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Design and analysis of an integrated suspension tilting mechanism for narrow urban vehicles

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ABSTRACT

This paper presents the design of an integrated suspension tilting mechanism for narrow tilting vehicles. The challenge in the design of such suspension tilting mechanisms is to allow large suspension travels to generate sufficient tilting angles to balance the vehicle in cornering, while at the same time remain as compact as possible to save the space for passengers and cargos. Existing solutions, which are mostly based on parallel mechanisms, are not space-friendly and add extra weight to the expected compact and light-weighted urban vehicles. This paper firstly examines the feasibility of various automobile suspension mechanisms by considering their complexity and space requirements, and identifies the trailing arm mechanism as a promising solution. Then the kinematic and dynamic properties of the vehicle during large suspension heave motions are examined to establish guidelines for detailed mechanism design. Finally, more detailed constraints and objectives are considered to arrive at an optimal design. Simulation results confirm that the longitudinal movement of the wheel can be utilized to improve vehicle stability.

1. Introduction

To resolve the issues like congestion, parking, fuel consumption and pollutions in urban transportation systems, narrow tilting vehicles (NTV) are proposed as a solution [1]. They are in many ways similar to common street cars but designed to be narrow to seat one or two people in tandem. Their reduced size in lateral direction saves the space, and thus proves to be more efficient in utilizing the current road infrastructure like lane space and parking space [2]. The reduced total mass as a consequence of reduced size also helps to improve fuel efficiency and reduce the pollution.

The narrow cabin design seems to be the cure for many of the transportation problems, but it also introduces a vital problem of such vehicles—they can easily have roll-over issues without a proper control. To enable such vehicles to be operated with normal vehicles on streets, the riding height of such vehicles needs to be almost equal to current vehicles, but their reduced track width greatly decreased the vehicle's capability to resist roll-over. The track width ratio, which is a rough measure of vehicle roll stability [3], is almost doubled for narrow vehicles compared with the normal width automobiles.

To resolve this, automotive engineers have come up with the idea of tilting the vehicle into the inner bend of the curve, just like what motorcyclists do. The tilting motion generated by the tilting mechanism not only stabilizes the narrow vehicle and enables it to negotiate the curve at a higher speed, but also makes the driving more fun [4]. All these along with the closed weather-proof cabin, better safety improvements suggest that narrow tilting vehicles are combining the best of

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Nomenclature

m	vehicle mass
a, b	nominal distance from front/rear axle to CG
l_0, l	wheel base before and after tilting, $l_0 = a + b$
h_0, h	CG height before and after tilting, $h = h_0 \cos(\phi_x)$
T_{w0}, T_w	track width before and after tilting, $T_w = T_{w0}/\cos(\phi_x)$ for trailing-arm
g	gravity constant, $g = 9.81\ m/s^2$
a_x, a_y	vehicle longitudinal and lateral acceleration
a_{yeff}	unbalanced vehicle lateral acceleration
ϕ_x	vehicle tilting angle
Δx, Δx_1, Δx_2	longitudinal displacement of the wheel
Δz, Δz_1, Δz_2	vertical displacement of the wheel
$\hat{n}_1$,$\hat{n}_2$	normal direction of the contact plane
F_{xi}, F_{yi}, F_{zi}	longitudinal, lateral and vertical forces on each wheel i
Δx_{in},Δx_{out}	longitudinal movement of the inner- and outer-side wheels during cornering

regular automobiles and motorcycles. Several tilting vehicle prototypes and models have been built and they can be classified into two major groups: single body tilting and chassis tilting [5].

For the single body tilting as shown in Fig. 1(a), the chassis acts as a fixed base like a normal car while the cabin can be tilted with regard to the chassis by actuators mounted between non-tilting (i.e. chassis) and the tilting part (i.e. the passenger compartment) of the vehicle [6]. The design can be seen in GM Lean Machine [1], Carver [6] and CLEVER [7,8] projects. Such solutions are simple and cost effective, but since the cabin and the load are relatively light compared to the net weight of the vehicle, tilting the cabin only have limited potential to improve the stability of the vehicle [9].

The chassis tilting as shown in Fig. 1(b), on the other hand, tilts the cabin as well as the chassis, and would be more appealing to narrow vehicle applications. This approach can usually be achieved by using actuators to change the nominal position of the independent suspensions. Examples of the chassis tilting vehicles are Mercedes-Benz F-300, as well as other research prototypes [10–12]. In these designs, either the suspension arms [10,11] or the mechanical synchronizer [12] needs to be assembled in the vehicle lateral plane to generate the desired motion of the suspension struts.

Such mechanisms take a large portion of the space from the narrow cabin, and the linkages increase the complexity and weight of the system. An integrated suspension tilting (IST) concept has been proposed in [13] to resolve these problems. The classical suspension system is known to contain three major parts [28]: a structure that supports the vehicle's weight and determines suspension geometry, a spring that stores kinematic energy and potential energy, and a shock absorber to dissipate kinetic energy. The novelty of the suggested solution is to use the interconnected hydro-pneumatic struts as the actuator and the spring and damper component as well. The interconnection magnifies the roll stiffness of the vehicle without affecting the bump stiffness. The adoption of the hydraulics makes it easier to synchronize the movement of the suspensions. Much space, as well as weight, can be saved due to the compact and integrated design. By moving the suspension struts in either reverse or same directions through control of the pumps, the vehicle tilting as well as riding height adjustment can be achieved as shown in Fig. 2.

To implement the proposed IST concept, a proper suspension mechanism still needs to be designed. Unlike the traditional suspension mechanisms on four-wheeled automobiles which only allow limited bump travels, a large vertical wheel displacement is needed to accommodate the necessary tilting angles. This, in turn, might change the vehicle kinematics and dynamics properties.

This paper, by adopting the multi-body kinematics approach [29,30], carefully examines the kinematic properties of suspension mechanisms for generating tilting motions. Different from the quarter car [31] or half-car models for traditional

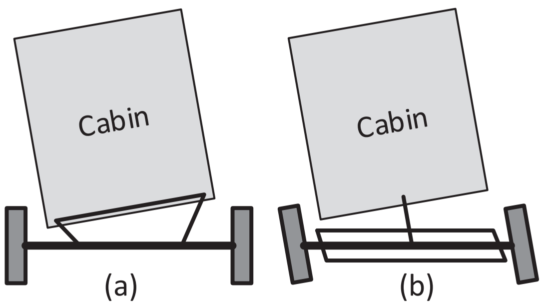

Fig. 1. a) Single body tilting, and b) chassis tilting.