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## **Optimal Time Steps for HVE SIMON Simulations**

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# Optimal Time Steps for HVE SIMON Simulations

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## Abstract

This white paper explores the impact of time step selection in HVE-SIMON simulations, emphasizing the trade-off between truncation and round-off errors. Choosing an inappropriate time step can compromise both accuracy and computational efficiency—a step that is too large increases truncation error, while a step that is too small amplifies round-off error.

We analyze numerical integration methods, focusing on the 4th-order Runge-Kutta (RK4) method, which SIMON employs to solve equations of motion. The study evaluates time step effects across three simulation scenarios:

1. Constant acceleration dynamics (free-fall under gravity)
2. Impact dynamics (vehicle-to-vehicle collision), and
3. Suspension dynamics (vehicle landing on its suspension).

Simulation results demonstrate where optimal time step selection minimizes errors. Based on these findings, we provide recommended integration time step ranges for SIMON users, ensuring accurate and computationally efficient simulations.

## Introduction

The accuracy of simulation results depends on the chosen integration time step. An improper time step can lead to either significant truncation errors (if too large) or round-off errors (if too small). Understanding the trade-offs and selecting the optimal time step is essential for vehicle dynamics, handling, and collision reconstruction simulations.

SIMON (Simulation Model Non-linear) with DyMESH (Dynamic MEchanical SHell) is a multi-body vehicle dynamics model within HVE, designed for simulating vehicle motion and collisions. Unlike simpler models, SIMON accounts for non-linear vehicle behavior, making it well-suited for detailed accident reconstruction and handling analyses. SIMON numerically integrates equations of motion using the 4th-order Runge-Kutta (RK4) method [1], which provides a balance between computational efficiency and numerical accuracy. Since SIMON operates in single precision, careful time step selection is necessary to prevent excessive round-off errors [1]. The choice of the integration time step size directly affects simulation stability and precision, making proper selection important for accurate results.

This study examines the interplay between truncation and round-off errors in numerical integration and their effects on simulation accuracy. By evaluating different integration step sizes across three scenarios (constant acceleration, impact, and suspension dynamics), we identify optimal step size ranges for accurate and computationally efficient SIMON simulations.

## Objectives

- Investigate the error trends in simulation methods.
- Provide guidelines for selecting the appropriate time step for various simulation scenarios.

## Numerical Integration Methods

Numerical integration is a computational technique used to solve differential equations when an exact analytical solution is not feasible. In the context of vehicle dynamics simulations, numerical integration calculates an object's position, velocity, and acceleration over time by approximating how forces influence motion. By breaking the simulation into discrete time steps,

numerical integration methods estimate changes in state variables at each step, progressively building an accurate representation of the system's behavior. The accuracy of this process depends on the integration method and the chosen time step size, which must balance precision and computational efficiency.

**Euler Method:**

Euler method is the simplest numerical integration approach for solving ordinary differential equations (ODEs). Given an initial value problem of the form:

$$\frac{dy}{dt} = f(y, t), \quad y(0) = y_0$$

The next value is computed using:

$$y_{n+1} = y_n + hf(y_n, t_n)$$

$h$  is the integration time step size. This method is computationally inexpensive but exhibits high truncation errors, making it unsuitable for problems requiring high accuracy.

**Runge-Kutta Methods (4th Order):**

Runge-Kutta methods are a family of iterative techniques for solving ODEs with improved accuracy over Euler method. The **4th-order Runge-Kutta (RK4) method** provides a good balance between accuracy and computational cost. It uses four intermediate calculations per step:

$$k_1 = hf(y_n, t_n)$$

$$k_2 = hf(y_n + \frac{k_1}{2}, t_n + \frac{h}{2})$$

$$k_3 = hf(y_n + \frac{k_2}{2}, t_n + \frac{h}{2})$$

$$k_4 = hf(y_n + k_3, t_n + h)$$

The next step is calculated as:

$$y_{n+1} = y_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4)$$

In RK4, halving the time step reduces truncation error by a factor of 16, significantly improving accuracy at the cost of higher computational load.

The RK4 method significantly reduces truncation errors while maintaining reasonable computational efficiency, making it widely used in engineering simulations, including SIMON.

**Errors**

Errors in numerical integration methods can broadly be classified into truncation errors and round-off errors:

**Truncation Errors:**

- Truncation errors arise due to the approximation of mathematical expressions in numerical methods.
- A large truncation error reduces accuracy because the solution deviates significantly from the true value.
- When using the RK4 method, the error decreases proportionally to the fourth power of the step size (" $h$ "). This means that halving the step size reduces the truncation error by a factor of 16.
- Using a large time step in a SIMON simulation may cause inaccurate vehicle trajectories due to poor resolution of forces and accelerations.

**Round-Off Errors:**

- Round-off errors result from the finite precision of computer arithmetic. When numbers are represented in a limited number of bits, small discrepancies accumulate over multiple calculations.
- Small round-off errors reduce precision by introducing variability in repeated calculations.
- When round-off errors accumulate (e.g., using excessively small time steps), they can also impact accuracy by drifting the solution away from the correct result.

- If a time step is too small, accumulated round-off errors in SIMON may lead to inconsistent or oscillating results, reducing precision and accuracy.

### Single vs. Double Precision in Numerical Simulations

Numerical simulations rely on floating-point arithmetic to represent real numbers. The choice between single precision and double precision affects both accuracy and computational performance.

| Precision Type            | Decimal Digits of Precision |
|---------------------------|-----------------------------|
| Single Precision (32-bit) | ~7–8 significant digits     |
| Double Precision (64-bit) | ~15–16 significant digits   |

Single precision has a limited number of significant digits (~7–8), leading to greater round-off errors, particularly in long simulations or when using very small time steps; however, single precision uses half the memory of double precision, allowing faster computations and reducing processing requirements.

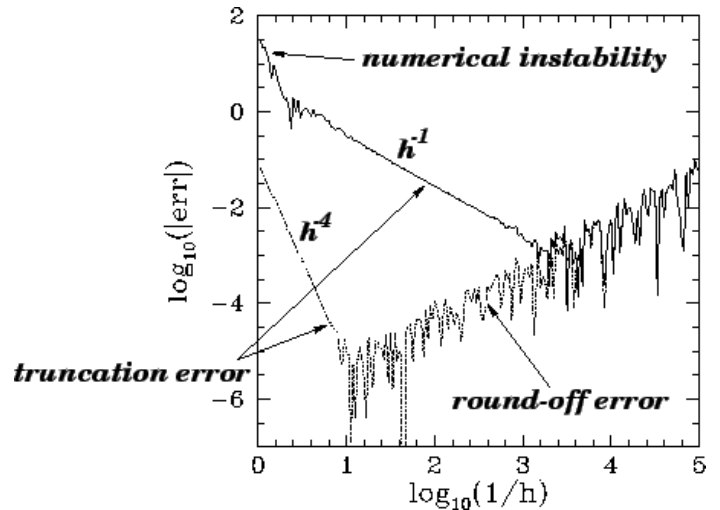
SIMON uses single-precision (32-bit) floating-point arithmetic for numerical integration [1]. This choice balances computational efficiency and memory usage, making simulations faster while maintaining sufficient accuracy for most vehicle dynamics applications. While double precision would reduce round-off errors, it would also increase memory usage and computation time.

It is important to understand that single precision introduces limitations, particularly when using very small time steps, where round-off errors can accumulate.

Excessively reducing the step size increases the computational burden and may lead to diminishing returns due to the introduction of round-off errors. The interplay between truncation and round-off errors creates a characteristic U-shaped curve when plotting global error against step size. The optimal step size is found at the minimum of this curve, where truncation and round-off errors are balanced.

Figure 1 is an illustration of the error profile for both Euler and 4<sup>th</sup> Order Runge-Kutta methods, where the left side (truncation error) and the right side (round-off error) define the limits for step size selection. The

minimum point represents the optimal step size for a given numerical precision.



**Figure 1.** Illustration of the error profile for Euler and 4<sup>th</sup> Order Runge-Kutta Method [2].

Given that SIMON operates in single precision, excessively small time steps increase round-off errors leading to the characteristic U-shaped error profile, where the optimal step size is found at the balance of truncation and round-off errors.

### Methodology

In order to determine the optimal integration time step for SIMON simulations three scenarios were investigated:

1. Constant acceleration dynamics
2. Impact dynamics
3. Suspension dynamics

Integration time steps were varied to examine their effect on numerical accuracy, computational efficiency, and solution stability across different types of vehicle dynamics. The integration time step directly affects how the equations of motion are solved, impacting both the precision of the results and the computational cost. Since total simulation time is proportional to the integration time step, smaller time steps increase computation time.

Varying the integration time step allowed us to:

- Evaluate truncation vs. round-off errors: Smaller time steps reduce truncation error but increase round-off error due to SIMON's single-precision calculations.
- Analyze the sensitivity of different simulation types: Constant acceleration simulations (e.g., free-fall) provide a controlled environment to measure numerical error relative to an analytically known solution. Impact simulations involve rapid velocity and acceleration changes, requiring sufficiently small time steps to accurately capture peak forces and impulses. Suspension dynamics require a balance—too large of an integration time step can smooth out critical oscillations, while too small a step can introduce excessive numerical noise.
- Determine the computational trade-offs: Excessively small integration time steps increase simulation time without significantly improving accuracy beyond a certain threshold.
- Identify optimal time step ranges: By systematically varying step sizes, we established practical recommendations that maintain accuracy without excessive computational burden.

In addition to varying the integration time step, different output time steps were also used in the impact and suspension dynamics simulations. The integration time step controls numerical accuracy, whereas the output time step determines how frequently simulation results are recorded and analyzed. Unlike the integration time step, the output time step has little effect on total simulation time but is directly proportional to file size. Smaller output steps result in larger data files, increasing storage requirements and post-processing effort, while larger output steps may reduce file size but risk losing resolution in fast-changing events.

Varying the output time step is important for:

- Ensuring critical events are not missed, particularly in high-speed impact simulations where abrupt changes in velocity and acceleration occur.

- Reducing redundant data storage, since overly small output steps generate excessively large datasets without adding significant analytical value.
- Identifying potential numerical artifacts, as finer output time steps may expose oscillations or numerical noise that could be misinterpreted.

By analyzing both integration and output time steps, we identified optimal step size ranges that ensure accurate and computationally efficient SIMON simulations while maintaining sufficient output resolution for engineering analysis.

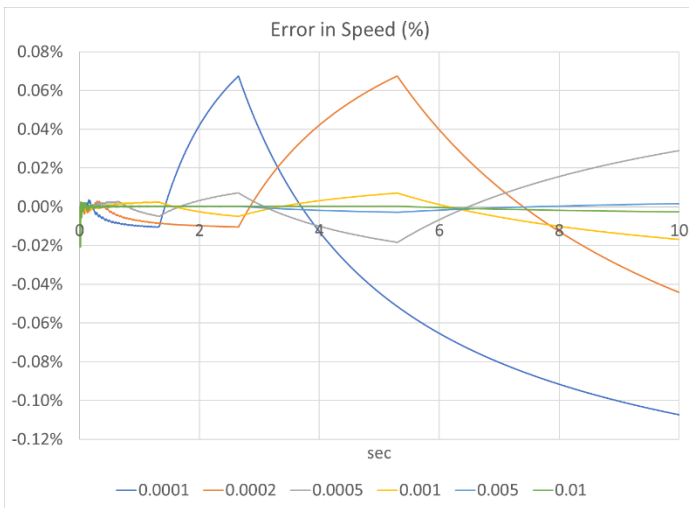
### **1. Constant acceleration dynamics**

#### **Setup:**

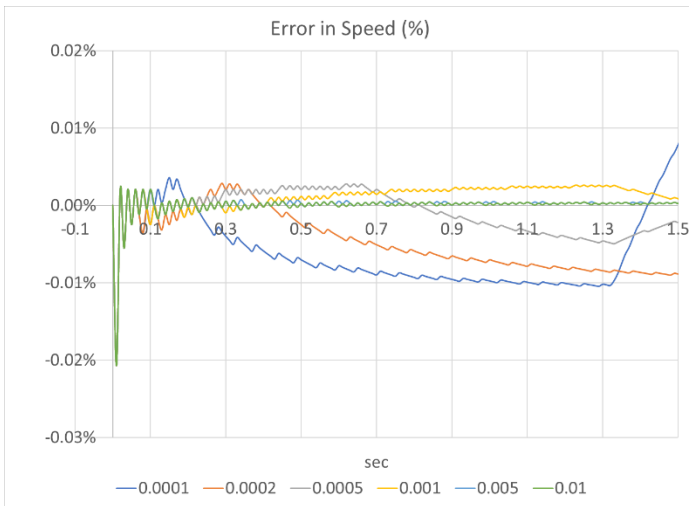
- A movable barrier is placed at a height of 2500 feet.
- Simulated free-fall under gravity ( $-1g$ ) for 10 seconds using the SIMON simulation environment.
- Adjusted integration step size from 0.01 to 0.0001 sec.
- The "true" solution for this scenario was determined mathematically, given that the only acceleration acting on the object was gravity.

#### **Evaluation Criteria:**

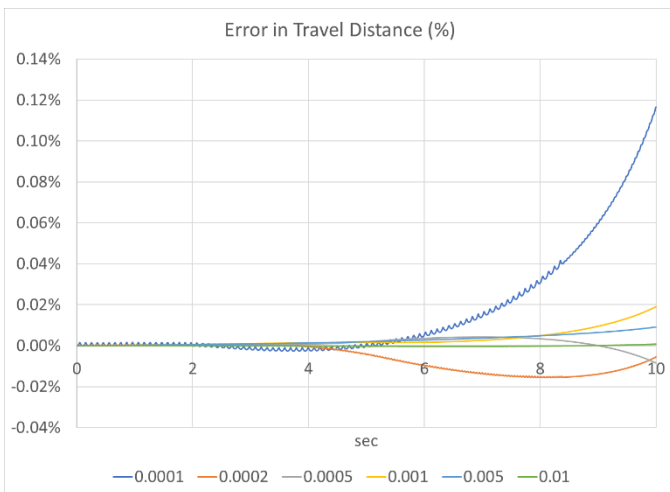
- Compare calculated speed and travel distance to HVE results.
- Figures 2 and 3 shows the calculated error in speed vs time for different integration time steps for the entire 10 seconds and for the first 1.5 seconds, respectively.
- Figure 4 and 5 shows the calculated error in travel distance vs time for different integration time steps for the entire 10 seconds and for the first 1.5 seconds, respectively.



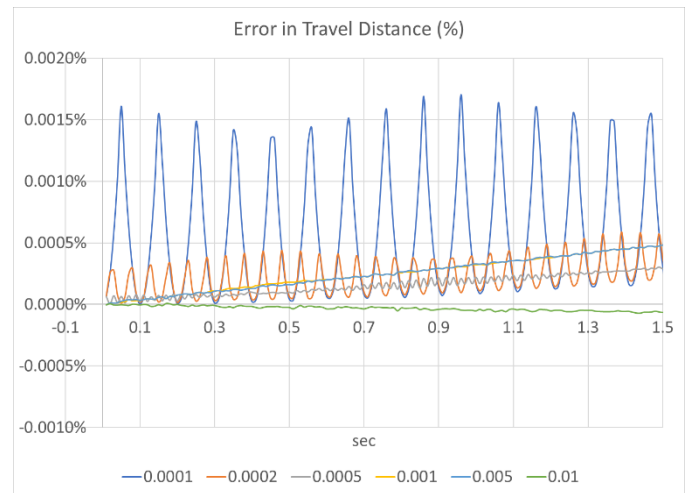
**Figure 2.** Calculated error in speed vs time for different integration time steps.



**Figure 3.** Calculated error in speed vs time for different integration time steps.



**Figure 4.** Calculated error in travel distance vs time for different integration time steps.



**Figure 5.** Calculated error in travel distance vs time for different integration time steps.

### Results:

- The percent error was small across all scenarios.
- The 0.0001, 0.0002, and 0.0005 sec time steps exhibited growing round-off errors over time.
- The optimal time step for constant acceleration simulations was determined to be between 0.01 and 0.001 sec.

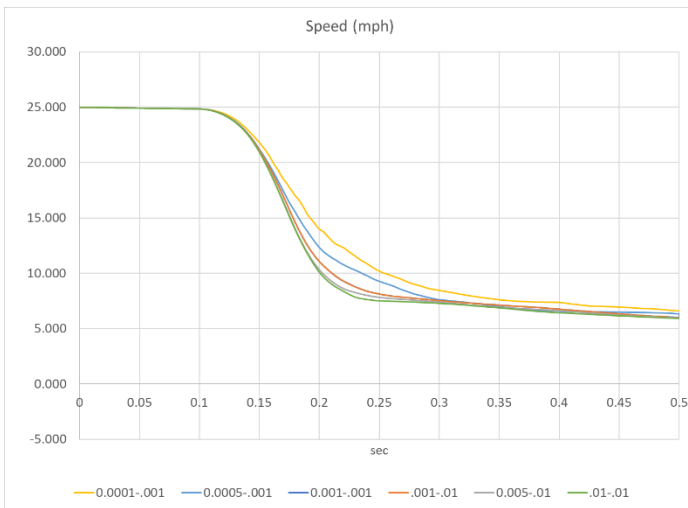
## 2. Impact dynamics

### Setup:

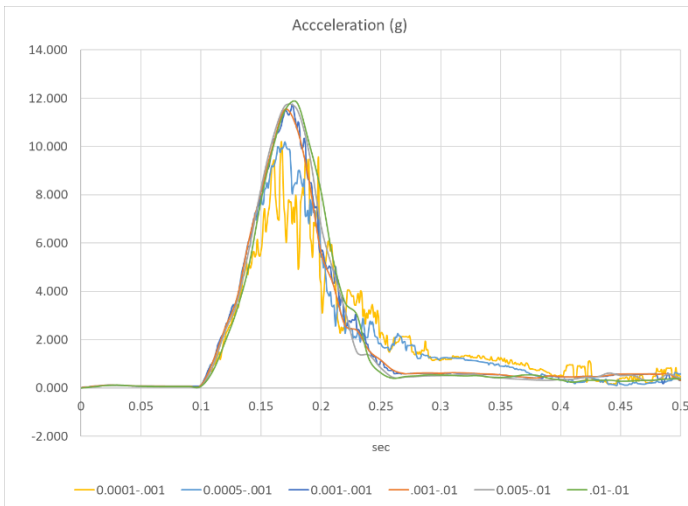
- Simulated vehicle-to-vehicle impact.
- Varied integration step size from 0.01 to 0.001 sec with an output step size of 0.01 sec.
- Varied integration step size from 0.001 to 0.0001 sec with an output step size of 0.001 sec.

### Evaluation Criteria:

- Differences in travel distance, speed, and acceleration under different time step conditions.
- Figure 6 shows a comparison of speed vs time for different integration and output time steps.
- Figure 7 shows a comparison of acceleration vs time for different integration and output time steps.



**Figure 6.** Comparison of speed vs time for different integration and output time steps for impact dynamics.



**Figure 7.** Comparison of acceleration vs time for different integration and output time steps for impact dynamics.

### Results

- No analytical solution exists to determine error, but excessive noise was observed at 0.0001 and 0.0005 sec time steps due to round-off error.
- The remaining time steps had similar peak values and curve shapes.
- The peak acceleration values for different step sizes were recorded as follows:

| Integration Time Step (sec) | Output Time Step (sec) | Peak Acceleration (g) |
|-----------------------------|------------------------|-----------------------|
| 0.0001                      | 0.001                  | 10.2042               |
| 0.0005                      | 0.001                  | 10.1884               |
| 0.001                       | 0.001                  | 11.7619               |
| 0.001                       | 0.01                   | 11.5337               |
| 0.005                       | 0.01                   | 11.6897               |
| 0.01                        | 0.01                   | 11.8144               |

- Excluding 0.0001 and 0.0005 sec cases, the average peak acceleration was ~11.7 g.
- The peak acceleration reported for an integration time step of 0.001 sec for 0.01 and 0.001 sec output time steps differs by ~.2 g out of ~11.7 g, which is less than 2%.
- The optimal time step for the impact simulations conducted was determined to be 0.01 to 0.001 sec.
- The output time step did not significantly impact results.

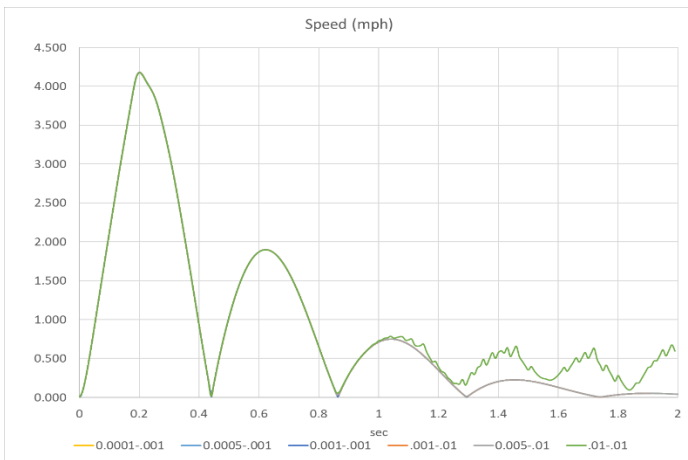
### 3. Suspension dynamics

#### Setup:

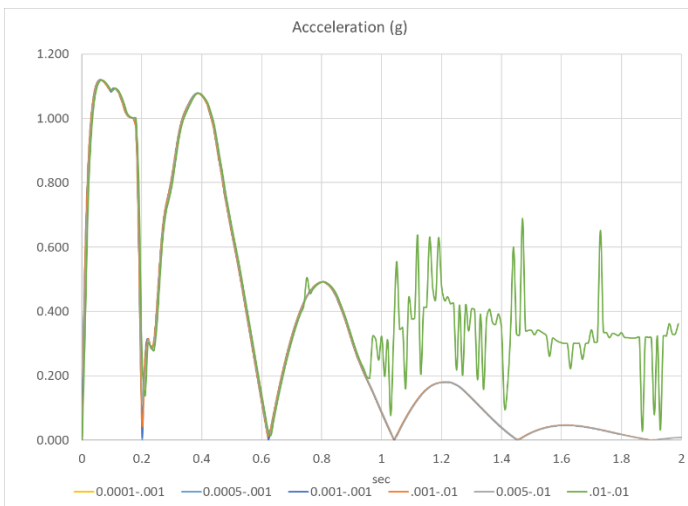
- Simulated a vehicle dropping from several feet onto its suspension.
- Varied integration step size from 0.01 to 0.001 sec with an output step size of 0.01 sec.
- Varied integration step size from 0.001 to 0.0001 sec with an output step size of 0.001 sec.

#### Evaluation Criteria:

- Differences in speed and acceleration under different time step conditions.
- Figure 8 compares speed vs. time for different integration and output time steps.
- Figure 9 compares acceleration vs. time for different integration and output time steps.



**Figure 8.** Comparison of speed vs time for different integration and output time steps for suspension dynamics.



**Figure 9.** Comparison of acceleration vs time for different integration and output time steps for suspension dynamics.

## Results

- No analytical solution exists for error estimation.
- Excessive noise was observed at 0.01 sec integration time step due to truncation error.
- The optimal integration time step was determined to be 0.005 sec or less.
- The output time step did not significantly impact results.

## Conclusion

The choice of the integration and output time step in simulation modeling is not universal but scenario-dependent. A thorough understanding of the underlying numerical methods and error dynamics is vital. Since SIMON operates in single precision, step sizes should be chosen carefully to avoid excessive round-off errors. The focus on Runge-Kutta methods in SIMON simulations highlights their importance in achieving high precision and robust results.

1. The best time step depends on simulation type and error trade-offs.
2. Testing across different simulation types shows an **integration step size in the range of 0.005 to 0.001 sec** was ideal for the scenarios tested.
3. An **output step size of 0.01 sec** was sufficient for the scenarios tested.
4. Reducing the integration time step below 0.001 sec in SIMON simulations may introduce round-off errors in single-precision calculations.

## Future Studies

Future studies can expand upon this research by investigating time step selection for other scenarios including more complex vehicle dynamics scenarios, such as high-speed rollover events or detailed tire-terrain interactions.

## References

1. Engineering Dynamics Company, LLC. Internal Documentation.
2. <https://farside.ph.utexas.edu/teaching/329/lectures/node37.html>.