

# USING QUEUEING THEORY TO FIND THE OPTIMAL CHARACTER-VEHICLE COMBINATION FOR 150CC MARIO KART WORLD RACES



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# SUMMARY

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This investigation entailed using Queueing Theory to determine the probabilities of possessing any given number of coins during a race and evaluating the expected overall speed of every possible character-vehicle combination according to its speed increase from its speed attribute for each terrain, its weight-dependent coin effects, the coin possession probabilities, and the effects of its acceleration attribute on the drift and trick boost durations to find the optimal character-vehicle combinations for 150cc races in Mario Kart World.

The optimal character-vehicle combinations were found to be a solid-focused heavyweight character (i.e. Wario or Wiggler) with the Reel Racer, which maximises the speed attribute for maximum progress while the racer is uninterrupted, and a flyweight character (i.e. Swoop, Para-Biddybud, Baby Peach, or Baby Daisy) with the W-Twin Chopper, which relies on faster recovery when necessary and higher speed increases at the middling numbers of coins in possession to enhance the racer's overall expected speed, with viable alternatives being a flyweight character with the Reel Racer, a solid-focused heavyweight character with the Junkyard Hog, and Bowser with the Reel Racer. The solid-focused middleweight character (i.e. Mario or Rocky Wrench) with the Baby Blooper, being 22nd best, is no longer a contender for the best character-vehicle combination.

The results of this investigation reveal two distinct dominant strategies for Mario Kart World that players may choose according to their preferred approach to the game.

All spreadsheets and Python scripts used in this investigation are available in the GitHub repository where this report resides.

## *ACKNOWLEDGEMENTS*

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Special acknowledgements to my Manufacturing Engineering lecturer in my final year at university for teaching me Queueing Theory, and my best friend and former coursemate for inspiring me to become proficient in Python.

Acknowledgements also to the members of the Mario Kart World community who came before me and made available the data needed for this investigation.

## *CONTRIBUTORS*

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# TABLE OF CONTENTS

1. INTRODUCTION	1
2. RELEVANT GAME MECHANICS	2
2.1. Speed attribute, coins, and weight attribute	2
2.2. The effects of the acceleration attribute	3
3. METHOD	4
3.1. The Markov chain of coin possession	4
3.2. Finding the rates	5
3.3. Evaluating the expected overall speed	5
3.4. Assumptions and simplifications	6
4. RESULTS	7
5. CONCLUSION	9
REFERENCES	10

## LIST OF SYMBOLS

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$\varepsilon$  = relative speed increase  
 $s$  = speed attribute  
 $c$  = number of coins in possession  
 $w$  = weight attribute  
 $t$  = terrain identifier  
 $a$  = acceleration attribute  
 $\tau$  = race duration (s)  
 $\zeta$  = zero-to-top-speed duration (s)  
 $\tau_1, \tau_2$  = different race durations (s)  
 $a_1, a_2$  = different acceleration attributes  
 $v$  = racer top speed ( $\text{px s}^{-1}$ )  
 $\Delta x$  = racetrack distance (px)  
 $\lambda$  = coin collection rate ( $\text{min}^{-1}$ )  
 $\mu$  = coin dispossession rate ( $\text{min}^{-1}$ )  
 $r$  = coin reset rate (i. e. frequency of races) ( $\text{min}^{-1}$ )  
 $P$  = coin possession probabilities  
 $d_1, d_2, d_3, b_1, b_2$  = intermediate calculation variables  
 $E$  = expected overall speed increase relative to the baseline  
 $\vec{B}$  = non-item boost rate column matrix ( $\text{min}^{-1}$ )  
 $\vec{T}$  = non-item boost duration column matrix (s)  
 $nib$  = non-item boost  
 $\tau_{\text{mean}}$  = mean race duration (s)

## NOMENCLATURE

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RAW      rails, air, and walls; a terrain in Mario Kart World

# 1. INTRODUCTION

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Selecting an optimal character-vehicle combination is essential for maximising one's chances of winning races in Mario Kart World. Members of the Mario Kart World community have found the performance attributes (i.e. speed, acceleration, weight, and handling) of each character and vehicle and how they interact with the in-game mechanics (e.g. *MK World Builder* [1], *Mario Kart World Stats* [2], and *The Mario Kart World Stratpedia* [3]), including how each coin's effect on the racer's speed depends on the number of coins in possession and the racer's weight attribute, but the probability distribution of the number of coins in possession from 0 to 20 for a racer at any given moment, the effects of the acceleration attribute on the racer's average speed through drift and trick (non-item) boost durations, and, by extension, the expected overall speed for each character-vehicle combination, have yet to be derived until this investigation.

Therefore, this investigation aimed to find the optimal character-vehicle combinations in 150cc Mario Kart World races by maximising the expected overall speed while maintaining a reasonable acceleration. This investigation was conducted via the following objectives:

- a. Apply Queueing Theory to determine the probabilities of possessing any given number of coins during a race from 0 to 20.
- b. Evaluate the expected overall speed of each possible character-vehicle combination, according to its speed increase from its speed attribute for each terrain, its weight-dependent coin effects, the coin possession probabilities obtained from objective {a}, and the effects of its acceleration attribute on the non-item boost durations.
- c. Find the character-vehicle combination with the highest expected overall speed and runners-up within a tolerance window.

## 2. RELEVANT GAME MECHANICS

The background information relevant to this investigation is as follows.

### 2.1. Speed attribute, coins, and weight attribute

For each terrain, the speed attribute increases the racer's 0-coin speed linearly from a baseline, and coins increase the racer's speed by up to 5% of the racer's 0-coin speed at 20 coins, where the weight attribute determines the rate at which each coin, from the 1st to the 20th, increases the racer's speed (Figure 1) [3].

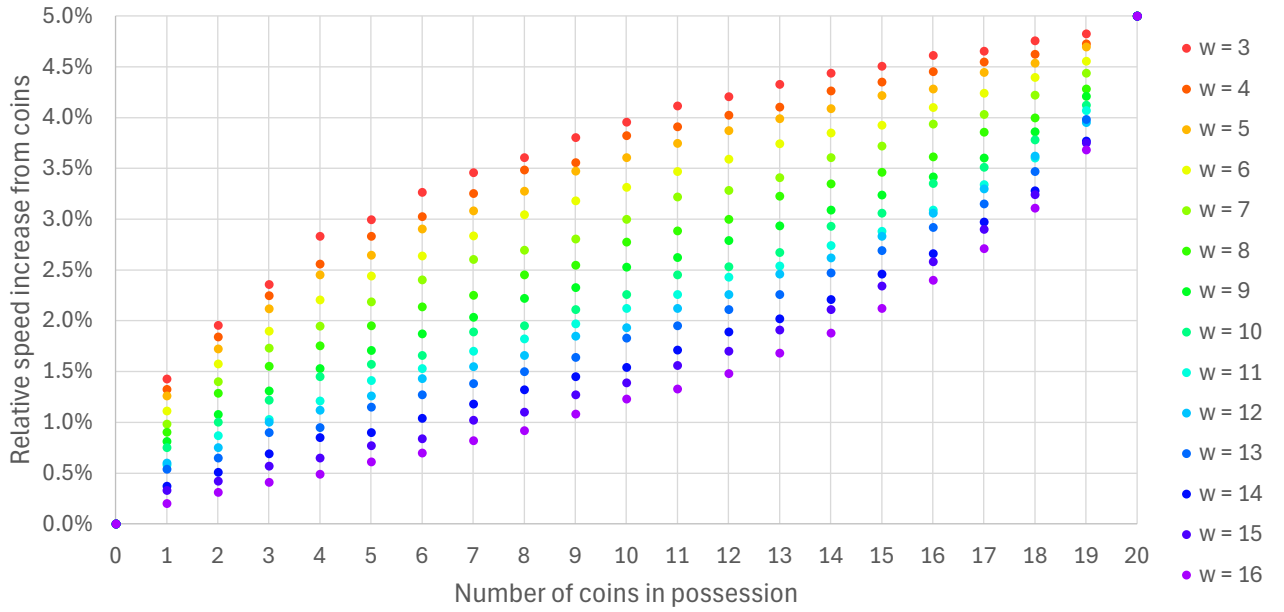


Figure 1. A simultaneous plot of  $\varepsilon_{c,w}$  vs the number of coins in possession for  $w \in \{3, 4, 5, \dots, 16\}$ .

$\varepsilon$  = relative speed increase

$s$  = speed attribute

$c$  = number of coins in possession

$w$  = weight attribute

$t$  = terrain identifier

(lowercase means specific and  
uppercase means averaged)

$$\varepsilon_{s,t} \approx 0.312\% \cdot s_t \quad (1)$$

$$\varepsilon_{s,t,c,w} = (1 + \varepsilon_{s,t})(1 + \varepsilon_{c,w}) - 1 \quad (2)$$

There are four terrains in Mario Kart World. They are solid (e.g. asphalt, brick, metal, carpet, wood, ice), grainy (e.g. sand, soil, snow), water, and rails, air, and walls (abbreviated RAW). The solid, grainy, water, and RAW terrains constitute 51.88%, 21.31%, 7.47%, and 19.34% of all roads in Mario Kart World [3]. While the solid, grainy, and water terrains have distinct speed attributes, that for RAW terrain is 13 points across all character-vehicle combinations. These proportions inform the weighted mean speed increase.

$$\varepsilon_{s,T,c,w} = 0.5188\varepsilon_{s,solid,c,w} + 0.2131\varepsilon_{s,grainy,c,w} + 0.0747\varepsilon_{s,water,c,w} + 0.1934\varepsilon_{13,RAW,c,w} \quad (3)$$

## 2.2. The effects of the acceleration and mini-turbo attributes

Meanwhile, the acceleration attribute determines the duration required to get to top speed from zero [3], and the mini-turbo attribute, which is a hidden attribute in the game, determines the duration of boosts from drifting and tricking [4]. The boost types are mini-turbos with their base, super, and ultra variations, charge jumps and rail or wall tricks with their base, super, and ultra variations, ramp or water tricks, and mid-air tricks. Only the boosts from ramp, water, and mid-air tricks were found to be independent of the mini-turbo attribute. The acceleration and mini-turbo attributes for each character-vehicle combination are constant across all terrains.

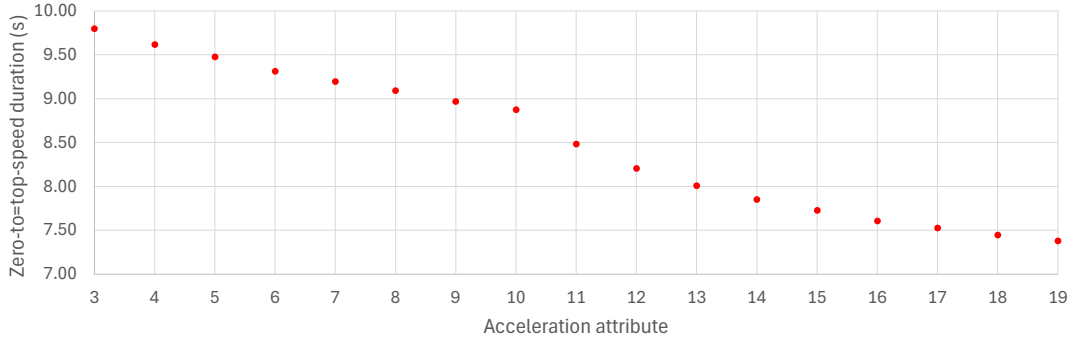


Figure 2. The zero-to-top-speed duration as the acceleration attribute increases from 3 to 19 points.

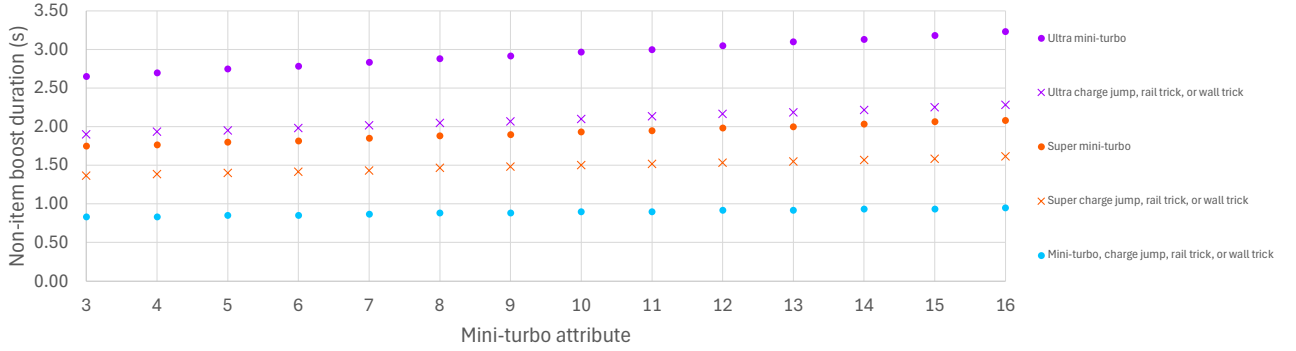


Figure 3. A simultaneous plot of the boost durations of the various drift and trick boosts (see legend).

Given that the frequency of zero-to-top-speed occurrences is once per race [3], the reduction in the acceleration attribute's contribution to the reduction in the duration of a race was evaluated as half the reduction in the zero-to-top-speed duration from picking a higher acceleration attribute, assuming the speed increase from zero to top speed is linear.

$a$  = acceleration attribute

$\tau$  = race duration (s)

$\zeta$  = zero-to-top-speed duration (s)

$\tau_1, \tau_2$  = different race durations (s)

$a_1, a_2$  = different acceleration attributes

$v$  = racer top speed ( $\text{px s}^{-1}$ )

$\Delta x$  = racetrack distance (px)

$$\Delta x = v \cdot (\tau_1 - \zeta|_{a_1}) + \frac{1}{2}(0 + v \cdot \zeta|_{a_1}) = v \cdot (\tau_2 - \zeta|_{a_2}) + \frac{1}{2}(0 + v \cdot \zeta|_{a_2})$$

$$\therefore \tau_1 - \tau_2 = \frac{1}{2}(\zeta|_{a=a_1} - \zeta|_{a=a_2}) \quad (4)$$



### 3. METHOD

The method used in this investigation is as follows.

#### 3.1. The Markov chain of coin possession

In Queueing Theory, each possible number of coins in possession, from 0 to 20, is treated as a state. In this model, collecting coins means moving to a higher state and dispossessing coins, either by being hit by an item, running into an obstacle, falling off track and requiring Lakitu to intervene, or finishing a race and starting a new one, means moving to a lower state. Given that coins are collected one at a time, each mid-race dispossession is 3 coins or the entire possession, whichever is less, and coin possessions reset at the start of each race to between 0 and 5 coins depending on the racer's position, the model of the coin possession probabilities can be illustrated as follows.

$\lambda$  = coin collection rate ( $\text{min}^{-1}$ )

$\mu$  = coin dispossession rate ( $\text{min}^{-1}$ )

$r$  = coin reset rate (i.e. frequency of races) ( $\text{min}^{-1}$ )

$P$  = coin possession probabilities

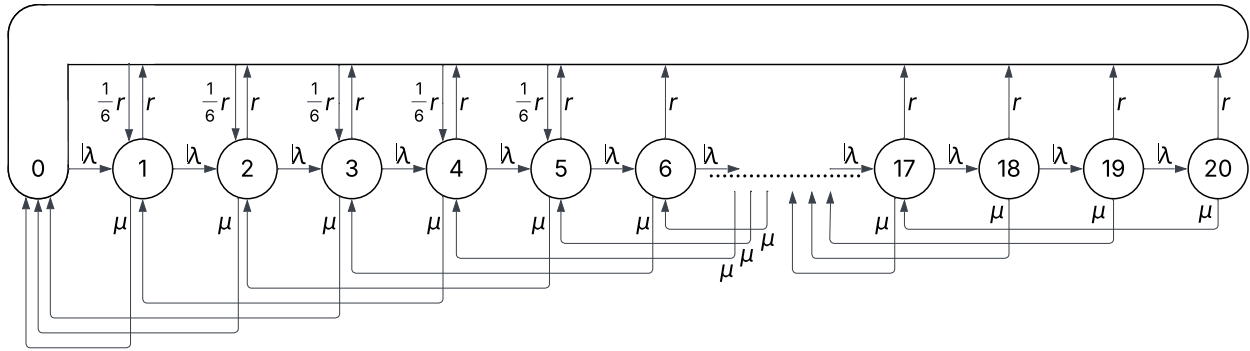


Figure 4. The Markov chain for coin possession in a 150cc Mario Kart World race.

Since the inflows and outflows at each state are balanced for any system at equilibrium, the following equations were derived.

$$-\lambda P_0 + \left(\mu + \frac{5}{6}r\right)(P_1 + P_2 + P_3) + \frac{5}{6}r(P_4 + P_5) + r(P_6 + P_7 + \dots + P_{20}) = 0 \quad (5)$$

$$\text{for } 1 \leq c \leq 5, \quad \lambda P_{c-1} - \left(\lambda + \mu + \frac{5}{6}r\right)P_c + \mu P_{c+3} = 0 \quad (6)$$

$$\text{for } 6 \leq c \leq 17, \quad \lambda P_{c-1} - (\lambda + \mu + r)P_c + \mu P_{c+3} = 0 \quad (7)$$

$$\text{for } 18 \leq c \leq 19, \quad \lambda P_{c-1} - (\lambda + \mu + r)P_c = 0 \quad (8)$$

$$\lambda P_{19} - (\mu + r)P_{20} = 0 \quad (9)$$

$$\text{and by definition} \quad P_0 + P_1 + P_2 + \dots + P_{20} = 1 \quad (10)$$

Substituting Equation 8 into Equation 7 when  $c = 19$  yields the following matrix-vector equation.

$$\begin{aligned}
& -\left(\lambda + \mu + \frac{5}{6}r\right) \rightarrow d_1, \quad -(\lambda + \mu + r) \rightarrow d_2, \quad -(\mu + r) \rightarrow d_3, \quad \left(\mu + \frac{5}{6}r\right) \rightarrow b_1, \quad \frac{5}{6}r \rightarrow b_2 \\
& \begin{bmatrix}
-\lambda & b_1 & b_1 & b_1 & b_2 & b_2 & r & r & r & r & r & r & r & r & r & r & r & r & r & r & r \\
\lambda & d_1 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \lambda & d_1 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \lambda & d_1 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \lambda & d_1 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \lambda & d_1 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 & 0 & 0 \\
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0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{bmatrix} \cdot \begin{bmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \\ P_7 \\ P_8 \\ P_9 \\ P_{10} \\ P_{11} \\ P_{12} \\ P_{13} \\ P_{14} \\ P_{15} \\ P_{16} \\ P_{17} \\ P_{18} \\ P_{19} \\ P_{20} \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (11)
\end{aligned}$$

### 3.2. Finding the rates

An hour-long YouTube video of Mario Kart World online gameplay uploaded by Shortcat [4] was watched. The occurrences of coin collections, coin dispossession, and drift boosts, trick boosts, and charge jumps of each kind were counted, and the race times were recorded. The coin collection, dispossession, and reset (i.e. the number of races) occurrences were divided by the total racing time to find  $\lambda$ ,  $\mu$ , and  $r$ . Similarly, the non-item boost rates were found by the number of occurrences divided by the total racing time.

### 3.3. Evaluating the expected overall speed

For each of the 480 unique character vehicle combinations (from 20 unique character classes and 24 unique vehicle attribute profiles), after evaluating  $\varepsilon_{s,T,c,w}$  for all  $1 \leq c \leq 20$  using Equations 1 to 3, finding the proportion of time spent in non-item boosts by the dot product of the boost rates and boost durations for the separated types, and finding the proportion of time saved from the zero-to-top-speed performance, the expected overall speed increase relative to the baseline during 150cc races  $E$  was evaluated using Equations 12 and 13. Finding the optimal character-vehicle combinations then required identifying the combination with the highest  $E$  and all runners-up within 0.100% from the highest  $E$ . ( $\varepsilon_{nib}$  was found through manual testing.)

$E$  = expected overall speed increase relative to the baseline

$\vec{B}$  = non-item boost rate column matrix ( $\text{min}^{-1}$ )

$\vec{T}$  = non-item boost duration column matrix (s)

$nib$  = non-item boost

$\tau_{mean}$  = mean race duration (s)

$$\varepsilon_{s,T,c,w,a} \approx \left(1 + \varepsilon_{s,T,c,w}\right) \left(1 + \frac{1 \text{ min}}{60 \text{ s}} \vec{B}_{(7 \times 1)} \cdot \vec{T}_{(7 \times 1)} \varepsilon_{nib}\right) \frac{\tau_{mean}}{\tau_{mean} - \frac{1}{2}(\zeta|_a = 3 - \zeta)} - 1 \quad (12)$$

$$E = \sum_{c=0}^{20} P_c \cdot \varepsilon_{s,T,c,w,a} \quad (13)$$

### *3.4. Assumptions and simplifications*

This investigation has relied on the following assumptions and simplifications:

- The terrain on which the racer is driving and the number of coins in possession were treated as independent events.
- The terrain on which the racer is driving and whether the racer is in a non-item boost were treated as independent events.

## 4. RESULTS

First, the following coin collection, dispossession, and reset rates were found (Table 1).

Table 1. The data collected on coin collection, dispossession, and resets [4].

Total number of			Total racing time (min)	$\lambda$ (min <sup>-1</sup> )	$\mu$ (min <sup>-1</sup> )	$r$ (min <sup>-1</sup> )
Coins collected	Dispossession	Races				
411	61	20	46.40	8.858	1.315	0.4310

The coin possession probabilities were found to be higher towards 0 coins and at 19 coins or 20 coins (Figure 5). This trend is supported by anecdotal evidence from gameplay, as frontrunning and sandbagging both enable the racer to collect coins easily, chaos in the racer pack in median positions tends to minimise coin possession, and there are no known phenomena to keep coin possession counts away from the extremes.

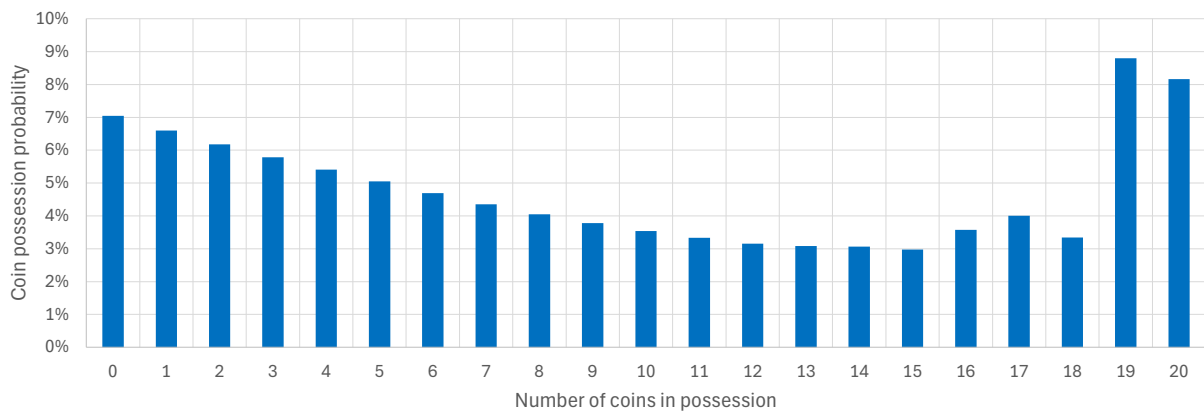


Figure 5. A bar chart of  $P_c$  versus  $c$ .

Then, the following non-item boost rates were found (Table 2).  $\epsilon_{nib}$  was found to be 9%.

Table 2. The data collected on the non-item boost occurrences and rates.

Non-item boost type	(Basic) Mini-turbo Charge jump Wall trick Rail trick	(Super) Charge jump Wall trick Rail trick	Super Mini-turbo	(Ultra) Charge jump Wall trick Rail trick	Ultra Mini-turbo	Ramp trick Water trick	Mid-air trick
Occurrences	273	2	72	0	21	241	12
Rates (min <sup>-1</sup> )	5.884	0.043	1.552	0.000	0.453	5.194	0.259

In light of the coin possession probabilities and the effects of the acceleration attributes on the average racing speed, the optimal character-vehicle combinations were found to be a solid-focused heavyweight character (i.e. Wario or Wiggler) with the Reel Racer at  $E_{max} \approx 10.103\%$  and a flyweight character (i.e. Swoop, Para-Biddybud, Baby Peach, or Baby Daisy) with the W-Twin Chopper at  $E_{max} \approx 10.084\%$ , with viable alternatives at  $E \geq E_{max} - 0.100\%$  being a flyweight character with the Reel Racer, a solid-focused heavyweight character with the Junkyard Hog, and Bowser with the Reel Racer. Figure 5 shows their  $\epsilon_{s,T,c,w,a}$  versus  $c$  profiles.

Table 3. The attribute profile of the optimal combinations and the viable alternatives.

Character class Vehicle	Attributes									E (%)
	Speed			Acceleration	Mini-turbo	Weight	Handling			
	Solid	Grainy	Water				Solid	Grainy	Water	
Solid Heavyweight Reel Racer	17	16	16	6	5	12	9	7	7	10.103
Flyweight W-Twin Chopper	10	10	10	13	10	5	14	14	14	10.084
Solid Heavyweight Junkyard Hog	17	16	16	7	9	13	7	5	5	10.051
Flyweight Reel Racer	11	11	11	12	6	6	13	13	13	10.046
Bowser Reel racer	17	17	17	5	5	13	7	7	7	10.022

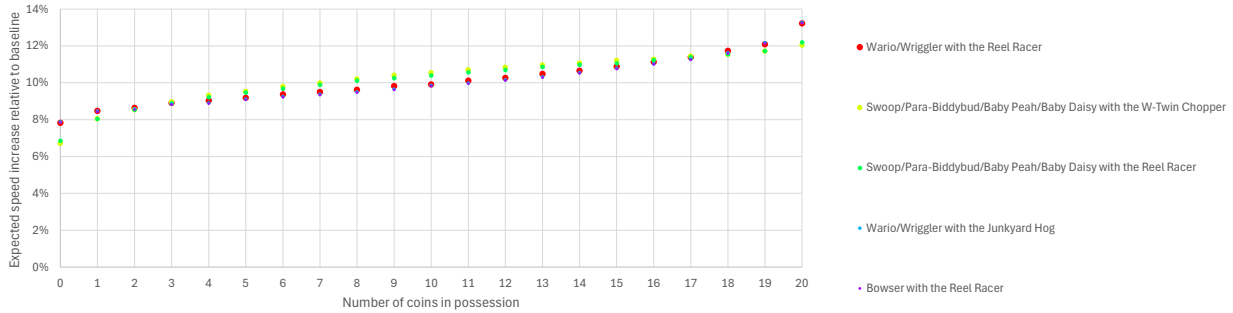


Table 4. A simultaneous plot of the  $\epsilon_{s,T,c,w,a}$  versus  $c$  profiles of the optimal combinations and the viable alternatives.

The results reveal two distinct dominant strategies to character and vehicle selection for 150cc races in Mario Kart World, being maximising the speed attribute with no other priorities or only while minimising the weight attribute and maintaining a reasonable acceleration attribute at 12 or 13 points. The maximum speed strategy maximises progress while the racer is uninterrupted, whereas the minimum weight strategy relies on faster recovery when necessary and higher speed increases at the middling numbers of coins in possession between 3 and 17 to compensate for the lower speed attribute. While the maximum speed strategy has a slightly higher  $E$  for skilled Mario Kart World players, the higher handling attribute (in all non-RAW terrains) of the minimum weight strategy is more forgiving for most players.

The Reel Racer was featured in both strategies as it offered 8 points of speed attribute for all non-RAW terrains for only 3 points of weight attribute, being one of the most advantageous vehicles in maximising the speed attribute while limiting the weight attribute. The W-Twin Chopper, offering 7 points of speed attribute for all non-RAW terrains for 2 points of weight attribute, was paired only with the flyweight character class, since the benefits of reducing the weight attribute to maximise speed increases from coins are not as pronounced in the maximum speed strategy.

Where the speed attribute is not uniform across all non-RAW terrains, emphasis should be placed on that on solid terrain, as it is the most common out of all non-RAW terrains in Mario Kart World.

The solid-focused middleweight character (i.e. Mario or Rocky Wrench) with the Baby blooper, being 30th best at  $E \approx 9.867\%$ , is no longer a contender for the best character-vehicle combination.

## 5. CONCLUSION

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To conclude, by using Queueing Theory to determine the probabilities of possessing any given number of coins during a race and evaluating the expected overall speed of every possible character-vehicle combination according to its speed increase from its speed attribute for each terrain, its weight-dependent coin effects, the coin possession probabilities, and the effects of its acceleration attribute on the drift and trick boost durations, this investigation has found the optimal character-vehicle combinations for 150cc races in Mario Kart World.

The results of this investigation reveal two distinct dominant strategies for Mario Kart World, being either maximising the speed attribute for maximum progress while the racer is uninterrupted or relying on faster recovery when necessary and higher speed increases at the middling numbers of coins in possession to enhance the racer's overall expected speed, that players may choose according to their preferred approach to the game.

The aim of this investigation was achieved successfully.

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