Influence of Flexible Bodies on Subjective Response and Driving Simulator Performance

Master's thesis in Mobility Engineering (MSc)

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DEPARTMENT OF MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2024
www.chalmers.se

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Master's Thesis 2024
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Cover: Driving simulator DiM150 at Volvo Cars Corporation

Typeset in LaTeX
Gothenburg, Sweden 2024

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Abstract

Conventional real-time Driver-in-Loop (DiL) methods use low-fidelity vehicle models in driving simulators.These simplified vehicle models compute the vehicle states from fewer bodies, where their relative motion is mapped in pre-simulated lookup tables. With the improvements of real-time capability in multi-body software, a question arises on how these high-fidelity vehicle models behave in DiL assessments and how they affect the performance of driving simulators.

The purpose of this thesis is to study the influence of flexible bodies on driving characteristics and the influence of these flexible bodies on the real-time performance of a simulator. Vehicle variants of different complexity are made by reducing the modal matrix of the flexible bodies. The goal is to develop a method to generate RT-MBD models that captures the effect compliance (through dynamic loading during driving) on the driving characteristics, while maintaining the real-time constraint. Results show that the computational cost is not weighted equally between the eigenmodes of flexible components. The geometric complexity of a flexible body is a significant factor in determining a model's computational efficiency. It is observed that while some characteristics from subjective analyses can be correlated to objective metrics, vehicle variants with similar objective metrics from certain driving scenarios show significant differences when driven in a simulator.

Keywords: real-time multi-body dynamics, driving simulator, flexible body, compliance, subjective vehicle assessment, eigenvector, mode shape, strain energy, compliance contribution, mode reduction

Preface

This report presents the outcome of the master's thesis project carried out at the Department of Mechanics and Maritime Sciences at Chalmers University of Technology during the spring of 2024. This thesis study was conducted with the Vehicle Dynamics Architecture department at Volvo Car Corporation.

Acknowledgements

I would like to thank my examiner, Petri Piiroinen (Associate Professor, Mechanics and Maritime Sciences), and the Mechanics and Maritime Sciences department of Chalmers University of Technology for allowing me to carry out my thesis. I thank Volvo Car Corporation for providing me with the opportunity to conduct my thesis at the company. I'm also grateful to my supervisor, Max Boerboom (Vehicle Dynamics Engineer, Volvo Car Corporation), for his assistance and constant supervision of the project. I also thank the Vehicle Dynamics department at Volvo Car Corporation for their support throughout the study.

Vinayanand Bangalore Venkatesh Prasad, Gothenburg, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

DiL	Driver-in-Loop
DOF	Degrees OF Freedom
FMU	Functional Mock-up Unit
HPG	Hällered Proving Ground
KPI	Key Performance Indicator
K&C	Kinematics & Compliance
MBD	Multi-Body Dynamics
MNF	Modal Neutral File
RT	Real Time
RTF	Real-Time Factor
SWA	Steering Wheel Angle
SWT	Steering Wheel Torque

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Introduction

1.1 Background

The performance of a vehicle is evaluated by its driving behavior. This driving behavior is assessed by objective and subjective tests. Objective traits are evaluated with a series of well-specified driving maneuvers, often assisted by steering robots. Due to the repetitive nature of objective tests, the results can be easily compared between vehicles or vehicle variants. A customer judges the overall driving behavior of the vehicle subjectively. To ensure that Volvo Cars driving characteristics is controllable, predictable and comfortable, expert drivers perform subjective tests. This subjective assessment will help improve the quality of the product given to society.

Building a verification prototype vehicle is expensive in terms of time and money. A cost-efficient approach to the subjective assessment of steering, handling, and ride attributes is to use a dynamic driving simulator. This would also reduce the usage of resources on remaking new prototypes after every assessment and lead to a more sustainable development process. For a good assessment, the vehicle models developed for the driving simulators must reflect a physical vehicle as accurately as possible.

A detailed vehicle model provides accurate results but comes with high computational cost. For subjective assessment in a driving simulator, the vehicle model must be computed in real-time (RT). Real-time means that 1 virtual second can be computed within 1 second of the actual time. A performance metric of computation is the real-time factor (RTF). This is the ratio of the simulation run time to the wall-clock time. The RTF should be less than 1 to be considered real-time capable. In this thesis, we strive for an RTF value below 0.9. To achieve real-time capability, current vehicle models often use a look-up table containing the suspension kinematics & compliance and force element data. These low-fidelity vehicle models run with RTFs as low as 0.4 on a single processor core.

A higher fidelity multi-body dynamics (MBD) model evaluates vehicle states with the effects of dynamic loading in consideration. It also accounts for the flexing of loaded components when a flexible body model is generated. Developing an RT-MBD model may provide a better understanding of the vehicle characteristics in a driving simulator. Moreover, with the use of high-fidelity models, MBD-based vehicle models do not have to be converted into look-up table based or other reduced models to be driven in the simulator.

1.2 Purpose

Although Adams/Car real-time is capable of RT-MBD simulations, high-fidelity models may cause overruns in the simulator. An overrun is when the simulation step is not completed within the specified fixed step time. The RTF in this case is greater than 1. Overruns of the vehicle model will interfere with the execution of other processes among which are processes for hardware control. This causes lagging visuals or jerking behavior of the motion platform. Therefore overruns should be avoided at all costs and a conservative maximum RTF of 0.9 is chosen. Therefore, a study has to be conducted on how each component (and its flexible body model) influences a vehicle's dynamic driving characteristics, and to what degree of detail each of these flexible bodies has to be modeled to obtain accurate results. This thesis study aims to investigate the influence of flexible bodies on the objective and subjective assessment of the vehicle while adhering to real-time requirements.

1.3 Limitations

This study is conducted with the following boundaries:

- Improvement of the simulator performance by optimizing the real-time algorithm is not within the scope of the study. The project focus is on how the best vehicle model can be created while respecting the real-time target.
- The study is not intended to optimize the structure of the flexible body components to improve vehicle performance. Mode shapes of the designed components are extracted to approximate the component deformation under loading. The study is not intended to change the deformation characteristics of the flexible bodies under different loading.
- Influence of flexible components is limited to suspension linkages, knuckle, and the subframe.
- The real-time performance investigation is limited to the use of Adams/Car real-time and no comparison is made between various RT-MBD tools.
- The study is limited to the Volvo EX90 vehicle project. The minimum degrees of freedom introduced by the type of suspension topology is therefore fixed.
- The real-time simulations are run on a Concurrent AutoHawk32 real-time computer (specifications in Appedix A.1). Performance charts presented in this thesis are valid for this hardware platform.
- The influence of computer hardware specifications might be shared but is not explicitly studied during this thesis (Such as CPU and RAM).

2

Theory

The current state-of-the-art at Volvo Cars uses a look-up table based approach to generate and run vehicle models in real time. Quasi-static simulations such as K&C, and property files containing spring and damper parameters are used to evaluate vehicle states for different inputs such as wheel travel and steering input. The results from these simulations, such as the wheel envelope characteristics, stiffness and damping, throttle mapping etc. are then used to generate look-up tables. When a driver provides inputs to the vehicle in the driving simulator, corresponding values from the look-up table are retrieved and summed to output the correct vehicle states.

Such a model is simplified and reduces the computational cost of running vehicle models in real-time. However, since the look-up tables are made with quasi-static simulations, the true driving characteristics are not represented well enough in the simulator as it does not show the effects of dynamic loading. The effect of dynamic loading is prominent in flexible components in the vehicle, which are not captured well by conducting quasi-static simulations. Moreover, the look-up tables are generated by conducting simulations at discrete steps in the wheel motion, and the vehicle states are interpolated and approximated between these steps. Lastly, a multi-body vehicle model is required for hardware dimensioning at the power requirements of active suspension components.

With recent developments in parallel computing and software efficiency, it is possible to run high-fidelity models in real-time. Using multi-body models in real-time would show better driving characteristics in dynamic driving conditions, and eliminate the interpolation and approximation that come with look-up table based models. With multi-body models, engineers can work with design parameters such as hardpoints and stiffnesses (same as offline simulations), which is an efficient way of working together with the suspension design teams. This would help understand the design proposals in the early design stages and deliver a better product to the customer.

A flexible body in an Multi-Body Dynamics (MBD) software is represented by a Modal Neutral File (MNF). MNFs are generated from Finite Element (FE) softwares by meshing (discretizing) a 3D CAD and providing it with the appropriate material properties and boundary conditions (constraints). Such an FE model is subject to a modal analysis to determine the eigenfrequencies and their corresponding eigenmodes. This data is exported to MNF format so that its deformations for various loading conditions can be evaluated without having to conduct a full-fledged finite element analysis on the component.

An MNF file contains the following information about a flexible body component [4]:

- Geometry (location of nodes and node connectivity)
- Nodal mass and inertia
- Mode shapes
- Generalized mass and stiffness for mode shapes

To evaluate the deformation of a flexible body, Adams uses a method called modal flexibility. A variable is assigned to each mode shape (eigenvector) and the relative amplitude of each eigenvector is calculated. Using the principle of linear superposition, the mode shapes are combined to evaluate the deformation at each time step. Figure 2.1 shows an example of linear superposition of two mode shapes with their respective amplitudes (Source: Adams/car user manual[4]).

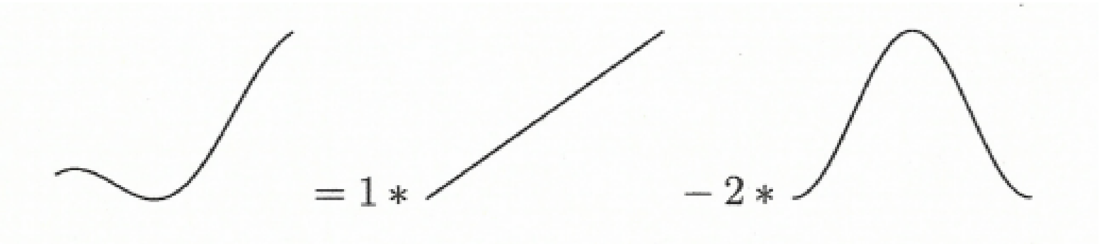

Figure 2.1: Linear combination of mode shapes

The linear deformations of a finite element mode u can be approximated as a linear combination of smaller number of mode shapes ϕ.

$$u = \sum_{i=1}^{M} \Phi_i q_i$$

Where M is the number of mode shapes and the scale factors or amplitudes, q, are the modal coordinates.

The computational cost of running a vehicle model in real-time can be measured with the real-time factor (RTF). This parameter is a ratio between the computation and run times for every time step. The real-time factor has to be under 1 for it to be said to "run in real-time" and not cause overruns. The computation performance of real-time simulations is sensitive to the hardware used. With the capability of parallel computing, real-time simulation can be specified to run on multiple cores for quicker solutions and lower real-time factors. A higher base clock frequency of the CPU linearly decreased the runtime of the simulation, whereas increasing the number of cores or simulation has a diminishing return of computational performance. Although increasing the number of cores improves performance, there is a limit after which, the distribution of tasks to multiple cores and collection of results from individual cores ("overhead") consumes significantly high time which negates the effect of work-load distribution. A study was conducted with a rigid body model of Volvo EX90 to visualize how the number of cores dedicated for a straight-line driving scenario would affect the frame rate. The test was carried out on a Concurrent AutoHawk32 real-time computer (A.1) and the results are shown in figure 2.2.

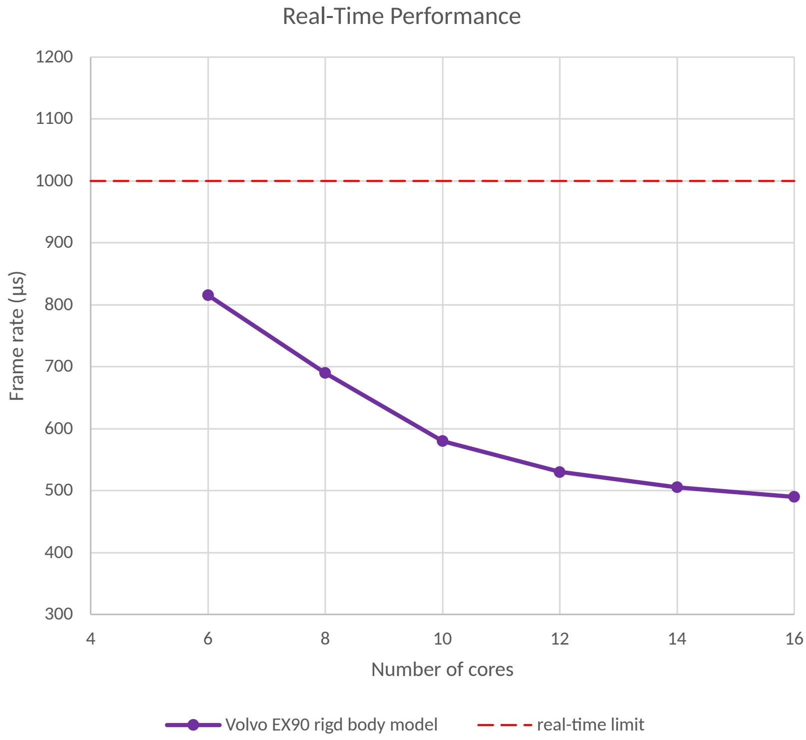

Figure 2.2: Real-time performance subject to number of CPUs

Each eigenvector in a flexible body corresponds to one DOF. To reduce computation cost, the fidelity of a flexible body can be reduced by disabling the modes that do not contribute significantly to the results[1]. Since the accuracy of deformation of a flexible body is subject to the modes enabled in the flexible body, this becomes an optimization problem to select the modes appropriately to reduce computation time without hampering the accuracy.

Modal effective mass and participation factor is a good parameter to understand what modes to select as it suggests how much of the total mass deflects under a particular mode for an excitation in a particular direction[2]. In a dynamic load case on a flexible body (such as in a real driving scenario), participation factors are of little help as they do not show the contribution of each mode to the deformation in all DOFs together. Instead, evaluating the strain energy contribution of each mode helps understand the significance of different modes in a flexible body better. Adams/Car measures the contribution of each mode to the total strain energy of a flexible body. Using this measurement in a given loadcase, the modes contributing to total strain energy less than a specified percentage can be disabled[3].

3

Methods

3.1 Vehicle Model Setup

The vehicle models have to be made "real-time ready" by removing unnecessary processes that require additional computing. It is also necessary to make the vehicle model compatible with the driving simulator hardware by generating outputs of signals necessary for its functioning. The Adams/Car model of the Volvo EX90 was prepared for real-time simulations by

- Replacing subroutines that refer to external files to evaluate vehicle states (such as gear backlash) with building internal expressions instead.
- Adding steering feedback torque output to be communicated to the simulator hardware.
- Removing unwanted output requests for real-time simulation. These requests were necessary for post-processing offline simulations.
- Activating the "high performance" option in the tires. This relaxes the accuracy window for tires, making them real-time compatible.

3.2 Vehicle Analyses

The driving characteristics of the vehicle and its sensitivity to compliance of different components can be understood by conducting objective and subjective assessments. With these assessments, comparisons can be made between different vehicle variants.

3.2.1 Objective Analyses

Objective analyses are conducted by a series of systematic events that actuate the vehicle in a specific, and repeatable manner and do not require a human driver. The lack of human error and the repeatability of these tests make straightforward comparisons between different vehicles and vehicle variants possible.

A preliminary study is carried out to understand the compliance contribution of each component in the suspension system. With a Kinematics & Compliance (K&C) test, the differences in the wheel envelope characteristics between a rigid system and one with flexible elements can be observed. Since K&C is a quasi-static process, it will not capture the complete influence of flexible components on wheel deflection in the suspension system during dynamic loading conditions. After K&C analysis, a set of driving maneuvers is conducted to obtain comparable metrics that can be compared between variants.

3.2.1.1 Kinematics & Compliance

K&C simulation is a quasi-static process in which the wheel is actuated by a force or a displacement and different parameters are observed. An investigation was conducted to understand the influence of the following components in the compliance of the vehicle: knuckle, upper control arm, lower control arm, subframe, tierod/toe link, and the fork. The compliance contribution of each of these components was studied by toggling them rigid individually and observing the change in compliance behavior. The front and rear axles were studied in the following loadcases:

- Parallel wheel travel
  - Wheels of an axle are actuated vertically and in the same direction.
- Opposite wheel travel
  - Wheels of an axle are actuated vertically and in opposite directions.
- Lateral force
  - A range of forces are applied to the tire contact patches in the lateral direction.
- Drive force
  - A range of longitudinal forces are applied to the wheel centers of the axle.
- Brake force
  - A range of longitudinal forces are applied to the tire contact patch and the rotor is clamped.
- Aligning torque
  - A torque is applied about the wheel's vertical axis.

The compliance contributions of each component and are discussed in section 4.1 and Appendix A.2

3.2.1.2 Creation of Vehicle Variants

The vehicle chosen for the study presented in this thesis is Volvo EX90. The vehicle has a double wishbone suspension architecture at the front axle and an integral link suspension at the rear axle. The multi-body model for this vehicle in Adams/car is used for the study. A rigid body model of this vehicle has 579 Degrees Of Freedom (DOFs). Each mode shape (eigenvector) in the flexible bodies correspond to an additional DOF. A fully flexible vehicle model has a total of 1195 DOFs (616 flexible body DOFs).

For the same EX90 vehicle, multiple variants are generated by modifying the flexibility of the suspension components in the vehicle model while keeping the same suspension topology across all variants. After studying the results of compliance contribution analyses, variants are generated by making some components rigid while keeping some others flexible; and disabling unwanted eigenmodes in the flexible bodies.

To determine which eigenmodes are necessary and which are not, a "pilot simulation" is conducted to analyze the amount of strain energy each mode contributes to a component undergoing a particular loading. Since a specific mode in a flexible body would have different strain energy contributions for different loading conditions, it is necessary to choose the right driving maneuver that helps decide which modes must be active in each flexible body.

An appropriate driving maneuver is to be selected such that it fulfills the following requirements

- The pilot maneuver must be similar to the maneuver conducted for the study since the components in the vehicle model must be loaded and deform as they would in a simulation conducted for the study. In this case, the pilot maneuver must be a handling maneuver, the same as the maneuvers conducted to evaluate the vehicle characteristics in the study.
- The pilot maneuver must be symmetric to ensure that the components on either side of the vehicle have the same modes enabled and deform in the same manner irrespective of the direction of steering in the handling maneuver.

Upon considering these factors, the pilot maneuver was selected to have sinusoidal steering with a frequency ramping up to 3Hz.

Table 3.1 shows some significant variants used in the study. The number of active mode shapes in each flexible body are shown in the vehicle variants generated. Variant ’v1’ is a variant with flexibility in components with the largest compliance contribution- knuckle and subframe. Variant ’v2’ has flexibility added in more components, in the order of each of their compliance contributions. Variant ’v3’ is made with complete flexibility in all the suspension linkages.

	active modes		
Variant	**v1**	**v2**	**v3**
Front Knuckle	12	12	0
Front Subframe	15	15	0
Front Fork	0	4	25
Front Lower Control Arm	0	6	18
Front Upper Control Arm	0	0	12
Tierod	0	0	15
Rear Knuckle	15	15	0
Rear Subframe	17	17	0
Rear Lower Control Arm	0	8	30
Rear Upper Control Arm	0	0	7
Toelink	0	0	16
Total	**86**	**122**	**246**

Table 3.1: Vehicle variants

3.2.1.3 Driving Maneuvers & Objective Metrics

At Volvo Cars, objective assessment of vehicles is performed by a catalog of well-defined driving maneuvers and the results are summarized in a so-called "DNA report". This DNA report is confidential and not to be publicized. Therefore, some common driving maneuvers are used to capture the lateral dynamics of the vehicle.

- Execution of scenario - Step steer: Drive with speed of 80 km/h and input a step function for steering wheel angle such that the lateral acceleration reaches between 3.5 - 4 m/s^2. Outputs extracted:
  - Maximum side-slip angle [deg]
  - Time lag in lateral acceleration vs steering wheel angle [ms]
  - Maximum yaw rate [deg/s]

- Execution of scenario - Frequency response (120 km/h): sinusoidal steering with frequency from 0Hz to 3Hz with an amplitude giving 3.14 m/s^2. longitudinal velocity maintained at 120 km/h. Outputs extracted:
  - Time at 45° phase lag between yaw and steering wheel angle [ms]
  - Time at 45° phase lag between lateral acceleration and steering wheel angle [ms]
  - Roll rate gradient at 1Hz [deg/s/g]

- Execution of scenario - Frequency response (80 km/h): sinusoidal steering with frequency from 0Hz to 3Hz with an amplitude giving 3.14 m/s^2. longitudinal velocity maintained at 80 km/h. Outputs extracted:
  - Percentage increase in yaw gain peak compared to yaw gain at 0.5 Hz [%]
  - Damping in roll - Roll rate gradient at 1Hz [deg/s/g]
  - Stiffness in roll - Roll gradient [deg/g]

- Execution of scenario - Ramp steer: Steering ramped at the rate of 0.06 - 0.1g/s until 0.6 lateral acceleration is reached. Longitudinal speed maintained at 80 km/h. Outputs extracted:
  - Understeer gradient [deg/g]
  - Steering wheel torque gradient measured between 0.3g and 0.5g [Nm/g]
  - Steering wheel torque at 0.3g [Nm]
  - Roll gradient between 0.1 and 0.35 g [deg/g]

3.2.2 The real-time trade-off

To generate vehicle variants and assess their driving characteristics on the simulator, the models first had to be verified if they were real-time capable. As mentioned in section 3.2.1.2, a completely flexible model contains over 1000 DOFs. At the time of conducting this thesis study, such a high-fidelity model is not real-time capable and the RTF exceeds 1. Therefore, the vehicle model has to be simplified by reducing the number of active mode shapes in the flexible elements. Observing the runtime of the vehicle variants provided a fair idea of how computationally expensive they were. The findings have been reported in section 4.3. Variants were generated by maximizing RTF by including flexibility in the suspension components while keeping the RTF under 0.9.

3.2.3 Subjective Analyses

To get a complete picture of a vehicle's characteristics, it is not sufficient to just study the objective metrics. Volvo Cars sells cars that should appeal to the driver. Their driving experience should be predictable, controllable, and comfortable. Therefore it is crucial to get a driver in the car and perform a thorough subjective assessment. The vehicle variants have been analyzed with Driver-in-Loop (DiL) simulations on the driving simulator. The biggest challenge with such an assessment is the coherence between different test drivers on vehicle characteristics as each driver has different driving styles and sensitivities. Along with eliminating the cost of prototyping, an added advantage of using driving simulators is minimizing variance in comparison between different vehicle models, and the assessment by different drivers by keeping constant environmental conditions such as the weather, track conditions, and tire wear status. Driving simulators also make switching drivers and vehicles faster and simpler.

The Adams/Car vehicle models have been packaged into Functional Mock-up Units (FMUs) to be used in the driving simulator. Feedback was given on subjective traits such as responsiveness, yaw characteristics, roll characteristics, stability, steering feel, on-center response, and off-center response.

On-center response refers to the behavior of the vehicle for small steering inputs around the "straight ahead" steering position. Straight driving characteristics such as yaw damping and steering deadband can be assessed with such an assessment. Off-center response refers to the vehicle's behavior for larger steering inputs, with which characteristics such as the non-linearity and progressivity of yaw and steering torque can be assessed.

At Volvo Cars, the subjective assessment of a vehicle is carried out by specialized test drivers on a proving ground. A "digital twin" of the proving ground is used in the driving simulator. This further minimizes the variance in driver assessment and improves the immersion of test drivers. Each driver gives a rating for different subjective characteristics in a vehicle. A report is generated from the cumulative feedback of the drivers. To maintain confidentiality, this report will not be publicized. Therefore, general subjective traits for assessment have been proposed for the test drivers to provide feedback on. The feedback of test drivers on the vehicle variants is shown in section 4.4.

4

Results

Table 4.1 shows the vehicle variants studied. An objective analysis was conducted on these variants by driving maneuvers offline. This was followed by a subjective analysis where specialized test drivers from Volvo Cars assessed their subjective characteristics.

Variant v1 is shown to have 12 modes enabled in the front knuckle, 15 modes enabled in the front subframe, 15 modes in the rear knuckle, and 17 modes in the rear subframe. The components with 0 modes enabled are rigid bodies. v2 has more components made flexible with some dominant modes enabled in each component. v3 has all modes enabled in all the suspension linkages while the rest of the components are rigid.

	active modes		
Variant	**v1**	**v2**	**v3**
Front Knuckle	12	12	0
Front Subframe	15	15	0
Front Fork	0	4	25
Front Lower Control Arm	0	6	18
Front Upper Control Arm	0	0	12
Tierod	0	0	15
Rear Knuckle	15	15	0
Rear Subframe	17	17	0
Rear Lower Control Arm	0	8	30
Rear Upper Control Arm	0	0	7
Toelink	0	0	16
Total	**86**	**122**	**246**

Table 4.1: Vehicle variants

4.1 Compliance Contribution

A Kinematics & Compliance (K&C) analysis was conducted on each axle separately, with all suspension components fully flexible. Each flexible component was turned rigid individually and the same K&C analyses were conducted. The difference in the wheel envelope characteristics from the fully flexible model to ones with each component turned rigid was used to understand the influence of each flexible body on the compliance behavior of the vehicle. Plots were generated to represent the influence of each component on compliance in the front and rear axles. Figure 4.1 shows the wheel envelope characteristics (positions and orientations of the wheel) of a parallel wheel travel simulation in the front axle when each of these components is turned rigid. These plots are compared with a model where all components are flexible, and a model with all components in the axle turned rigid. This shows the absolute change and the influence of a flexible body on the wheel envelope. The pie charts underneath show the relative contribution of each flexible body in the axle as compared with the rest. This gives an idea of the significance of a given component in a given wheel envelope characteristic, for a specific K&C loadcase. Plots for the rest of the K&C loadcases are found in Appendix A.2

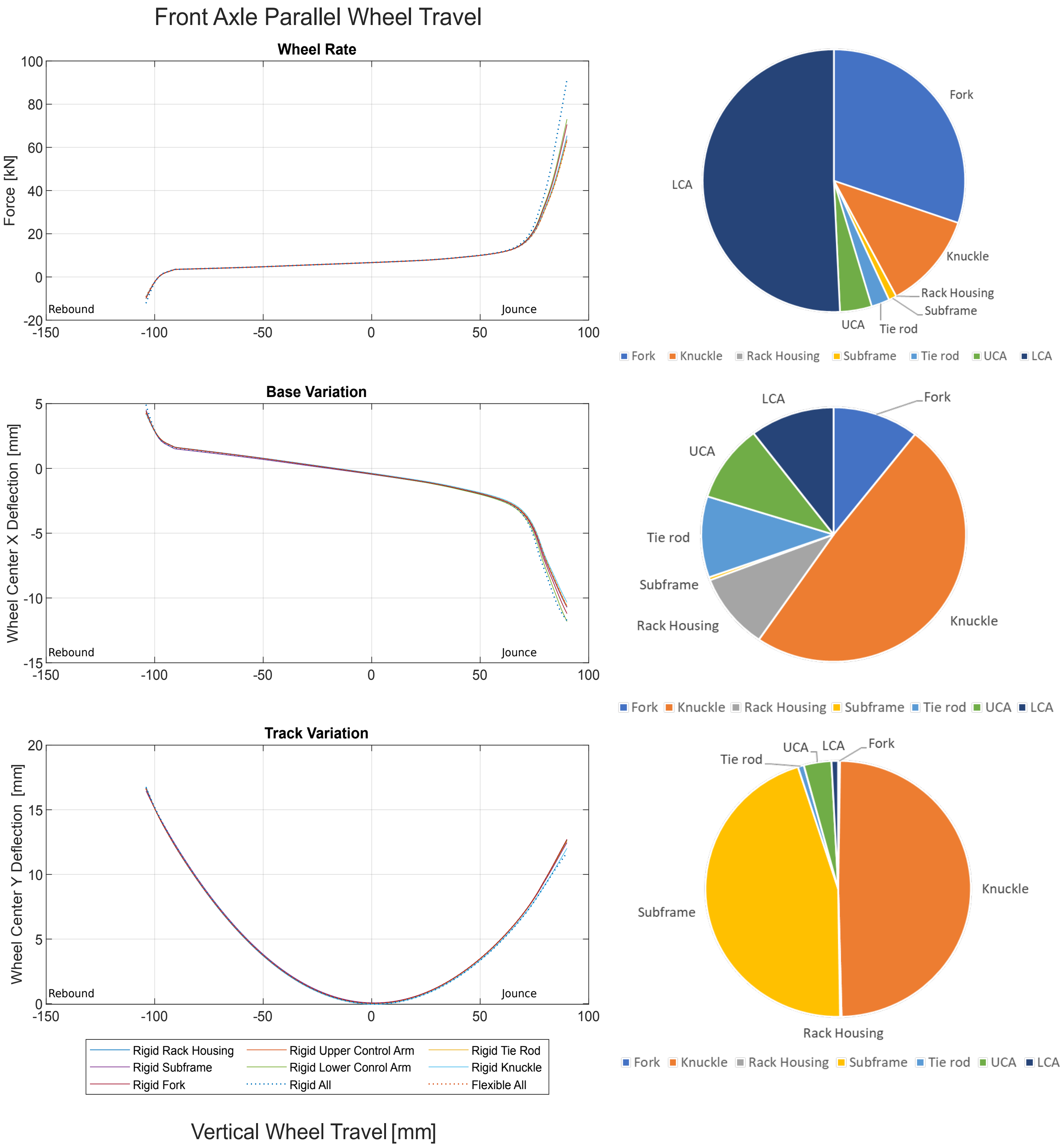

Figure 4.1: Vertical load on the wheel, X, and Y deflections vs parallel wheel travel at the front axle

4.2 Objective Metrics

The KPIs from simulated driving maneuvers have been represented in a spider chart in the figures 4.2 and 4.3. Each axis has been normalized to a range of values shown under the metric. Figure 4.2 shows the variation in objective metrics when the vehicle model is completely rigid as compared to when it is completely flexible. Figure 4.3 compares the KPIs between variants v1, v2 and v3. The KPIs are shown in more detail in Appendix A.3

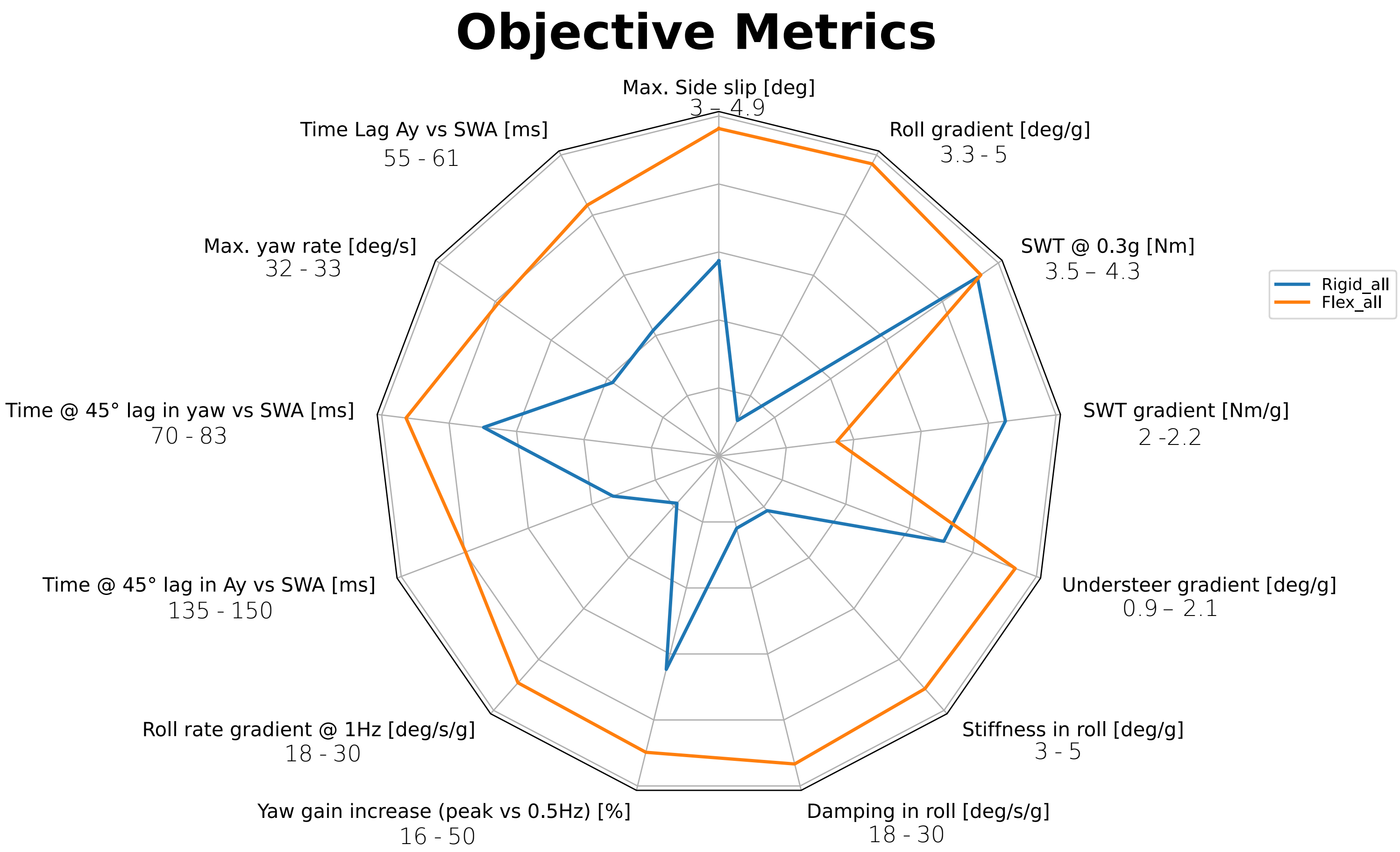

Figure 4.2: KPIs of rigid body model and fully flexible model

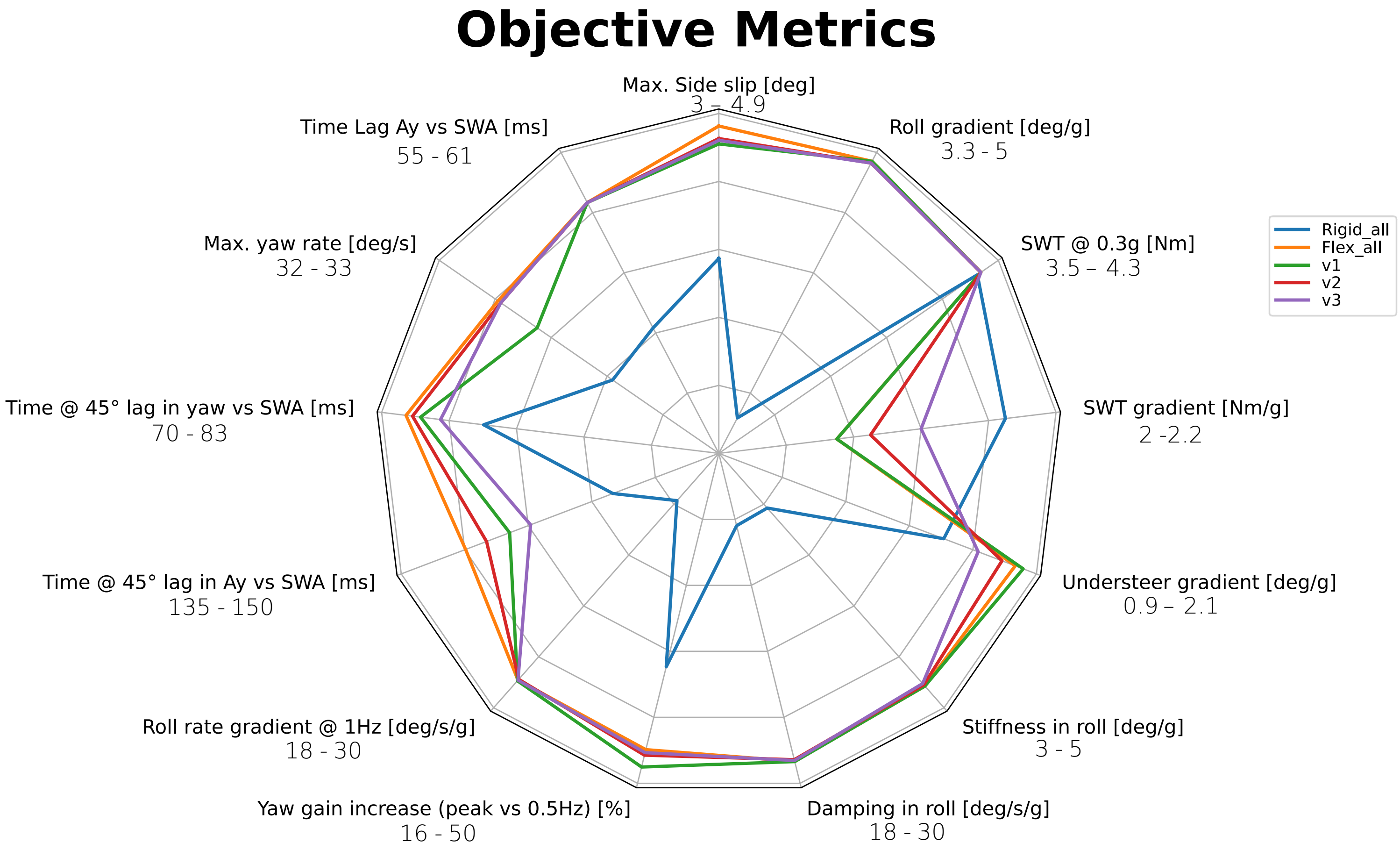

Figure 4.3: KPI comparison with v1, v2 and v3

4.3 Simulator Performance

Table 4.2 shows the driving simulator performance (through the Real Time Factor) and how it varies with model fidelity. The RTF increases with the increase in number of active modes in the model, making the model computationally more expensive. It is also observed that the RTF does not vary linearly with the number of active modes. With an increase by 50% in the number of modes between v1 and v2, the difference in run-time is 90 μs (0.09 RTF). Whereas an increase by 200% in the number modes between v2 and v3 gives an increase in run-time by 75 μs (0.075 RTF). The reasoning for such a non-linear behavior is found in section 5.2.

Variants	**v1**	**v2**	**v3**
No. of active modes	86	122	246
RTF	0.720	0.81	0.885

Table 4.2: RTF comparison between variants

4.4 Subjective Assessment

A fully rigid Volvo EX90 was generated and used as a baseline model for the specialized drivers at Volvo Cars. Then, blind tests were conducted with the test drivers to understand the subjective characteristics of the variants created. These variants are compared against the baseline model.

Rigid body model: The drivers felt high off-center steering torque and damping. The vehicle was more responsive than v1 and v2 and feels agile. Front-rear roll characteristic was said to be balanced. The vehicle was nervous around high-speed corners.

v1: The vehicle seemed to be lacking in roll and yaw damping. A dead band in on-center response was noticeable. Compared to the rigid body model, the response was slow. The vehicle rolled quickly and returned quickly, giving a "head toss" feeling to the driver. The drivers felt a high steering wheel torque and undamped steering return.

v2: The variant performed better in yaw and roll damping. On-center dead band is lower than the previous variants. The drivers appreciated the steering response. There was a noticeable delay in the front-rear axle roll. Steering wheel torque was lower than v1 and still felt undamped on return.

v3: The vehicle was said to have the sharpest on-center response and that it stabilizes better than v1 and v2. Roll and yaw characteristics were underdamped but within a tunable range, unlike v1 and v2. The steering response is progressive. Drivers felt high steering torque and undamped steering wheel return with violent oscillations. Steering torque build-up was higher off-center. The rear axle felt soft with low wheel control; drivers felt the forces on the rear axle were high.

5

Conclusion

5.1 Objective Assessment

Figure 4.2 shows the differences in a rigid variant as compared to the one with all suspension elements flexible. Comparing the two, the metrics "time lag @ 45° lag in yaw vs SWA" and "time lag @ 45° lag in A_y vs SWA" are lower in the rigid body model, which shows that the rigid body model is more responsive to driver inputs. The rigid body model tends to oversteer more as compared to the flexible body model, which can be observed with the "understeer gradient" metric.

Figure 4.3 shows little difference in most objective metrics between variants v1, v2, and v3. A significant difference can be observed in some metrics such as "SWT gradient", "time lag @ 45° lag in yaw vs SWA", "time lag @ 45° lag in A_y vs SWA", and "understeer gradient". These variants are to be tested in the driving simulator to understand if a driver's perception aligns with the objective results, or if a subjective assessment would help perceive things differently.

5.2 Real-Time Performance

An increased number of active modes in a flexible body increases the computational cost and consequently increases the Real Time Factor (RTF). Non-linearity in the relation between RTF and the number of active modes suggests that the mesh size and number of interfaces a component has plays a significant role in the computational expense. Having twice the number of active modes (200%) in smaller and simpler components (v2 to v3) shows an increase in RTF by 0.075. An increased number of modes (by approximately 50%) in models with large and more complex components such as the knuckle and subframe shows an increase in computational cost (RTF) by 0.09. Although it is not a part of this thesis, significant computational performance improvements were observed on Volvo Cars new real-time hardware (AutoHawk32) when comparing the RTF to older generation real-time machines. These efficiency gains in the 25-30% range are partially attributed to the new micro architecture, but more importantly the higher memory bandwidth (DDR5 RAM).

5.3 Subjective Assessment

Despite the objective metrics for the vehicle variants showing little difference, the test drivers felt they were driving different vehicles.

Some feedback can be correlated with the objective metrics. Feedback from drivers on the "rigid body model" having high off-center steering torque is observed in the "SWT gradient" metric. The rigid body model being more responsive than v1 and v2 is seen in objective metrics "Time @ 45° lag in yaw vs SWA" and "Time @ 45° lag in Ay vs SWA". The drivers provided feedback that the vehicle gets nervous in high-speed cornering scenarios, which can be correlated to the lower "Understeer gradient" in the rigid body model.

Other traits from the subjective tests suggest that Driver-in-Loop simulations help understand differences between model variants better than objective assessment. For example, the comment on roll damping in v3 being the best, followed by v2, and the least roll-damped variant being v1 is not seen in the objective metric "Damping in roll", where all values are very close. This suggests that there are things a driver would be more sensitive to and would understand better when compared with objective analysis in steady-state conditions.

There are still other traits that can be understood by driving the vehicle. Comments by drivers such as v3 stabilizing better than v1 and v2, progressive steering response behavior in v3, and v2 having a delay in front and rear axles roll show that some characteristics are observed in subjective assessment, which may not even have been thought of while conducting objective analyses through computer simulations.

6

Future Work

The objective tests show little difference on KPIs that are calculated. The drivers detect however significant differences between models which suggest that the objective tests do not fully capture the driving experience of the vehicle. It is hypothesized that this is due to the quasi-stationary nature of objective tests compared to the stochastic behavior of a real driver. The driver is perceptive to the "settling" or "decay" of their input while these differences are poorly captured by the objective KPIs presented. Adding modes or increasing the number of flexible bodies to a model will affect this phenomena. Better objective tests and metrics that capture the transmissibility are required.

Adding flexibility in the vehicle model is observed to have a significant effect on the driving characteristics. The car body is the largest flexible component in a vehicle. Therefore, it is imperative to study its influence on driving characteristics.

The pilot simulation for selecting the mode was done by conducting a frequency response maneuver. Other maneuvers can be investigated to understand how they change the strain energy contribution percentages of mode shapes. After studying results from different maneuvers (or even a combination of multiple ones), an appropriate maneuver can be chosen for mode selection.

Reducing the degree of discretization in the anti-roll bars and including more mode shapes in the flexible bodies is worth investigating to optimize the vehicle models.

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A

Appendix

A.1 Machine Specifications

Real-time computer

Concurrent AutoHawk32
CPU: 2x Intel Xeon Gold 6444Y (4th gen) 3.6 GHz Base Frequency
RAM: 251.6 GB DDR5 RAM type 4800 MT/s
OS: RedHawk Linux 8.4 (Hadron)
GPU: NVIDIA T400 4GB

Driving simulator

DiM150
9 Degrees of freedom
Screen: 13 x 2.7 m, R = 3.5m, Angle = 210°

Tripod:
Acceleration up to 1.2 G's
Velocity up to $1.7m/s^2$
Motion ~±0.75m (X and Y)
Frequency range 0-5Hz
Yaw angle ±25°

Hexapod:
Acceleration up to 3 G's
Velocity up to $2m/s^2$
Motion ~±0.25m (X, Y and Z)
Frequency range 0-30Hz
Pitch/roll/yaw angle ±20°

A.2 Compliance Contribution

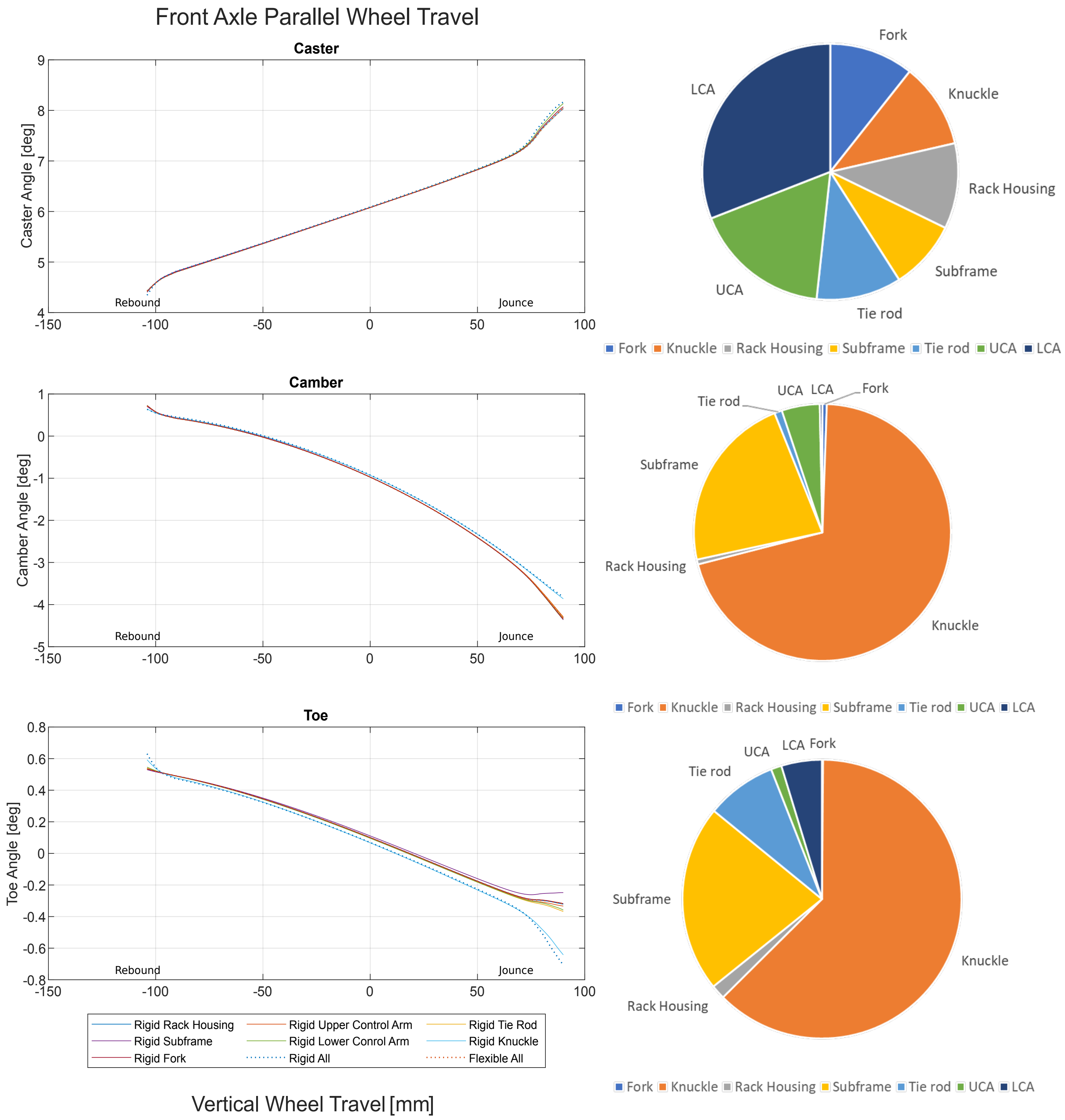

Figure A.1: Caster, camber and toe angle vs parallel wheel travel at the front axle

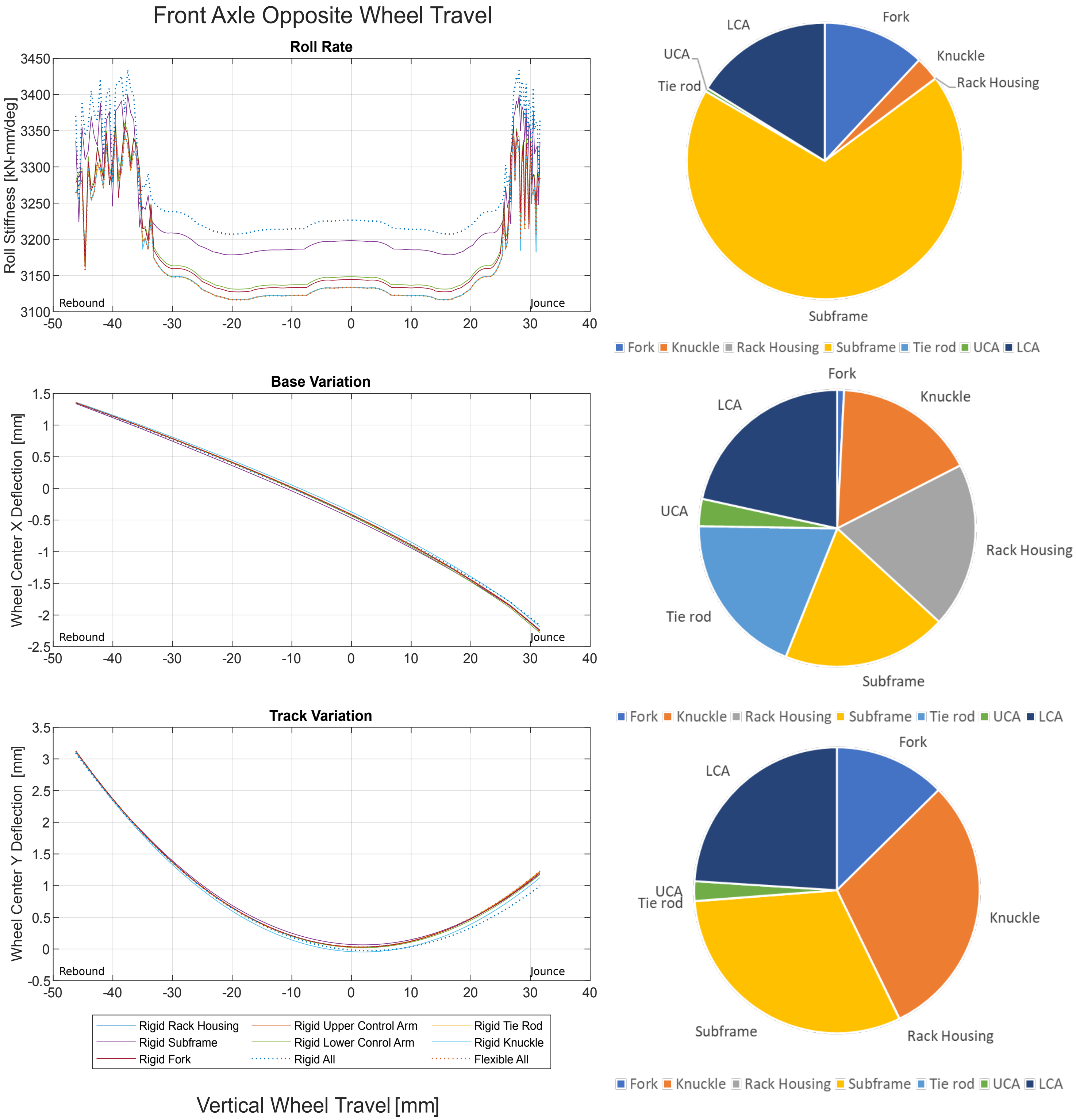

Figure A.2: Roll stiffness, X nd Y deflections vs opposite wheel travel at the front axle

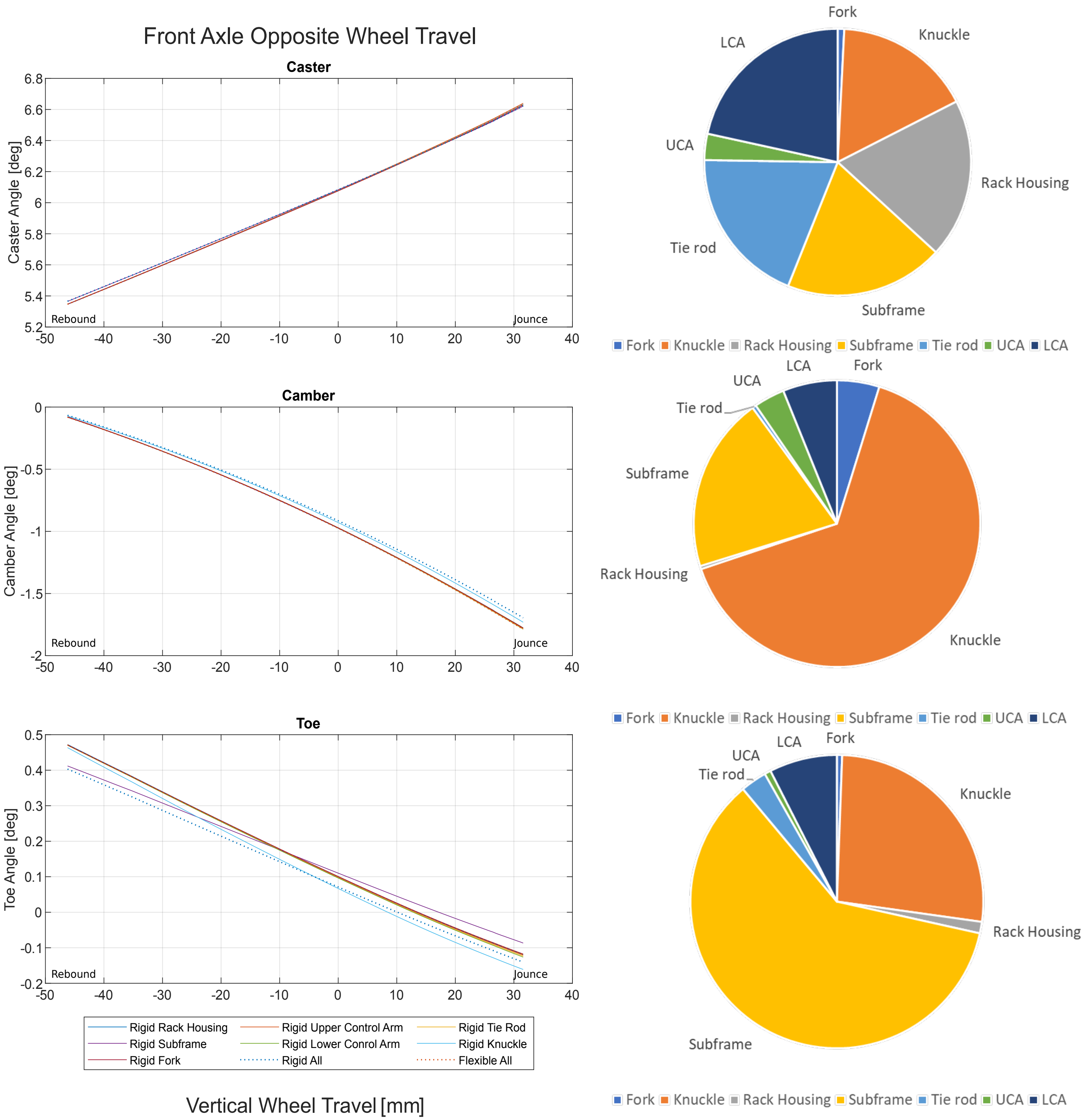

Figure A.3: Caster, camber and toe angle vs opposite wheel travel at the front axle

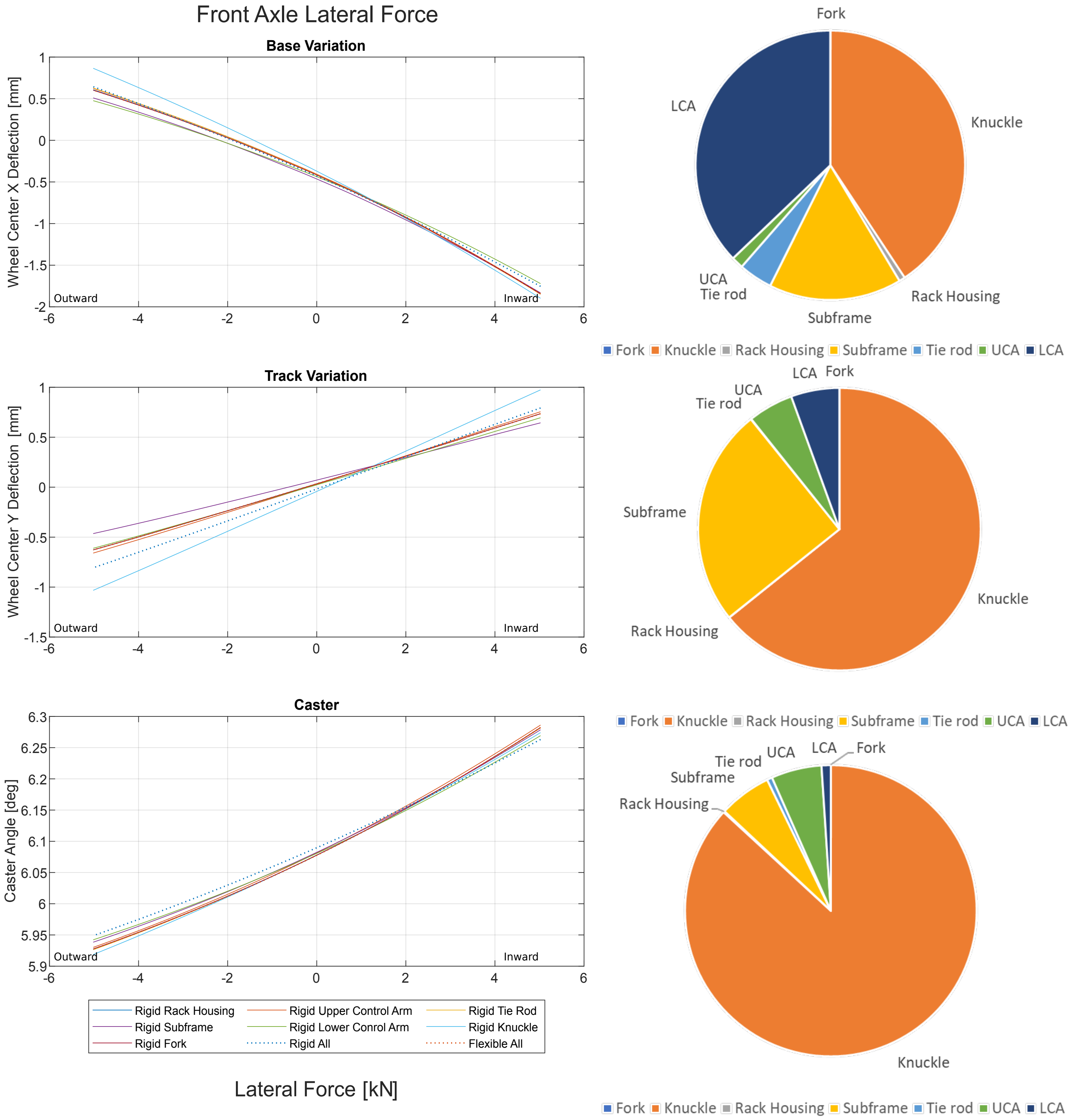

Figure A.4: X deflection, Y deflectionx, and caster angle vs lateral force at the front axle

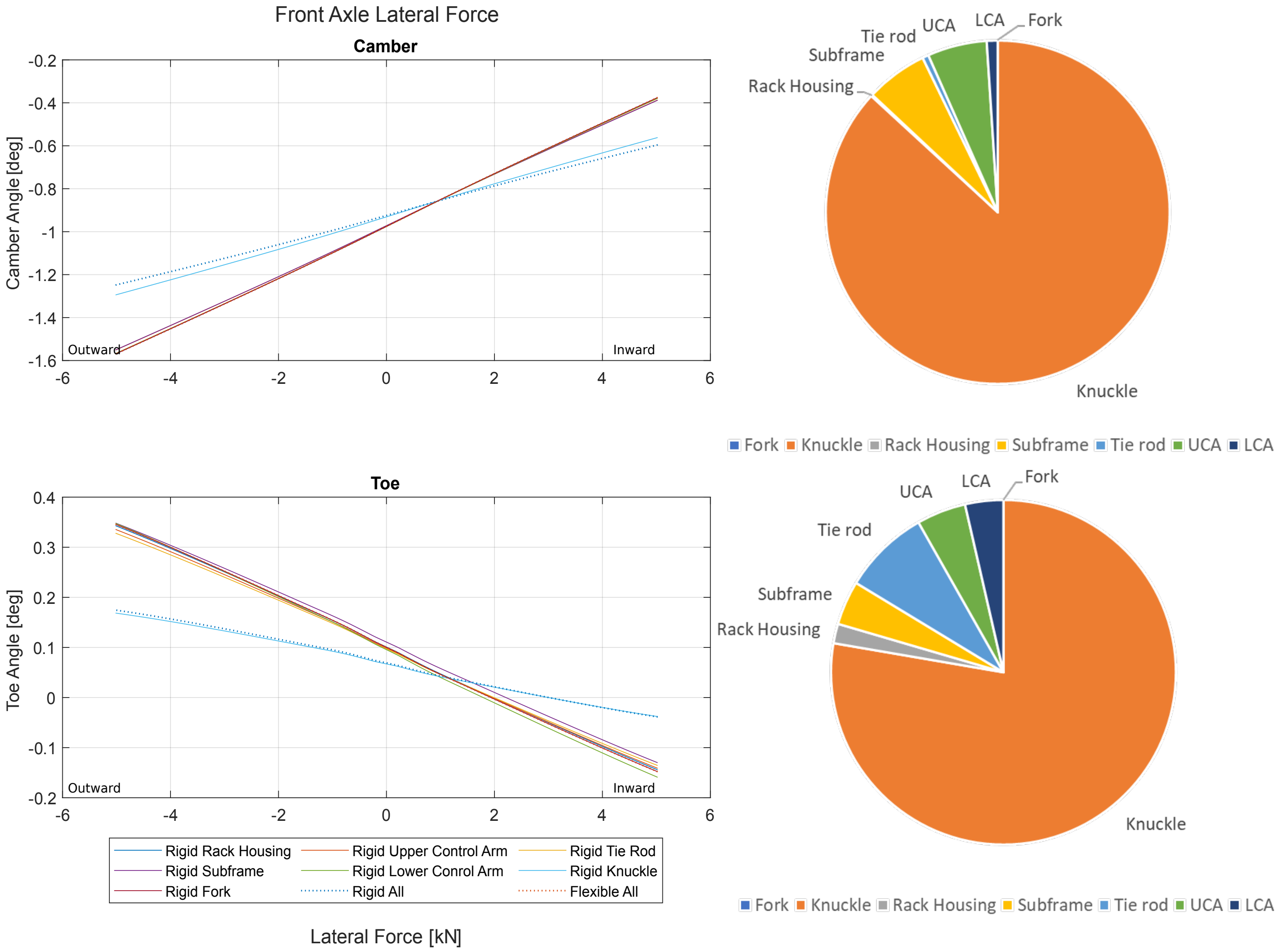

Figure A.5: Camber and toe angles vs lateral force at the front axle

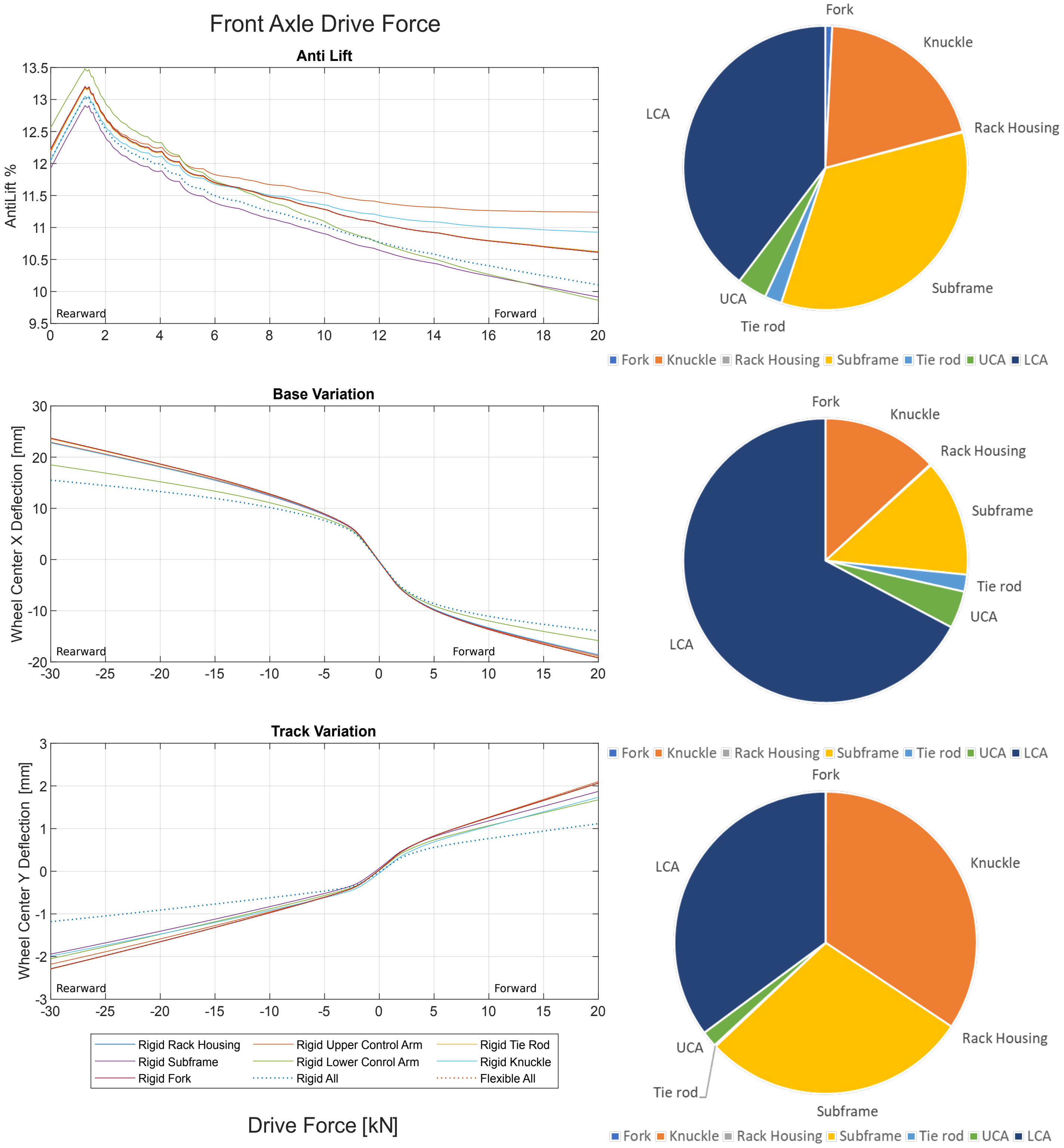

Figure A.6: Anti-lift, X deflection, Y deflection vs drive force at the front axle

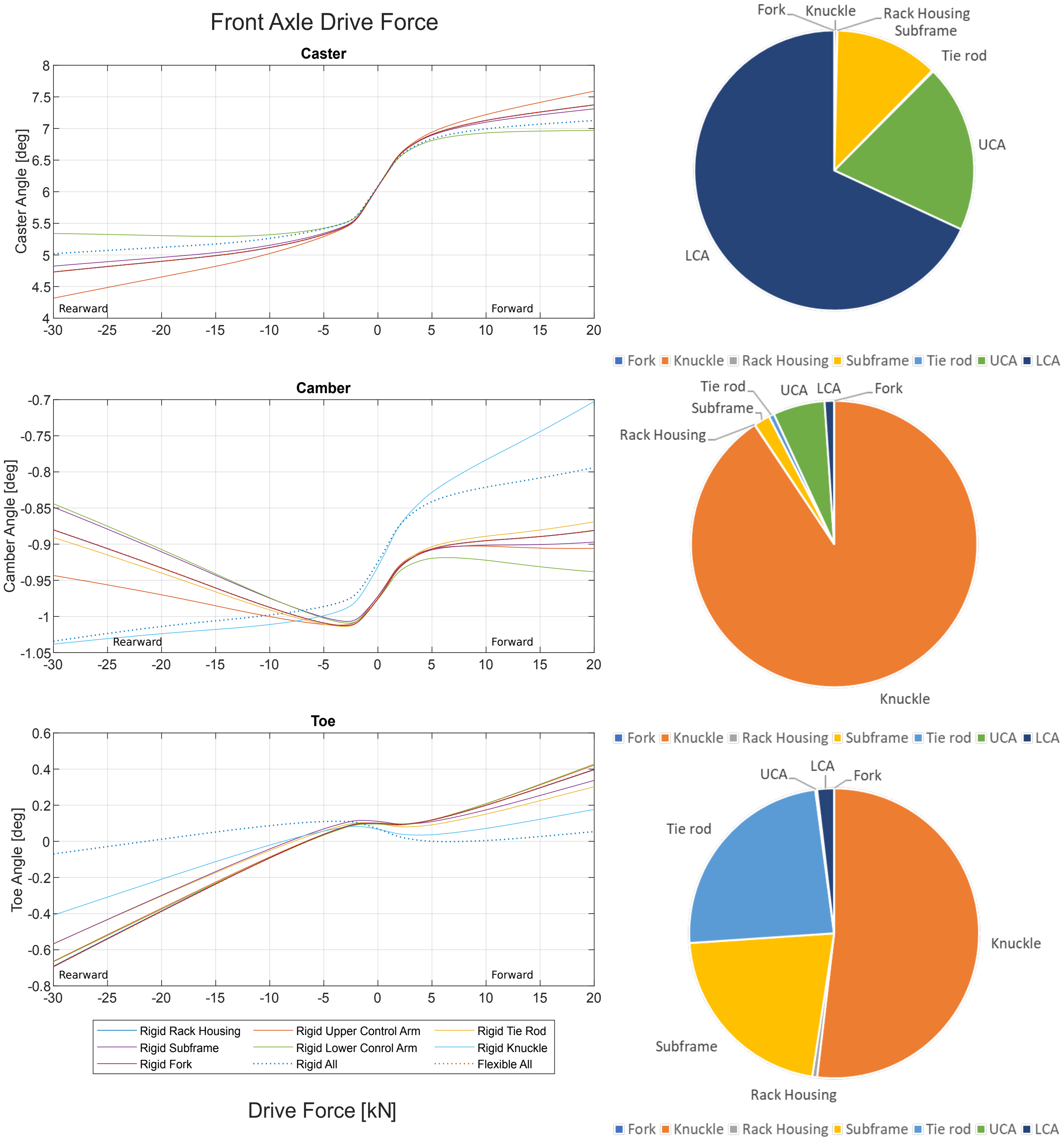

Figure A.7: Caster, camber, toe angles vs drive force at the front axle

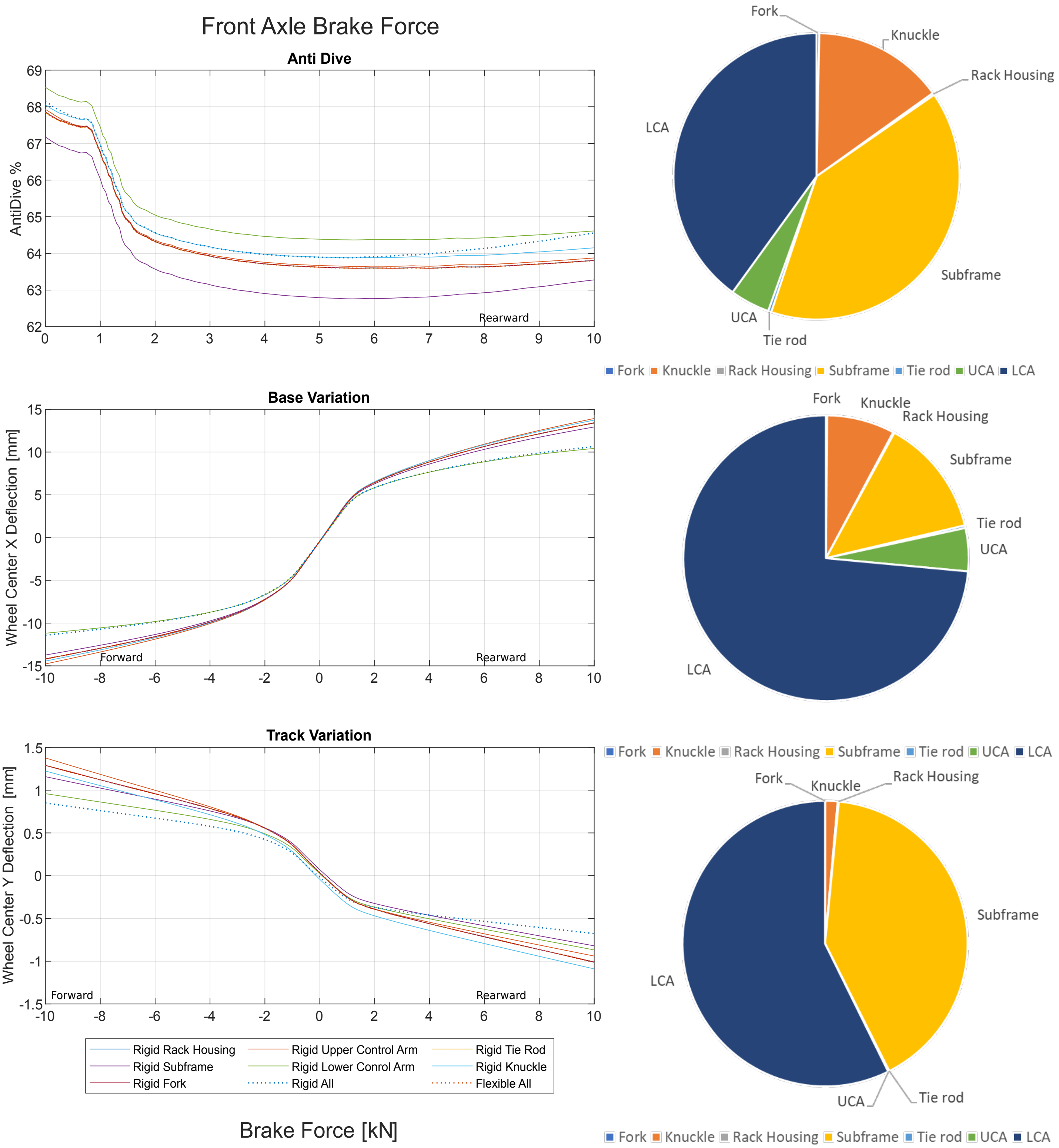

Figure A.8: Anti-dive, X deflection, Y deflection vs brke force at the front axle

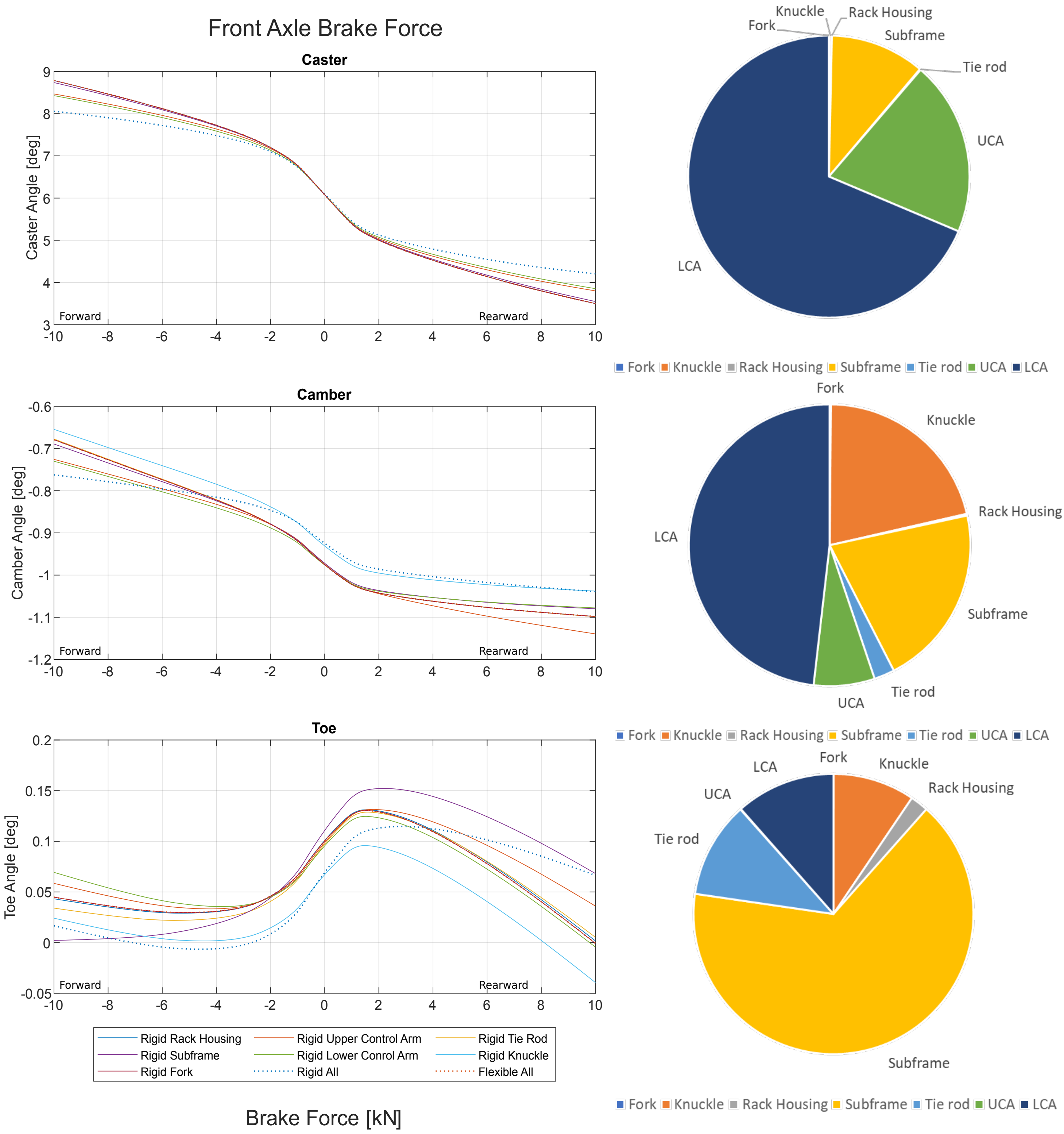

Figure A.9: Caster, camber, and toe angles vs brake force at the front axle

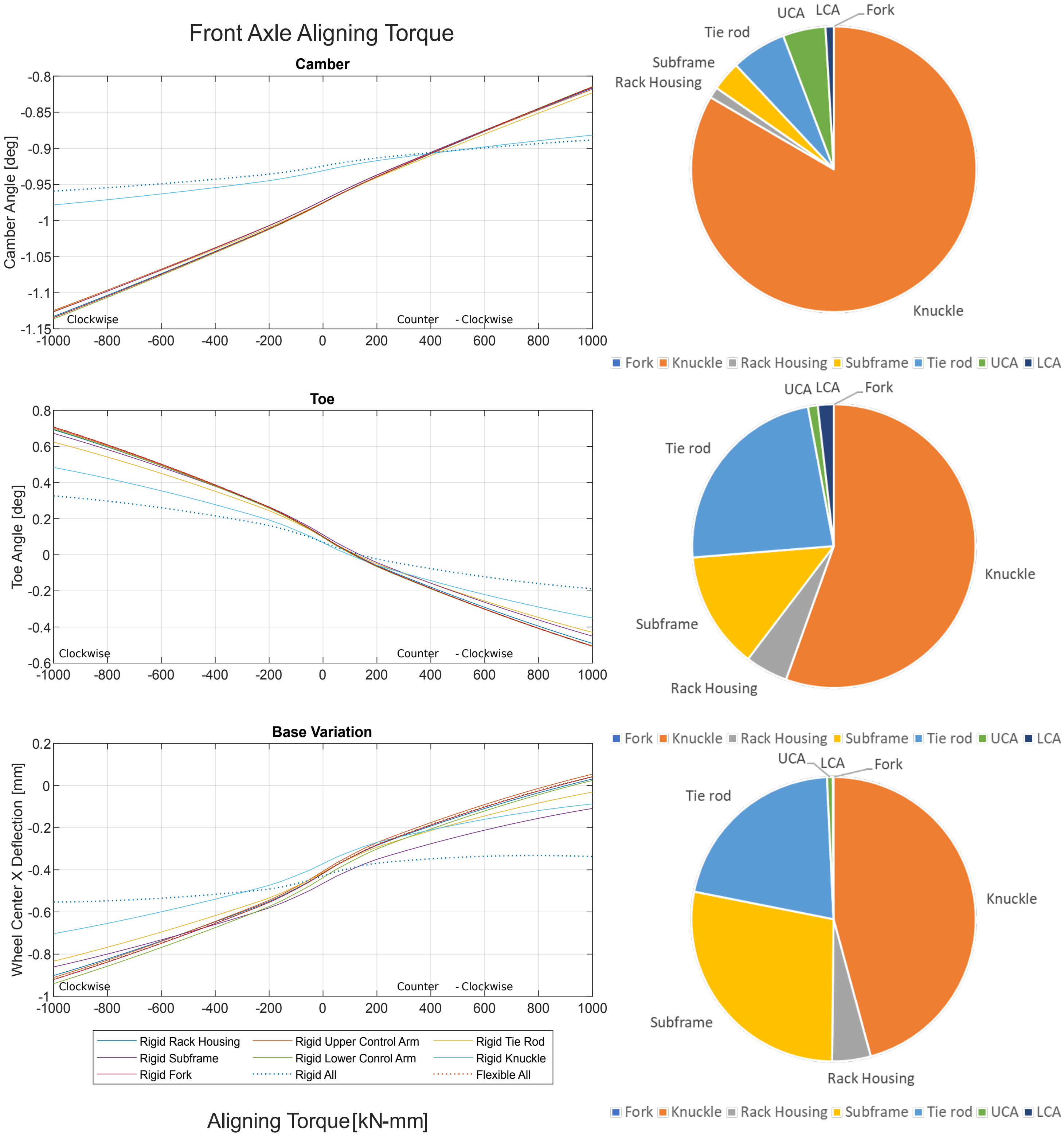

Figure A.10: Camber angle, toe angle, X deflection vs aligning torque at the front axle

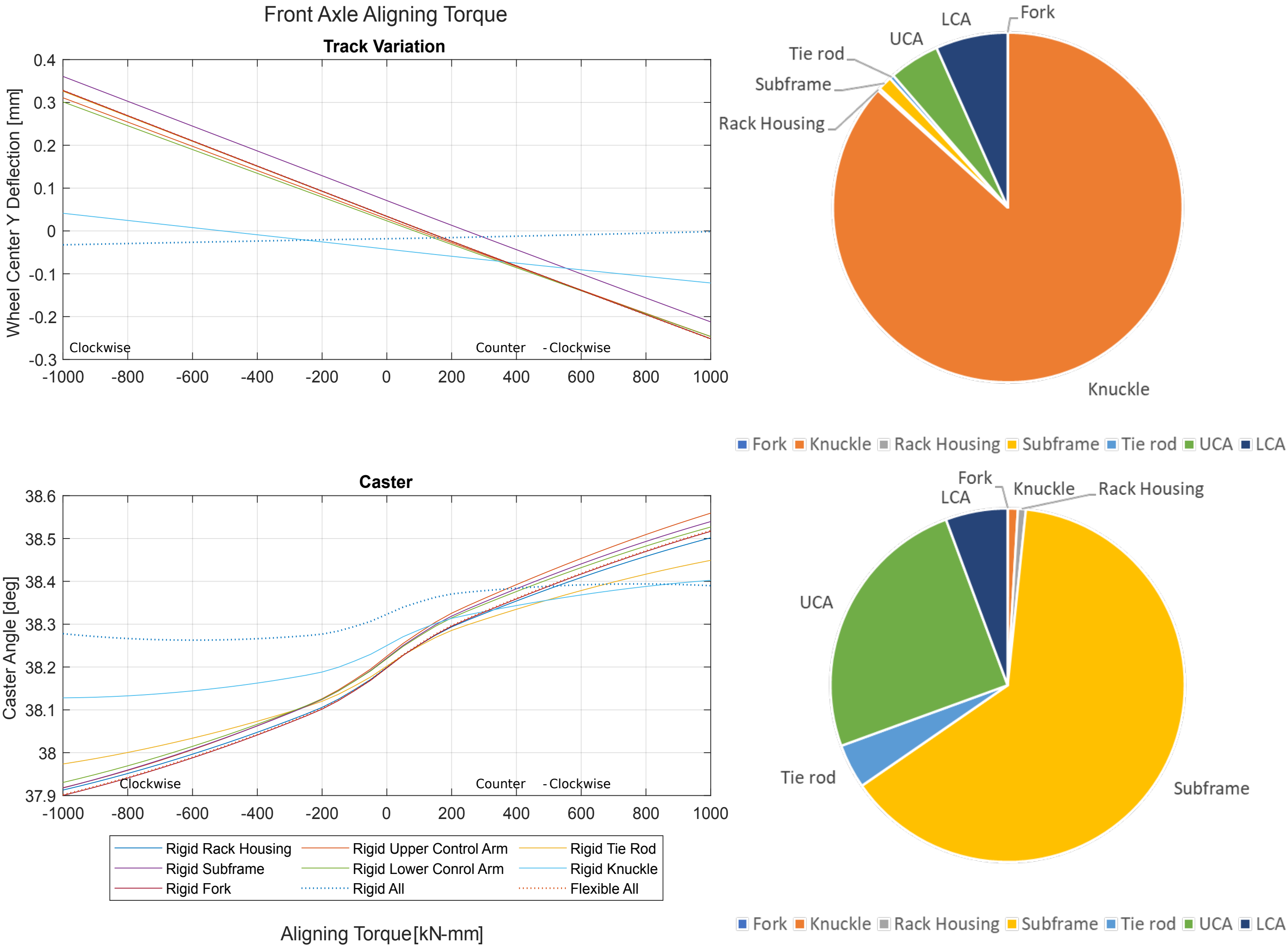

Figure A.11: Y deflection, caster angle vs aligning torque at the front axle

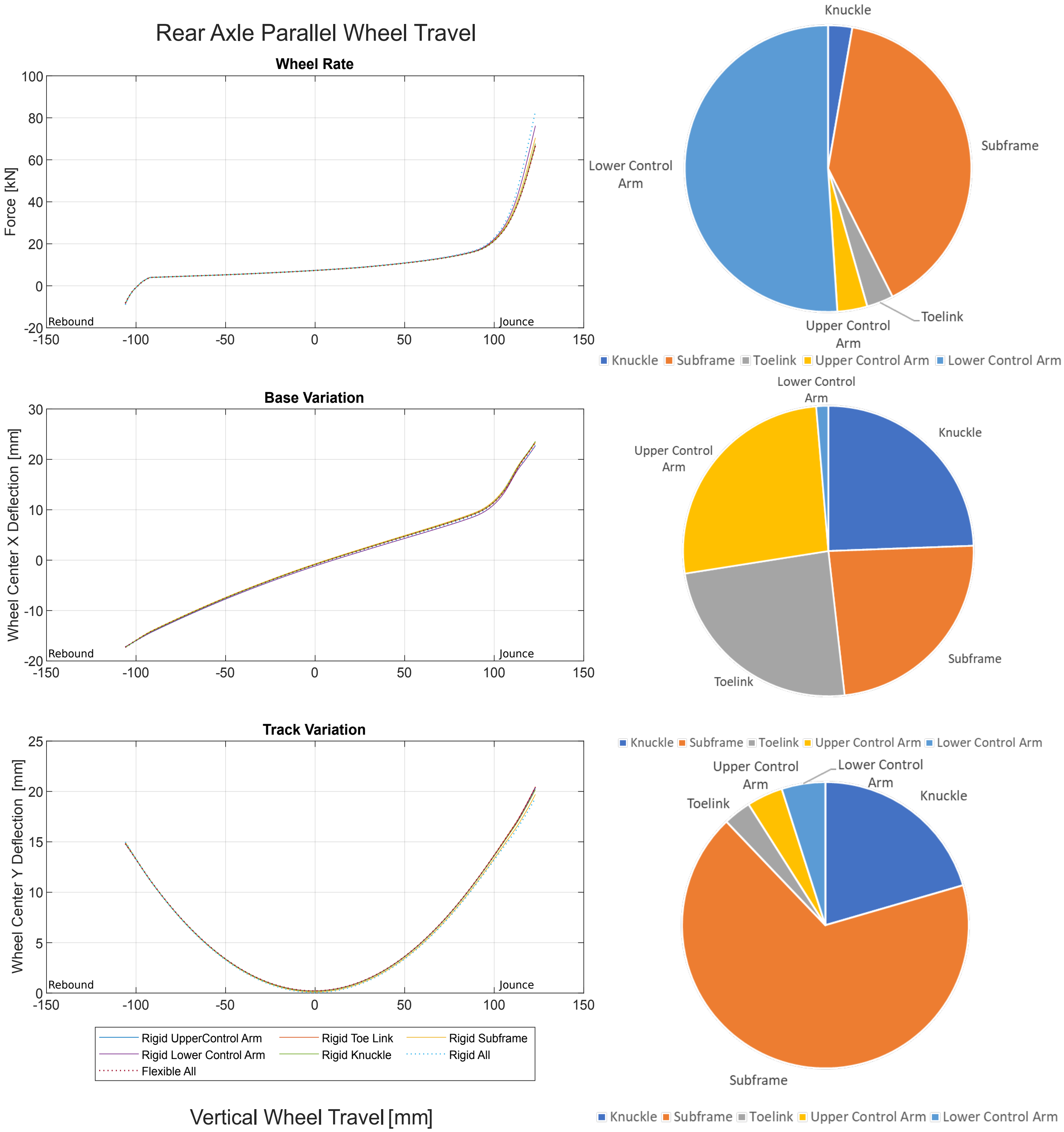

Figure A.12: Vertical load on the wheel, X deflection, Y deflection vs parallel wheel travel at the rear axle

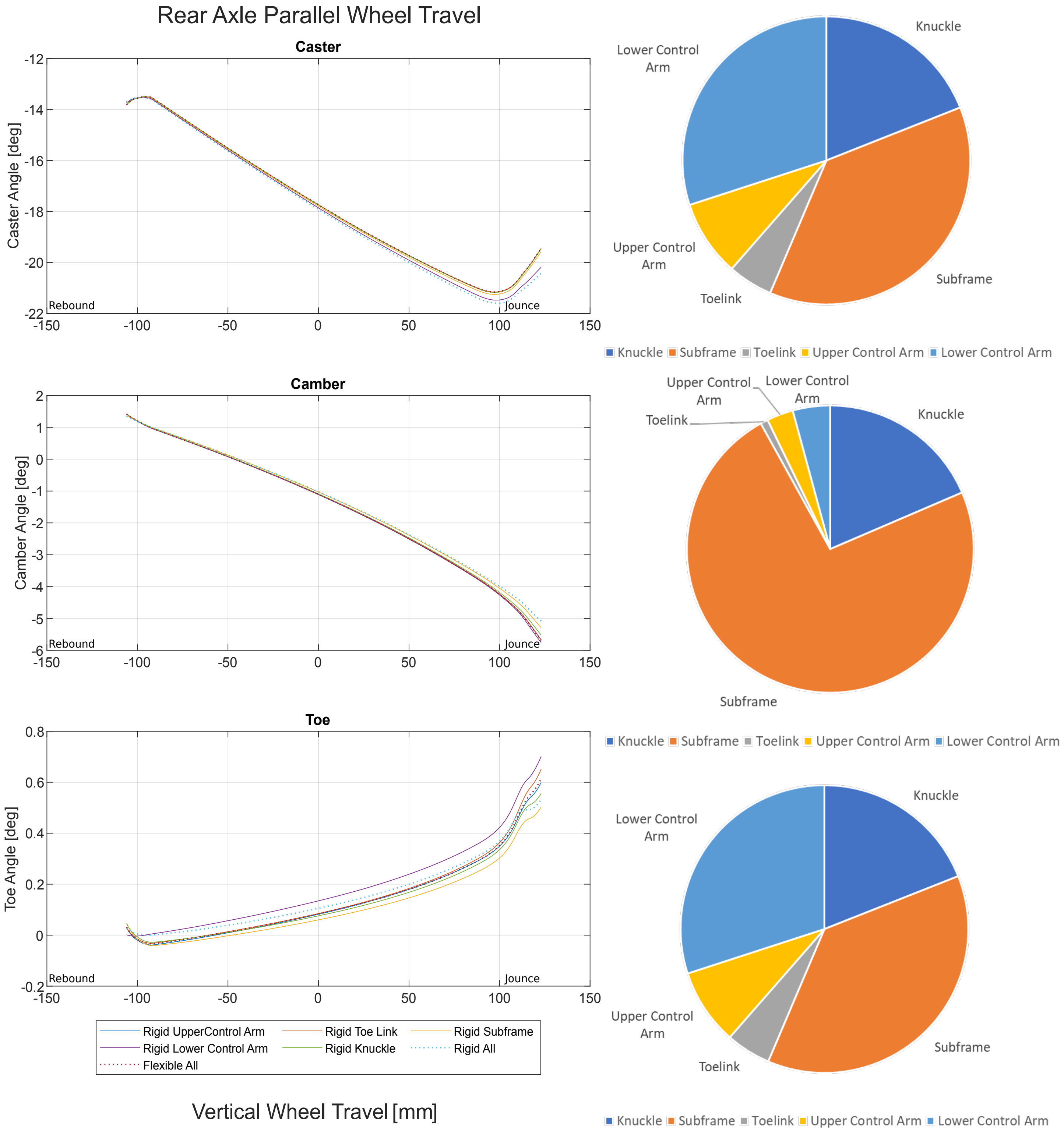

Figure A.13: Caster, camber, toe angles vs parallel wheel travel at the rear axle

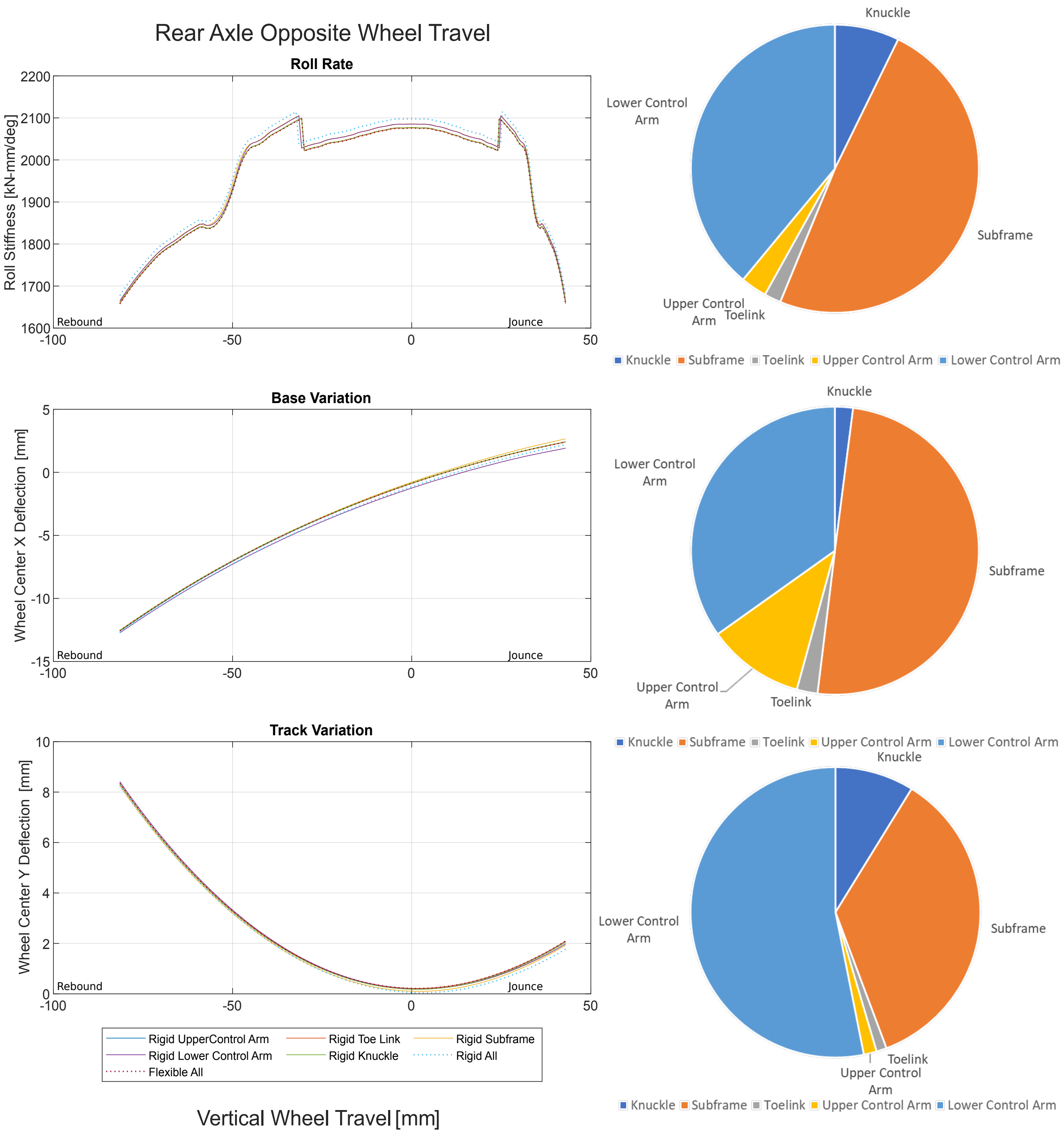

Figure A.14: Roll stiffnesss, X deflection, Y deflection vs opposite wheel travel at the rear axle

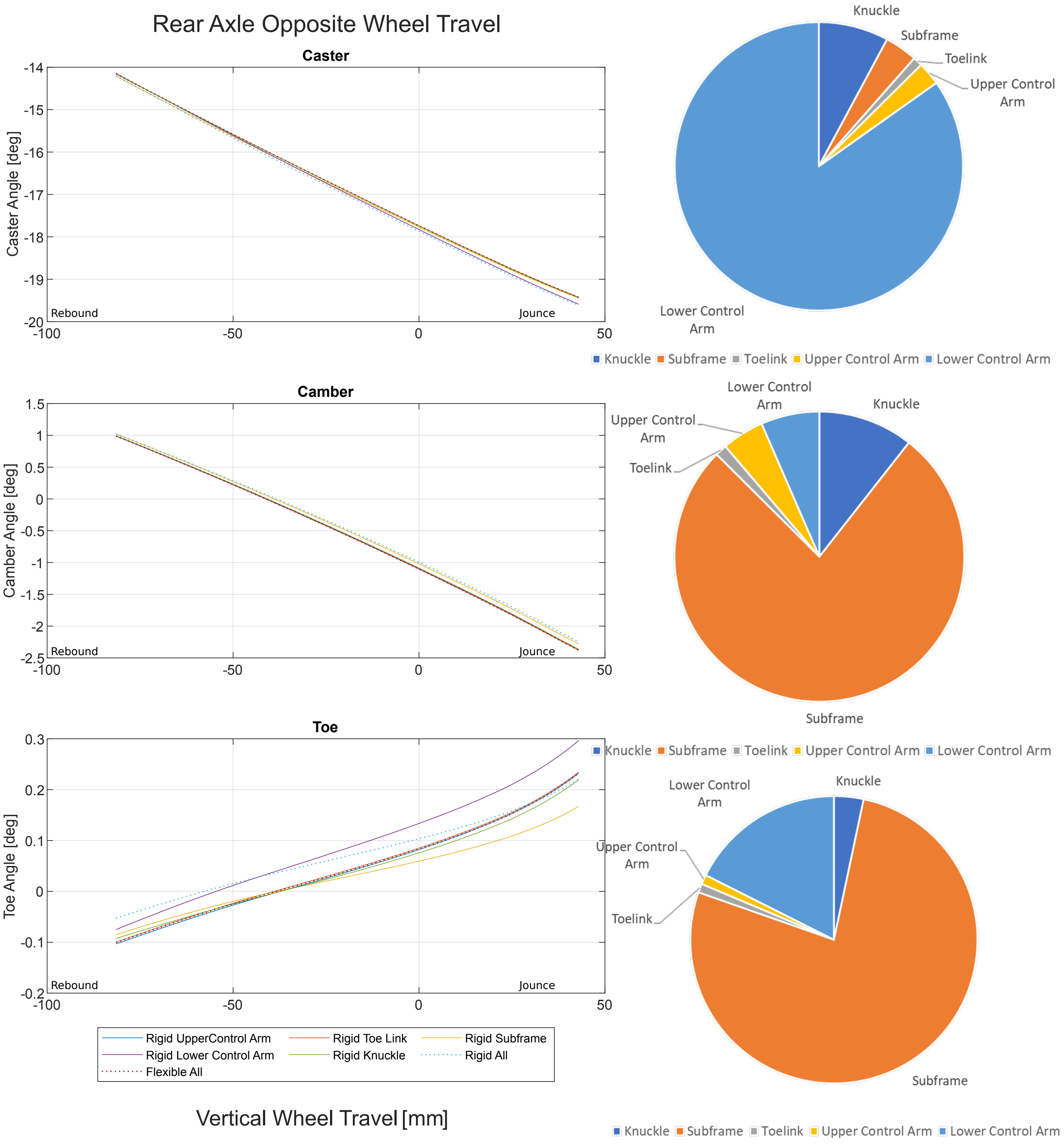

Figure A.15: Caster, camber, toe vs opposite wheel travel at the rear axle

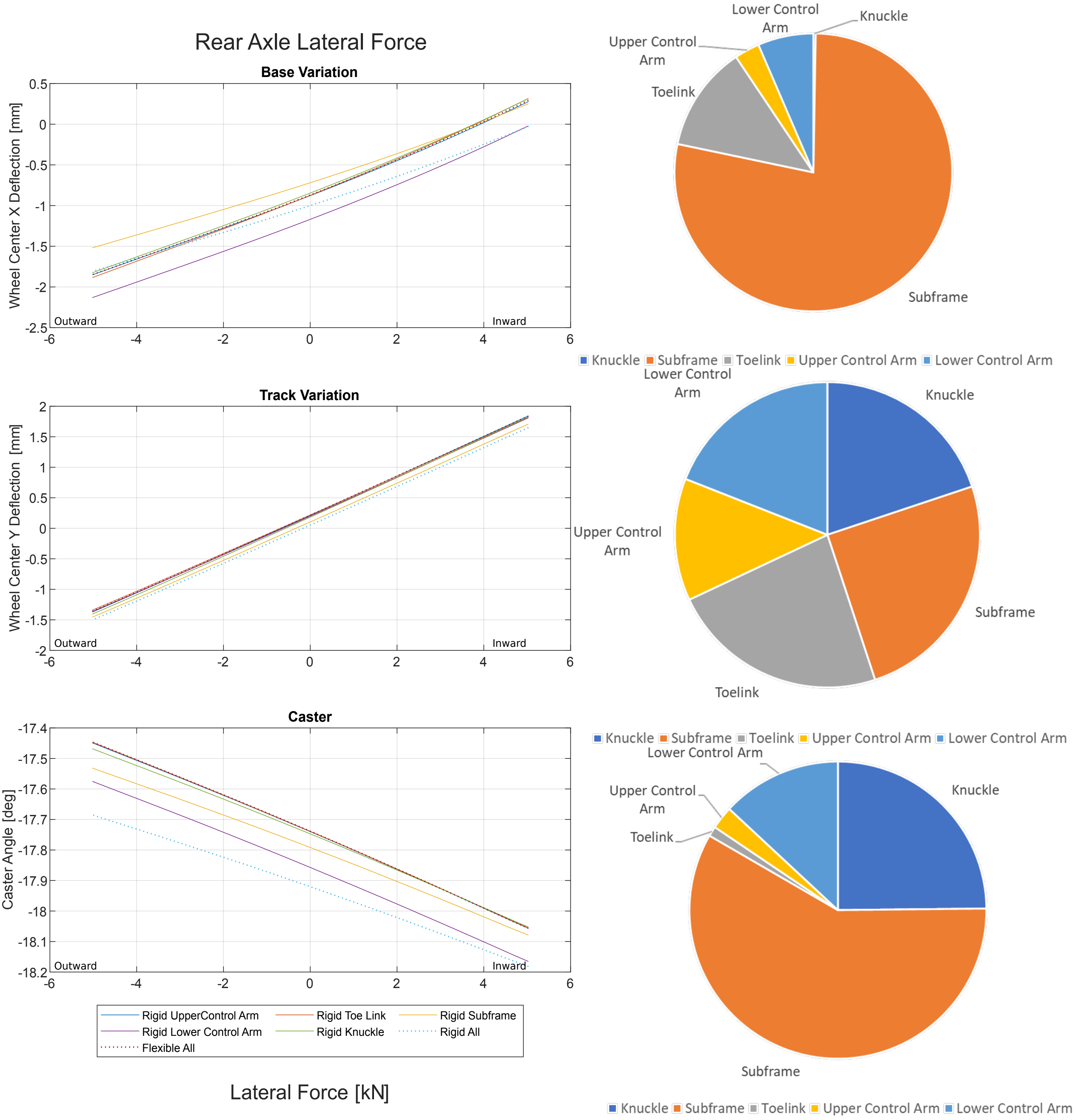

Figure A.16: X deflection, Y deflection, caster angle vs lateral force at the rear axle

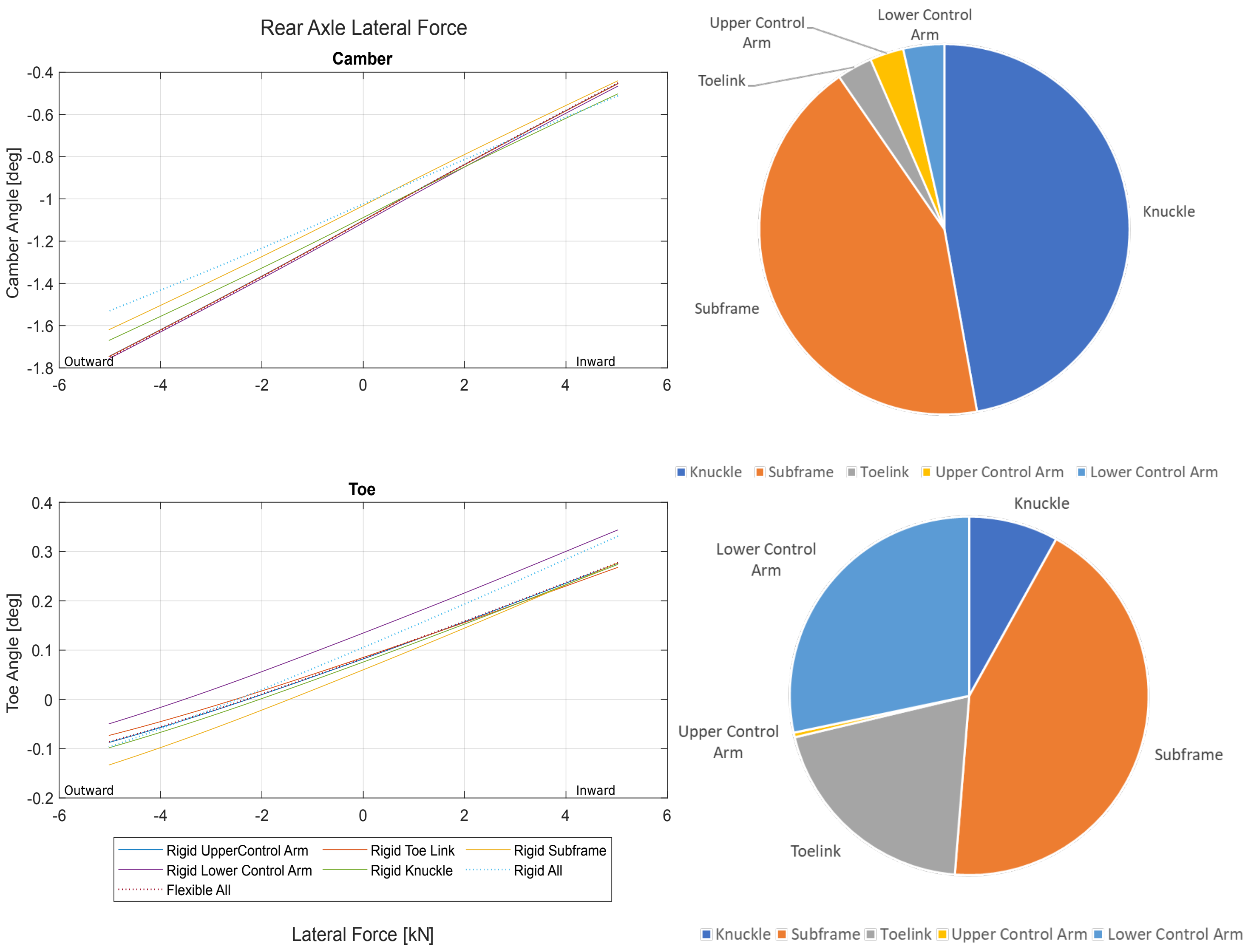

Figure A.17: Camer angle, toe angle vs lateral force at the rear axle

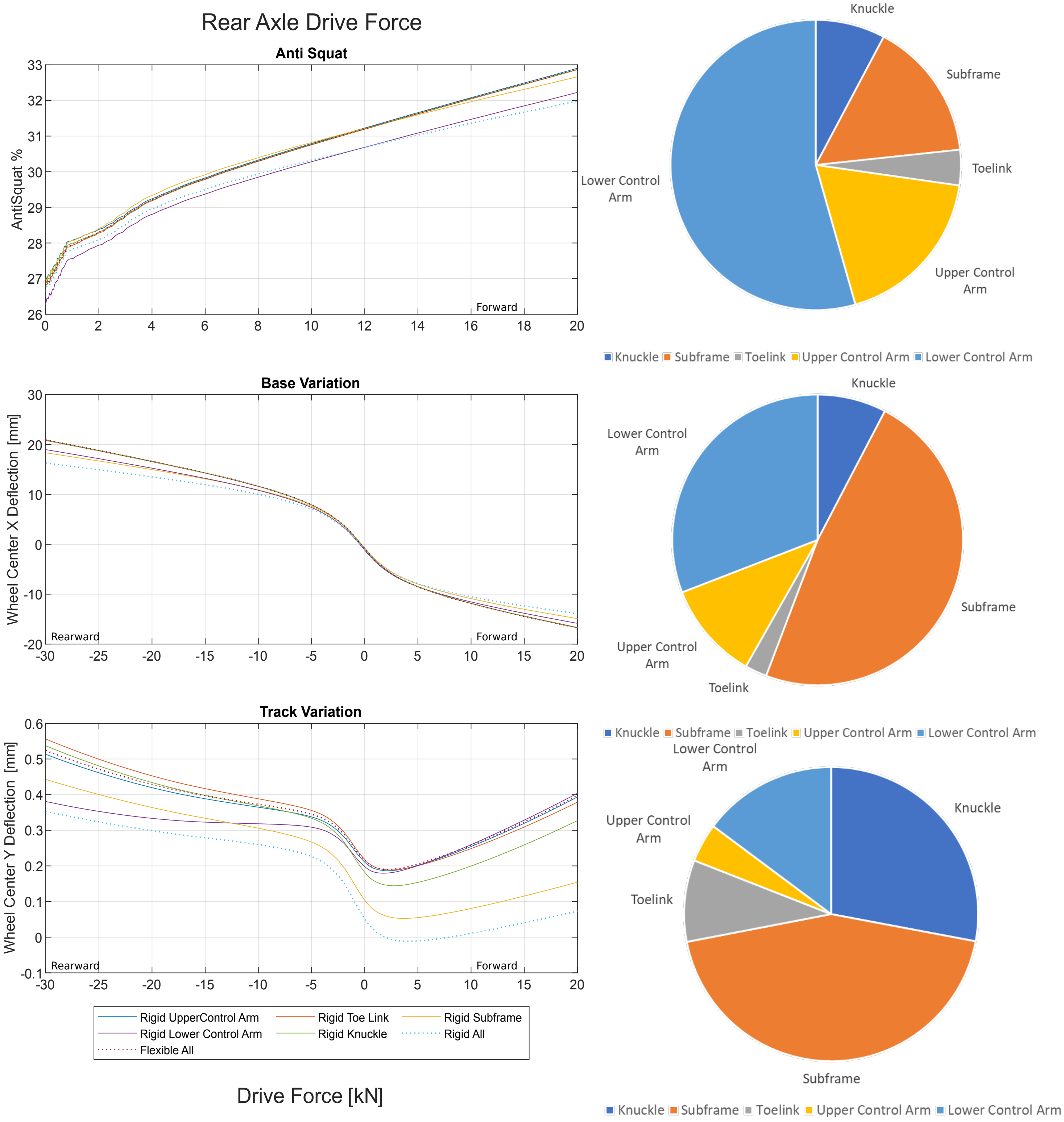

Figure A.18: Anti-squat, X deflection, Y deflection vs drive force at the rear axle

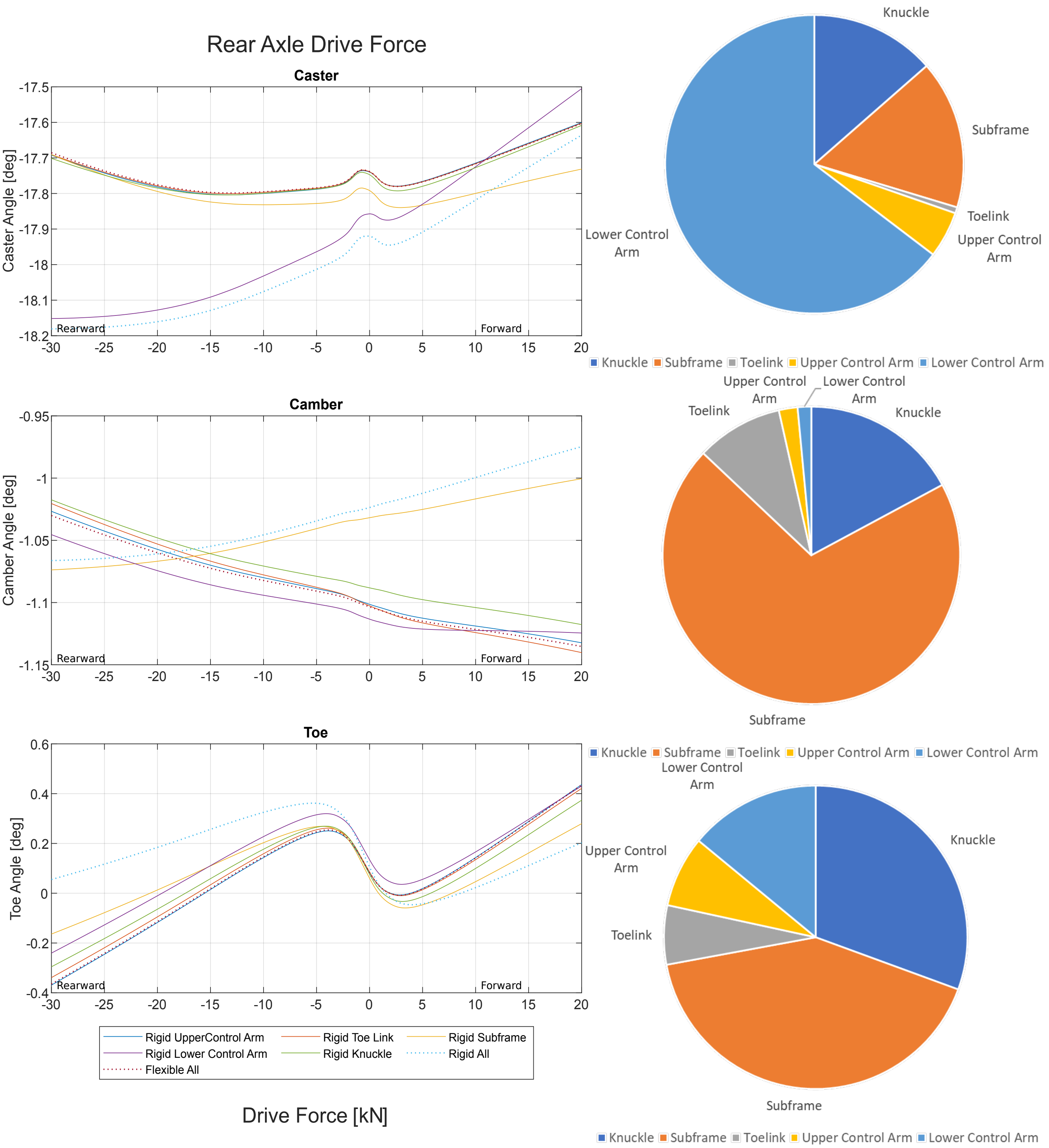

Figure A.19: Caster, camber, toe angles vs drive force at the rear axle

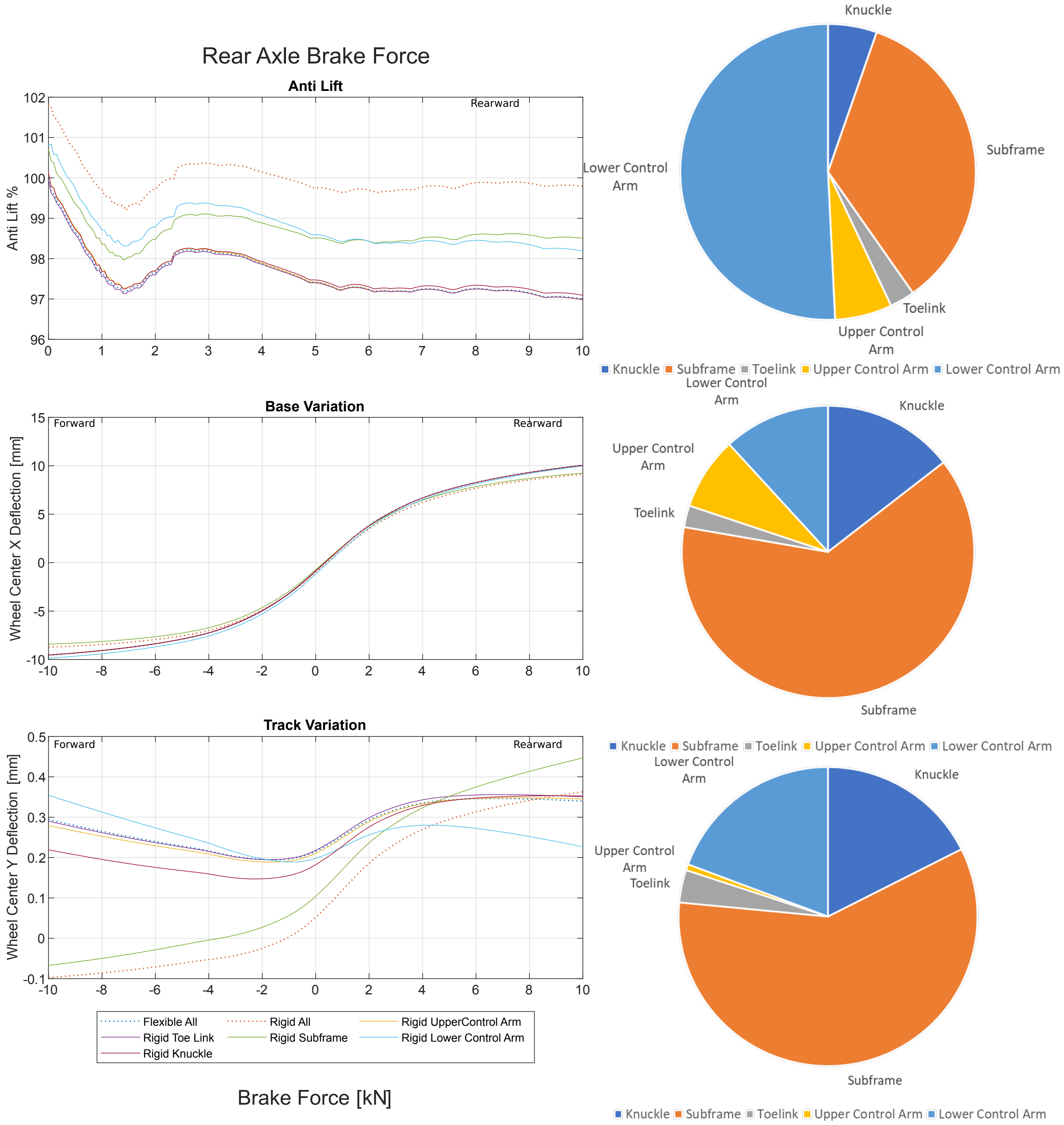

Figure A.20: Anti-kift, X deflection, Y deflection vs brake force at the rear axle

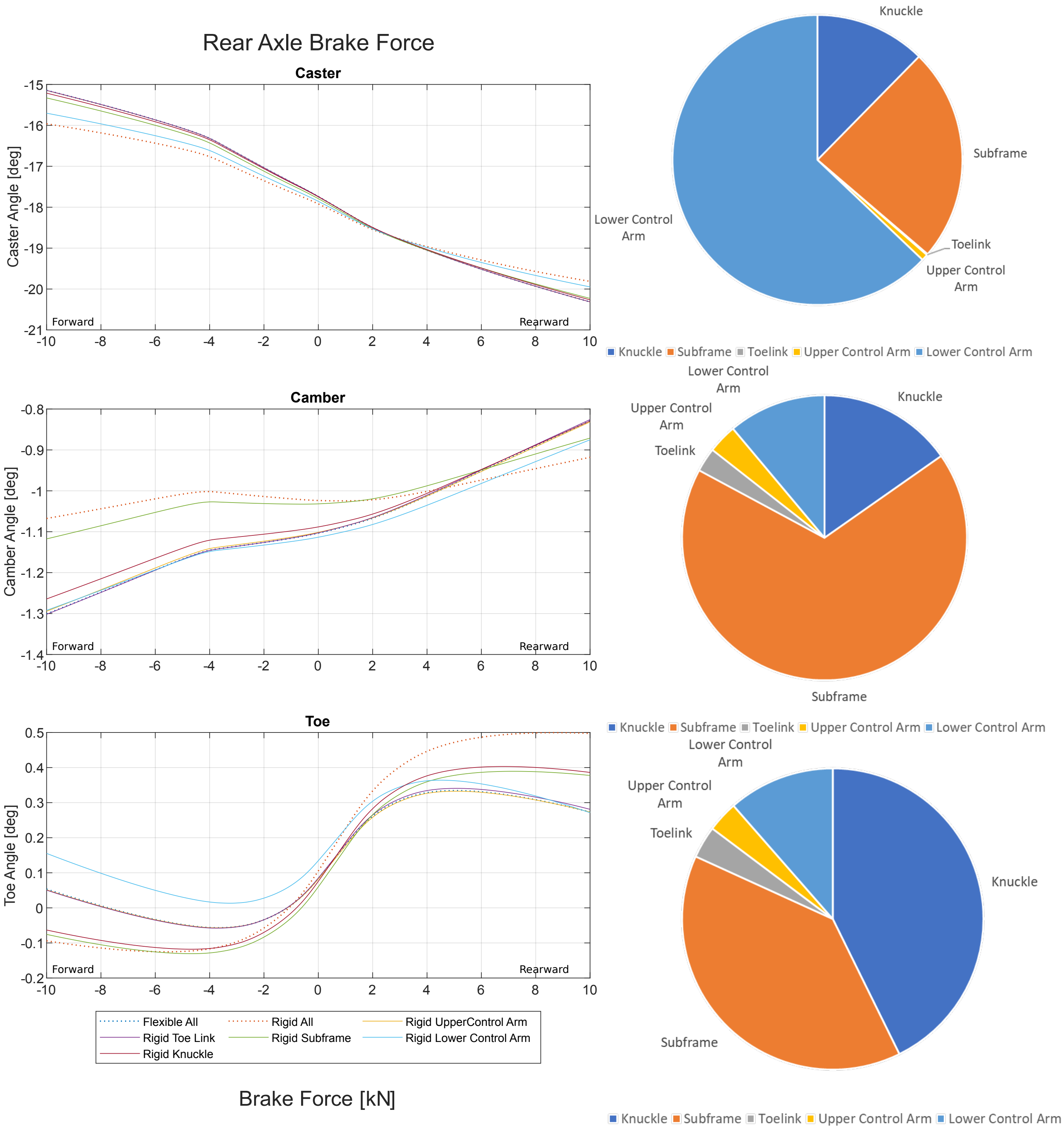

Figure A.21: Caster, camber, toe angles vs brake force at the rear axle

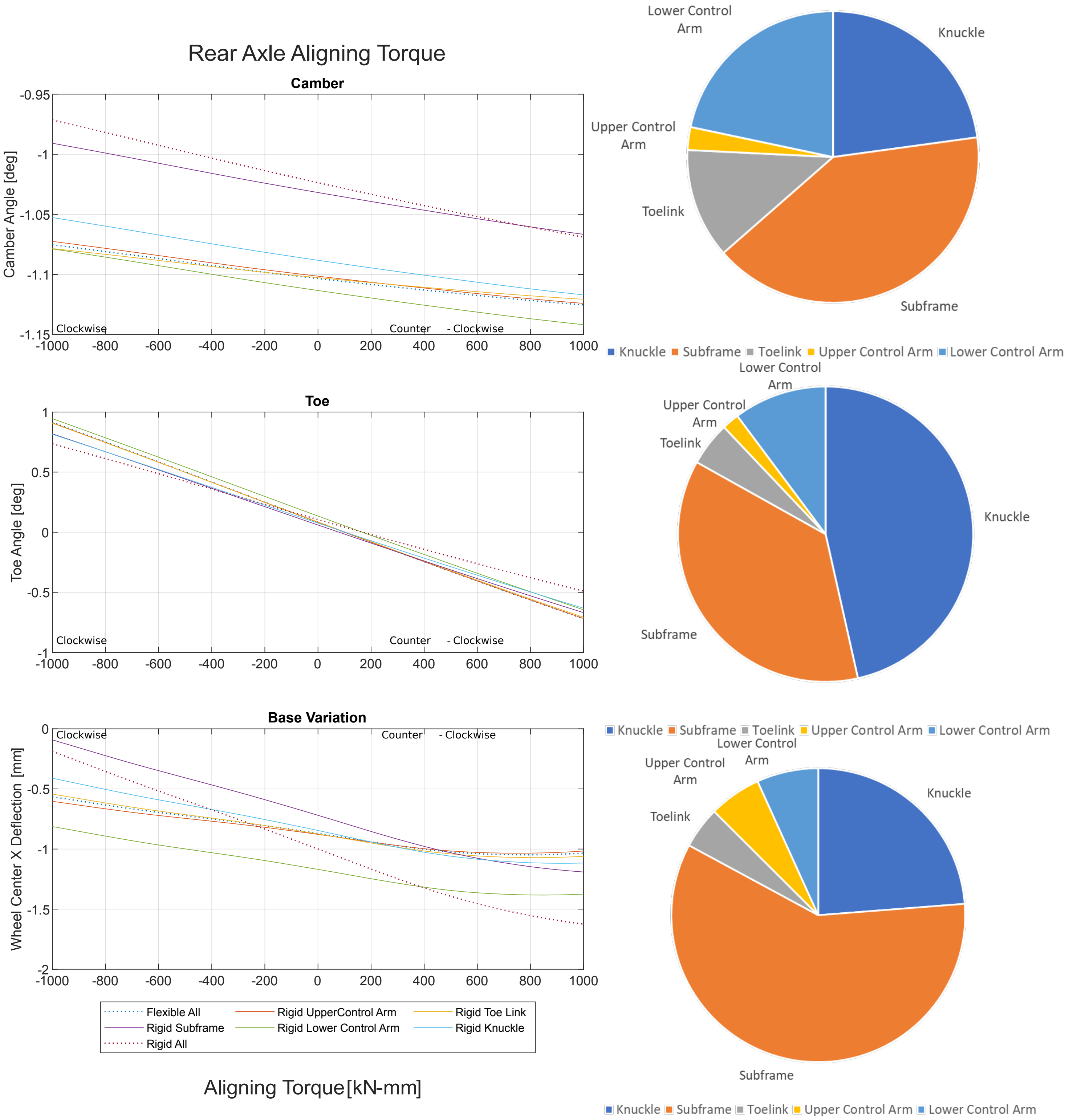

Figure A.22: Camber angle, toe angle, X deflection vs aligning torque at the rear axle

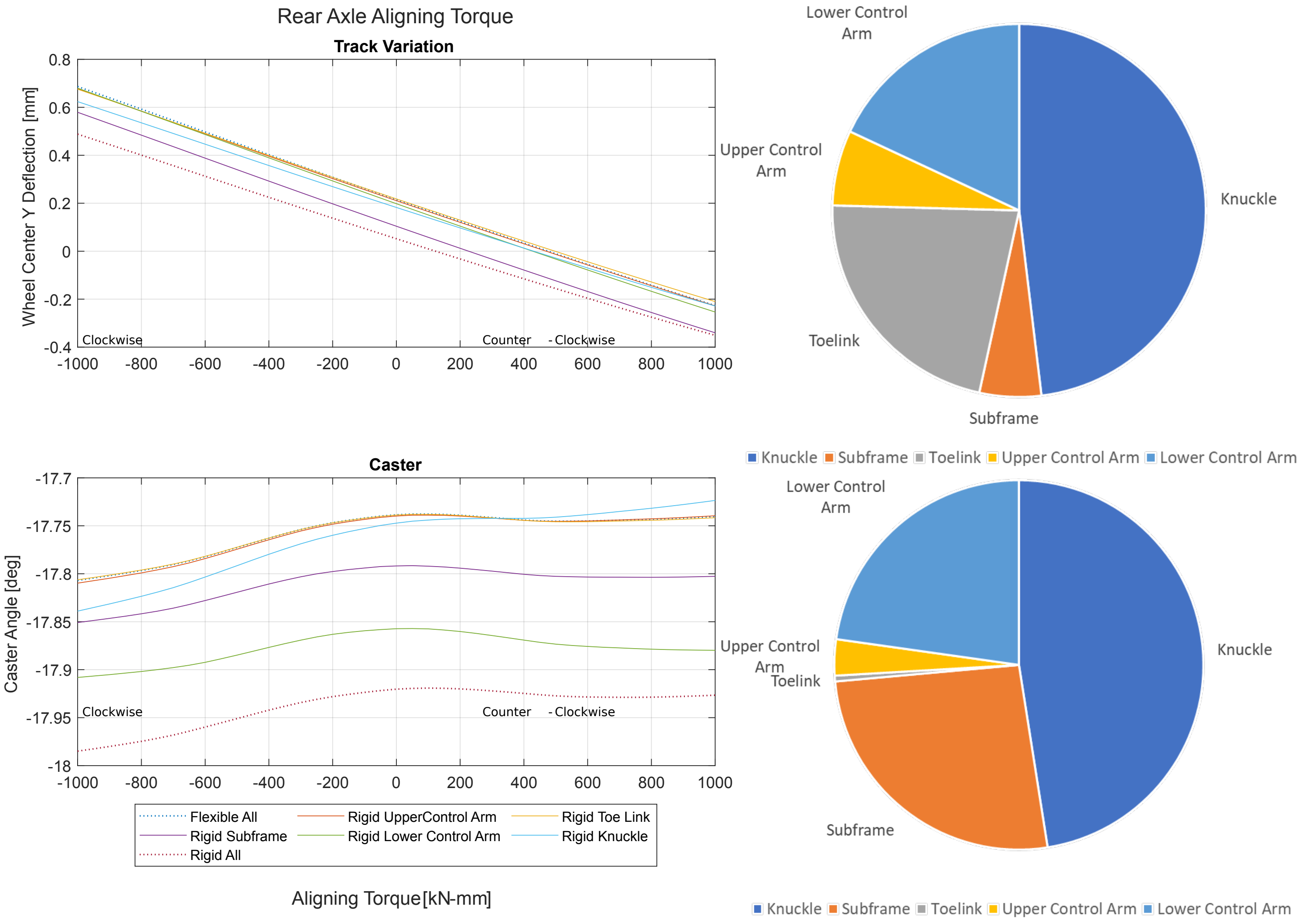

Figure A.23: Y deflection, caster angle vs aligning torque at the rear axle

A.3 Objective Metrics

	Rigid_all	**Flex_all**	**v1**	**v2**	**v3**
Max side slip [deg]	4.09	4.39	4.73	4.76	4.75
Time lag Ay vs SWA [ms]	57.5	59.5	60	60	60
Max. yaw rate [deg/s]	32.38	32.22	32.65	32.78	32.78
Time @ 45°lag in yaw vs SWA [ms]	79.07	81.18	81.5	81.81	80.73
Time @ 45°lag in Ay vs SWA [ms]	140	144.72	144.88	145.97	143.89
Roll rate gradient @ 1Hz [deg/s/g]	20.23	20.39	28.73	28.66	28.7
Yaw gain increase (peak vs 0.5Hz) [%]	37.99	36.36	48.32	47.1	46.84
Damping in roll [deg/s/g]	20.63	20.08	29.21	29.14	29.17
Stiffness in roll [deg/g]	3.43	3.47	4.83	4.82	4.81
Understeer gradient [deg/g]	1.75	1.9	2.05	1.97	1.88
SWT gradient [Nm/g]	2.17	2.1	2.07	2.09	2.12
SWT @ 0.3g [Nm]	4.24	4.24	4.25	4.25	4.25
Roll gradient [deg/g]	3.5	3.53	4.95	4.94	4.94

Table A.1: Objective metrics of vehicle variants

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