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Real–Time Modeling of Soft Soil–Tire Interaction Using a Map–Based Approach

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***Abstract*—**Accurate modeling of tire–terrain interaction represents a key aspect essential for assessing the performance of wheeled and tracked vehicles operating in off–road conditions, with direct applications in planetary exploration, agriculture, and military domains. Over the years, several families of models have been developed, including physical and semi–empirical approaches, capable of capturing detailed soft soil–tire interaction phenomena. However, their high computational cost restricts their use mainly to offline vehicle dynamics simulations. This limitation is particularly critical in real–time contexts, such as driving simulators, where computational efficiency and time constraints are essential. This paper introduces a novel contact model tailored for real–time simulation, based on precomputed force maps. These maps store tire forces and moments generated offline using a custom semi–empirical contact model. By systematically evaluating the original formulation across its independent variables, the maps provide comprehensive coverage of the expected operating conditions. The tabulated model is then integrated into a virtual quarter–car and benchmarked against the original semi–empirical approach. Numerical results show that the proposed map-based formulation preserves the accuracy of the semi–empirical model while drastically reducing computational effort, thereby enabling its use in real–time applications such as driving simulators for the safe and cost–effective training of military operators.

Keywords—Terramechanics, Off–road mobility, Driving simulators, Military vehicles, Numerical simulation.

I. INTRODUCTION

Soft soil–tire modeling plays a crucial role in vehicle dynamics, supporting both performance assessment and mobility prediction in off–road conditions [1–3]. The interaction between pneumatic tires or tracks and fine–grained, unconsolidated surfaces such as sand, clay, or snow is the subject of Terramechanics [4]. In the literature, modeling approaches are generally classified according to their level of detail and numerical formulation [5–7].

- Empirical models are derived directly from experimental data and are mainly used for quick mobility assessments under known conditions [8]. While computationally efficient, they are limited to specific tire–terrain combinations and unsuitable for dynamic simulations.
- Physics–based models rely on fundamental mechanics and numerical techniques such as the Finite Element Method (FEM) and the Discrete Element Method (DEM) [9–12]. These approaches provide high fidelity but are computationally expensive and often require complex parameterization that may not reflect actual soil behavior. They are effective for studying individual tire dynamics but impractical for full–vehicle simulations.
- Semi–empirical models combine analytical formulations with empirical evidence, offering a compromise between accuracy and computational efficiency [13,14]. Thanks to this balance, they are widely adopted in vehicle dynamics studies.

Standard semi–empirical models typically compute contact forces and moments by integrating stress distributions over the contact patch. Although they provide a physically meaningful representation of the tire–soil interaction and are computationally lighter than physics–based models, they remain still not optimized for real–time applications. This work aims to develop a map–based soft soil–tire contact model (SSTCM.1–mb) suitable for real–time use. The study is part of a broader initiative aimed at implementing a contact model in a driver training simulator for military vehicles operating in off–road conditions. The proposed model employs precomputed maps that store contact forces and moments generated offline using a custom semi–empirical contact model (SSTCM.1–se [15]) experimentally validated on snow and sand [16,17]. The maps are built by systematically sampling the outputs of the reference model, i.e., the forces and the moments exerted by the ground to the wheel, across its main independent variables (wheel speed, slip, and vertical load), ensuring full coverage of the expected operating conditions. The tabulated structure is integrated into a virtual quarter–car and benchmarked against the original semi–empirical formulation. Numerical results demonstrate that the proposed approach preserves the accuracy of the reference model while significantly reducing computational demands, making it well–suited for real–time applications such as hardware–in–the–loop testing, control system development, and driving simulators. This preliminary work focuses on longitudinal dynamics only.

The manuscript is organized as follows.

- Section II introduces the semi–empirical soft soil–tire contact model (SSTCM.1–se) used for the generation of the maps.
- Section III describes the workflow for designing the map–based contact model (SSTCM.1–mb).

- Section IV presents the numerical comparison between SSTCM.1–se and SSTCM.1–mb within a simplified quarter–car dynamic model.

II. Semi–Empirical Contact Model

The semi–empirical formulation (SSTCM.1–se [15]) used for generating the force and moment maps is an advanced MATLAB subsystem developed to capture the interaction between automotive tires and fine–grained soil. The model is based on well–known analytical and empirical Terramechanics principles and introduces several novel features, including:

- a refined representation of tire radial deformability;
- the integration of wheel moments arising from both the stress distributions over the contact patch and the sidewalls;
- an adaptive evaluation of the contact patch geometry, particularly effective at low–velocity and in standstill conditions.

Fig. 1 provides a lateral sketch of SSTCM.1–se and highlights its main characteristics. The tire, with its undeformed radius r_u, rolls on a flat and homogeneous surface. The local tire reference frame is centered at point O, with the spin axis aligned with the lateral (y) axis and the mid–plane lying in the xz–plane, where x is the longitudinal and z the vertical axes. The contact arc, shown as a thick blue line and centered at point A, is defined by the augmented radius r_a. The coordinates (x_A, z_A) and the corresponding radius r_a are determined through an approximated approach based on the tire radial stiffness and the applied vertical load. Each point of the contact arc is identified by the circumferential coordinates θ and η and are characterized by a sinkage depth h from the undisturbed soil plane. Points within the contact patch experience normal stress σ, tangential shear stress τ_t, and lateral shear stress τ_y. These stresses are assumed constant across the tire width.

The normal stress σ, responsible for the tire bearing capacity, is non–linearly related to the sinkage h according to the Bekker pressure–sinkage law. Shear stresses τ_t and τ_y depend on σ via the Mohr–Coulomb failure criterion and the relative motion between the tire tread and soil through the Janosi relationship. Additional contributions arise from lateral bulldozing, caused by the pressure exerted on the tire sidewall (blue shaded area in Fig. 1). This effect is accounted using the Hegedus' blade theory, with the resultant force applied at the centroid B of the sidewall contact area. The overall forces and moments acting on the wheel are obtained by integrating all stress contributions.

The model inputs include:

- time–varying signals: vertical load, F_z, longitudinal and lateral components of the wheel velocity, V_x and V_y, and angular velocity Ω;
- soil properties such as cohesion, friction angle, pressure–sinkage stiffness and exponent;

model parameters governing the transition across operating conditions (e.g. high–to–low speed, driving/braking/coasting, etc.).

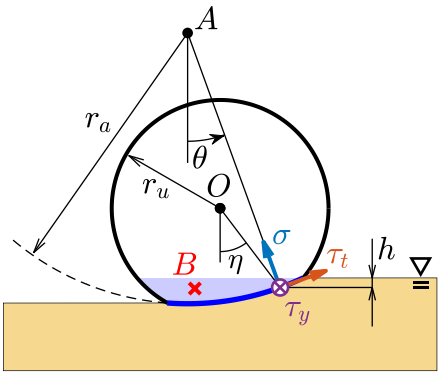


Figure 1 Lateral sketch of SSTCM.1–se.

The outputs of the model are the longitudinal and lateral forces, F_x and F_y, the overturning moment M_x, the rolling resistance moment M_y, and the aligning moment M_z.

III. Map–Based Contact Model

The primary objective of this work is to enable real–time simulation of soft soil–tire interaction. However, the semi–empirical contact model is not directly applicable due to its reliance on iterative routines and integral computations, which impose a substantial computational burden. The present work is an exploratory activity restricted to longitudinal wheel dynamics, aimed at assessing the potential benefits of the proposed approach, while neglecting lateral forces and motions.

To meet real–time requirements, a faster approach is adopted by implementing lookup tables that store precomputed contact forces and moments. This structure is populated offline by systematically evaluating the reference contact model (SSTCM.1–se) across a set of steady–state operating conditions, each defined by a unique combination of input variables, as shown in Fig. 2. The input space is defined by three variables characterizing the wheel state:

- vertical load F_z;
- longitudinal velocity V_x;
- longitudinal slip κ as defined in (1), where r_e represents the effective rolling radius.

$$\kappa = \begin{cases} \dfrac{\Omega r_e}{V_x} - 1 & \Omega r_e \geq V_x \\ 1 - \dfrac{\Omega r_e}{V_x} & \Omega r_e < V_x \end{cases} \tag{1}$$

A critical aspect in the development of the map–based contact model is the discretization of the input space, which must balance two conflicting requirements: a finer discretization increases resolution and reduces interpolation errors, thereby improving accuracy, while a coarser discretization lowers the offline computational cost and reduces memory usage and access time during simulation. The resulting maps inherently depend on both the soil properties and the wheel configuration. In this exploratory activity, the reference case considers the IVECO Light Multirole Vehicle (LMV)

operating under soft soil conditions representative of a clayey terrain.

Tab. I presents the discretization parameters used in the generation of the maps, including the number of sampling points and the corresponding ranges for the three inputs. The vertical force range is chosen to cover typical static and dynamic conditions, excluding extreme conditions such as wheel lift–off. Longitudinal slip is also discretized uniformly over the full range, from locked–wheel in braking to spinning–wheel in traction. Conversely, the longitudinal velocity is discretized non–uniformly: the interval from 0 to 10 km/h is sampled with ten evenly spaced points to capture low–speed sensitivity, while additional points at 36, 60, and 90 km/h are added in the higher–speed domain.

TABLE I. DISCRETIZATION AND RANGE OF THE MAPS

Variables	Discretization	Range
F_z	20	5 to 30 kN
V_x	13	0 to 90 km/h
κ	100	-1 to 1

The force maps are generated by iterating over all input combinations and evaluating the longitudinal force F_x and rolling resistance moment M_y of SSTCM.1–se. The resulting dataset, denoted as SSTCM.1–mb, is stored for direct use in simulation. The entire workflow, illustrated in Fig. 2, is developed in MATLAB environment, where j denotes the loop counter for each variable (F_z, V_x and κ) and N the maximum number of iterations for each loop. In this configuration the map structure (.mat file) has a size of 18.7 MB. Preliminary analyses estimate that integrating the lateral contact submodule (F_y, M_x, and M_z) would increase the total size to nearly 30 MB.

IV. NUMERICAL SIMULATION

The capability of SSTCM.1–mb to predict the contact forces and moments and its computational efficiency are benchmarked against the original SSTCM.1–se. Both the map–based and semi–empirical contact models are integrated into a quarter–car simulation framework, which computes the kinematic response of a single wheel.

A. Quarter Car Model

The quarter–car used for the dynamic simulation is based on a simplified two degrees of freedom (2–DoF) representation of a single–wheel system. The free–body diagram of the model is shown in Fig. 3, while the governing equations of motion are provided in (2) and (3):

$$H_e - F_x = m\dot{V}_x \tag{2}$$

$$T_e - M_y = J\dot{\Omega} \tag{3}$$

In (2) and (3) as well as in Fig. 3:

- H_e and T_e are the external force applied to the wheel hub along the x–axis and the external torque acting on the wheel y–axis;
- F_x and M_y are the longitudinal force and the rolling resistance moment provided by SSTCM.1–se or SSTCM.1–mb.
- $m\dot{V}_x$ and $J\dot{\Omega}$ are the inertial force and torque where the parameters m and J correspond to the equivalent quarter–car mass and the moment inertia of the wheel.

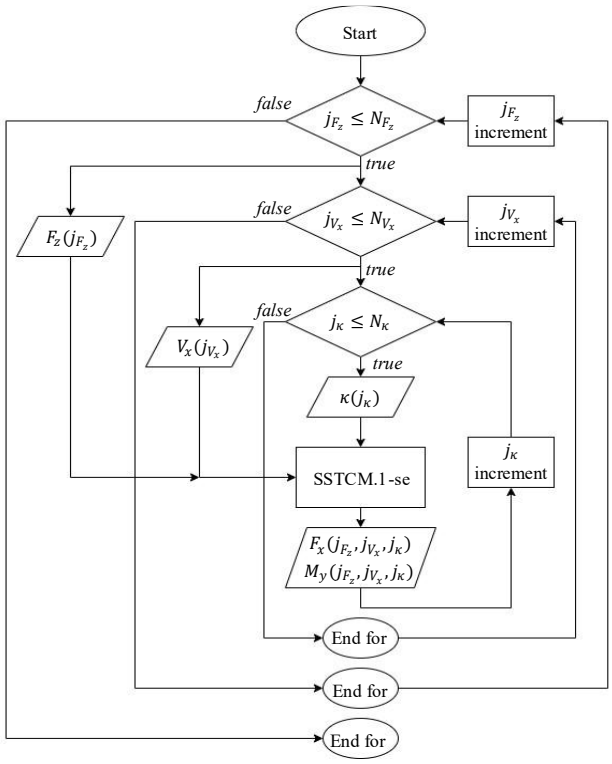


Figure 2 Schematic workflow of the generation process for the map–based contact model SSTCM.1–mb.

The longitudinal velocity V_x and angular velocity Ω, computed according to (2) and (3) are feedbacked as inputs to the contact model, which provides F_x and M_y. The vertical force F_z is held constant in accordance with m. To evaluate the performance of the two modeling approaches under realistic operating conditions, time–varying inputs (H_e and T_e) are applied to simulate different phases of the vehicle dynamics, including acceleration, free rolling, braking, and both driving and driven wheel conditions. The maneuver consists of a pure longitudinal dynamic scenario on a clayey terrain, in which the wheel is first subjected to a driving torque, then a braking torque, and finally a longitudinal force applied at the hub. The simulations are performed on an INTEL® CORE(TM) i5 processor with 8 GB of RAM.

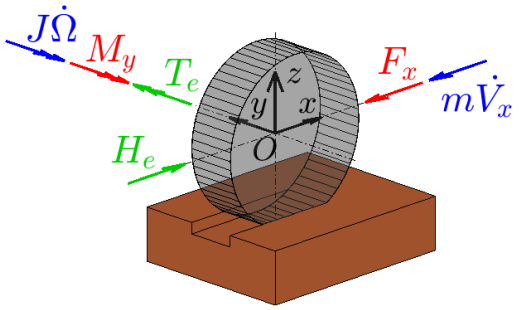


Figure 3 Free body diagram of the quarter car model equipped with SSTCM.1–se and SSTCM.1–mb.

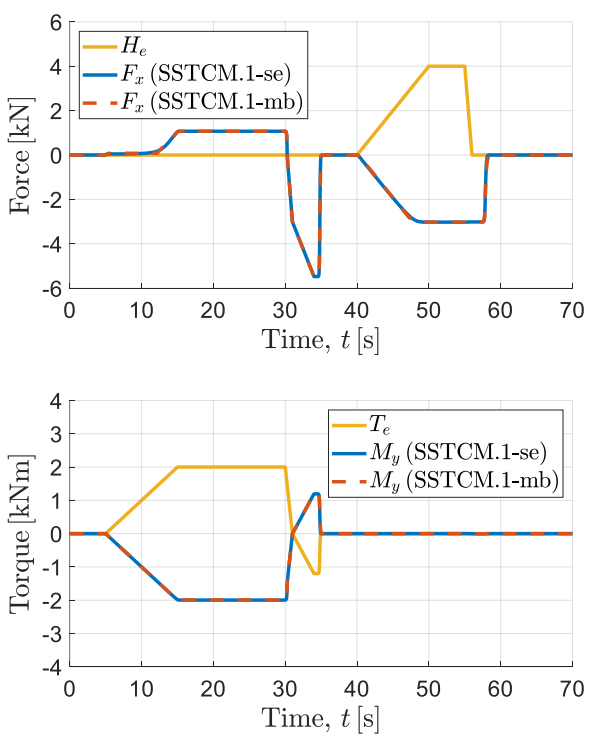
B. Results and Discussion

Fig. 4 compares the simulation outputs of the quarter–car model equipped with SSTCM.1–se and its counterpart with SSTCM.1–mb. Specifically, Fig. 4a displays the external

longitudinal force H_e and the resulting contact longitudinal force F_x, while Fig. 4b shows the external torque T_e and the corresponding rolling resistance moment M_y. The kinematic response, i.e., the longitudinal velocity V_x and the angular speed Ω of the wheel, are presented in Fig. 4c and Fig. 4d, respectively. Across all variables and throughout the entire maneuver, a strong agreement between the two modeling approaches is observed. Both dynamic quantities (forces and moments) and kinematic variables (velocity and angular speed) are well reproduced by the map–based model. The only noticeable difference concerns the angular speed during the acceleration phase, where minor discrepancies appear due to the high torque imposed as input.

The quantitative comparison of the two models is summarized in Tab. II, which reports the root mean square error (RMSE) and the maximum absolute error (MAE). Both the dynamic outputs and kinematic quantities exhibit extremely low RMSE values, demonstrating the robustness of SSTCM.1–mb of reproducing the reference semi–empirical formulation. Even the maximum deviation remain small and well within acceptable bounds for real–time simulation purposes.

The analysis of the computational performance highlights the main advantage of the proposed approach: a simulation of 70 s requires 78.6 ± 4.7 s using the quarter car system equipped with SSTCM.1–se compared to 5.3 ± 0.8 s with SSTCM.1–mb. The corresponding real–time factors (RF), summarized in Tab. III, confirm a reduction of more than one order of magnitude, thus enabling real–time feasibility. The reported mean values of the computational times and real–time factors are evaluated over 100 calls of the model to ensure statistical consistency.



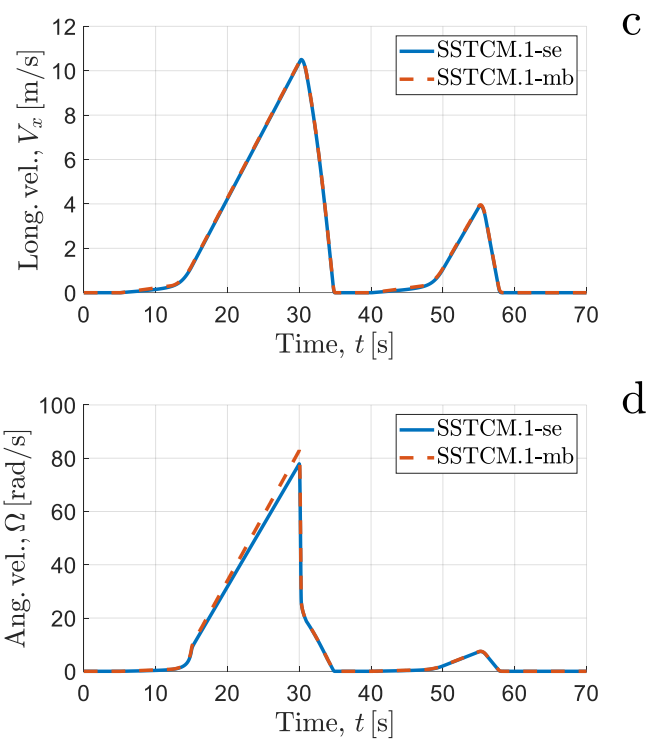


Figure 4 Inputs and outputs of the quarter–car model equipped with SSTCM.1–se and SSTCM.1–mb: external longitudinal force and longitudinal contact force (a); external torque and rolling resistance moment (b); longitudinal velocity (c); angular speed (d).

TABLE II. ROOT MEAN SQUARE ERROR AND MAXIMUM ABSOLUTE ERROR OF SSTCM.1–MB WITH RESPECT TO SSTCM.1–SE IN TERMS OF DYNAMICS AND KINEMATICS OUTPUTS.

	RMSE	MAE
F_x [N]	0.027	0.351
M_y [Nm]	0.006	0.144
V_x [m/s]	0.034	0.069
Ω [rad/s]	1.490	4.985

TABLE III. REAL–TIME FACTOR OF THE QUARTER–CAR MODEL USING SSTCM.1–SE AND SSTCM.1–MB.

	RF
SSTCM.1–se	0.9
SSTCM.1–mb	13.2

CONCLUSIONS

This study presented the development of a map–based soft soil–tire contact model (SSTCM.1–mb) suitable for real–time simulation. This research is motivated by the target of integrating an off–road tire model into driving simulators for the training of military drivers. The map–based structure is derived from a semi–empirical formulation (SSTCM.1–se) that provides a semi–physical description of soft soil–tire interaction but not suitable for direct integration in real–time applications because of its computational cost.

To overcome this limitation, a high–fidelity dataset of contact forces and moments was generated offline by the reference model over a discretized input space and stored in multidimensional force maps. These maps were integrated into a quarter–car simulation to assess the trade–off between computational efficiency and model fidelity.

Comparative simulations showed that the map–based model successfully reproduces the behavior of the original semi–empirical formulation under a range of longitudinal driving conditions, with negligible deviations in key dynamic and kinematic outputs. The results confirm that the proposed approach provides a reliable and computationally efficient alternative to the semi–empirical model, maintaining accuracy while drastically reducing simulation time. Moreover, this methodology is not limited to the clayey soil considered in this study but can be extended to other deformable terrains such as sand and snow, thus broadening its applicability to different off–road scenarios.

Future developments will focus on extending the work to lateral dynamics, with the aim of achieving a complete representation of all operating conditions encountered by the wheel and further enhancing the model's suitability for real–time vehicle dynamics simulations.

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