still cannot be avoided completely up to now. After a tire blow-out, directional stability are destroyed, begins with a spin or slide that in severe cases can cause a continuous roll of the vehicle, and collide with the guardrail or other vehicles. So the path following and directional stability are two crucial problems when a road vehicle experiences a tire blow-out or sudden tire failure. Considering that a blow-out forces a driver to react swiftly and decisively, but in reality many inexperienced drivers are very likely to take wrong operations, and ordinary active safety systems cannot achieve a satisfactory effect, the active safety system specifically designed to deal with the blow-out is urgently needed and worth studying.

During the past two decades, the transient vehicle behaviors during and after a tire blow-out or failure were investigated through well-instrumented vehicle handling tests and computer simulations [1–8]. These researches show that the location of the flat tire is the predominant factor in determining how the road vehicle initially responds. The corrective action of the driver would take the form of a minor steering input, and the amount of it is dependent on the vehicle, tires and current lateral acceleration. Slamming on the brakes and yanking the wheel are wrong and very dangerous behaviors. In addition, the effect of dropping tire pressure on the value of key tire parameters is obtained from these researches as shown in Table 1. This offers a foundation for establishing the control-oriented vehicle dynamic motion model when a tire blow-out occurs.

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* Corresponding author at: State Key Laboratory of Automotive Simulation and Control, Jilin University (Campus NanLing), Renmin Str. 5988, 130025 Changchun, PR China.

E-mail addresses: chenh@jlu.edu.cn, chenh98cn@hotmail.com (H. Chen).

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Table 1
Relationship between key tire parameters and decreasing inflation pressure.

Tire parameter	Effect
Cornering stiffness	Decreases
Radial stiffness	Decreases
Camber stiffness	Decreases
Tire radius	Decreases
Rolling resistance	Increases
Self-aligning torque	Increases
Longitudinal slip stiffness	Increases

At present, research concerning vehicle motion control right after a tire blow-out can be divided into three types: steering-only control, braking-only control, and the integrated control. In order to minimize the negative impact of vehicle lateral deviation due to a tire blow-out, *Patwardhanetal.* presented a steering-only control approach where a blow-out controller switches on right after a tire blow-out, and this switching is triggered by the blow-out alarm generated by the tire pressure measurement [1]. The vehicle speed threshold for the control during the testing was only 32 km/h. As is known to all, a quick turn of the steering wheel is a very dangerous behavior after a tire blow-out at high speed. This is because a high vehicle lateral acceleration would tend to lead the flat tire to detach from the wheel, and the wheel will be in direct contract with the road which can lead to a rollover accident [8]. To avoid this problem, the braking-only controller is used for enhancing vehicle lateral stability. The control principle is similar to Electronic Stability Program (ESP): differential braking is applied to generate the additional yawing moment which can help the vehicle follow the driver intention. In [9], the optimal control algorithm was used to determine the optimal vehicle yaw moment based on the 2-DOF (degree-of-freedom) vehicle model and according to the location of the flat tire, different braking force distributions are given. However, the randomness of the driver behavior is a challenging problem.

There have been major technological advances in the automotive sector in the past few decades, and the industry now is experiencing significant development in automated vehicle technologies [10–15]. The rapid and continuous advances in autonomous vehicle technologies empower active safety systems further with real-time information about the surrounding environment and to share control with a driver or replace the human driver in certain circumstances. This offers the possibility of realizing the automatic control of a road vehicle after a tire blow-out. In addition, with the development of the chassis control technology, such as Anti-lock Braking Systems (ABS) [16,17], Traction Control Systems (TCS) [18], Active Front Steering (AFS) system [19,20], the Electronic Stability Program (ESP) [21], control suspensions [22–24], integrated chassis control systems [25–28], and so on [29–31]. the existing mechanical executive system is capable of performing the proposed control function and pave the way for the system achievement. As mentioned above, the path following and directional stability are two crucial problems after a tire blow-out, the former is related to the steering controller while the latter is related to the braking controller, as a consequence, coordinating and integrating two controllers is proposed in [32]. The proposed controller can automatically take the right and proper actions in place of the human driver once a burst-alarm is detected. But in [32], only the straight driving condition is considered.

In this paper, a novel integrated approach is provided which can be used not only in the straight driving condition but also in the turning driving condition. In a very recent study of the author's group [33,34], a novel nonlinear control method was developed and the simulation experiments prove that this method can effectively deal with the control problems for road vehicles after a tire blow-out [34]. However, taking into account the rapid control requirements, as well as the cost problems from market competition pressure, the optimization procedure in [34] is not welcomed by engineers. For this reason, some improvements are made in this paper. With the new proposed design procedure, the optimization process is no longer needed and a new way for selection of control parameters which is a trouble problem for engineers is suggested by using the random algorithm. The controller is re-designed in the framework of feed-forward feedback with three steps. The first step is to design a steady-state-like feedback control which is obtained by setting the system in steady state and implemented according to the current measured or estimated state x, but not the true steady state x_s. In order to improve the response performance of the system, a feed forward control related to the reference dynamics is designed in the section step. To deal with the final tracking offset error, a state-dependent PD/PID error feedback control is added as the last part of the control action. On this basis, the proposed control method realizes self-tuning decoupling control for the multi-variable system and it is also an innovation for non-blind parameter adjustment in engineering implementation. The evaluating indicators for controller performance are presented and a performance related control parameter distribution map is obtained based on the stochastic algorithm. Since the optimization algorithm is no longer needed, by comparison with [34], the proposed method in this paper is more suitable for engineering application. Considering that the vehicle model is simplified to facilitate the control system design, certain system modeling uncertainties do exist. Therefore, the robustness analysis of the integrated controller is given. Here, it is worth noting that due to the improvement of control methods the closed-loop system is linearized. This makes the analysis of the system performance become simple and clear, which has the potential to be more acceptable for the engineers.

The paper is presented as follows. Section 2 outlines the vehicle model with a flat tire used by controller design. Section 3 describes the methodologies for generating the control law in the modified triple-step controller design framework and the