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

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[1]
SUMMARY

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 combination was found to be a flyweight character (i.e. Swoop, Para-Biddybud, Baby Peach, or Baby Daisy) with the Reel Racer, with viable alternatives being a flyweight character with the W-Twin Chopper or the Junkyard Hog, a solid-focused lightweight character (i.e. Nabbit or Toadette) with the Baby Blooper or the Junkyard Hog, a solid-focused middleweight character (i.e. Mario or Rocky Wrench) with the Baby Blooper, and a solid-focused heavyweight character (i.e. Wario or Wriggler) with the Reel Racer.

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

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

ACKNOWLEDGEMENTS

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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LIST OF SYMBOLS

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

NOMENCLATURE

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

1. INTRODUCTION

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, coin-responsiveness, 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* [1]), including how each coin's effect on the racer's speed depends on the number of coins in possession and the racer's coin-responsiveness 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 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 coin-responsiveness 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 coin-responsiveness attribute determines the rate at which each coin, from the 1st to the 20th, increases the racer's speed (Figure 1) [1].

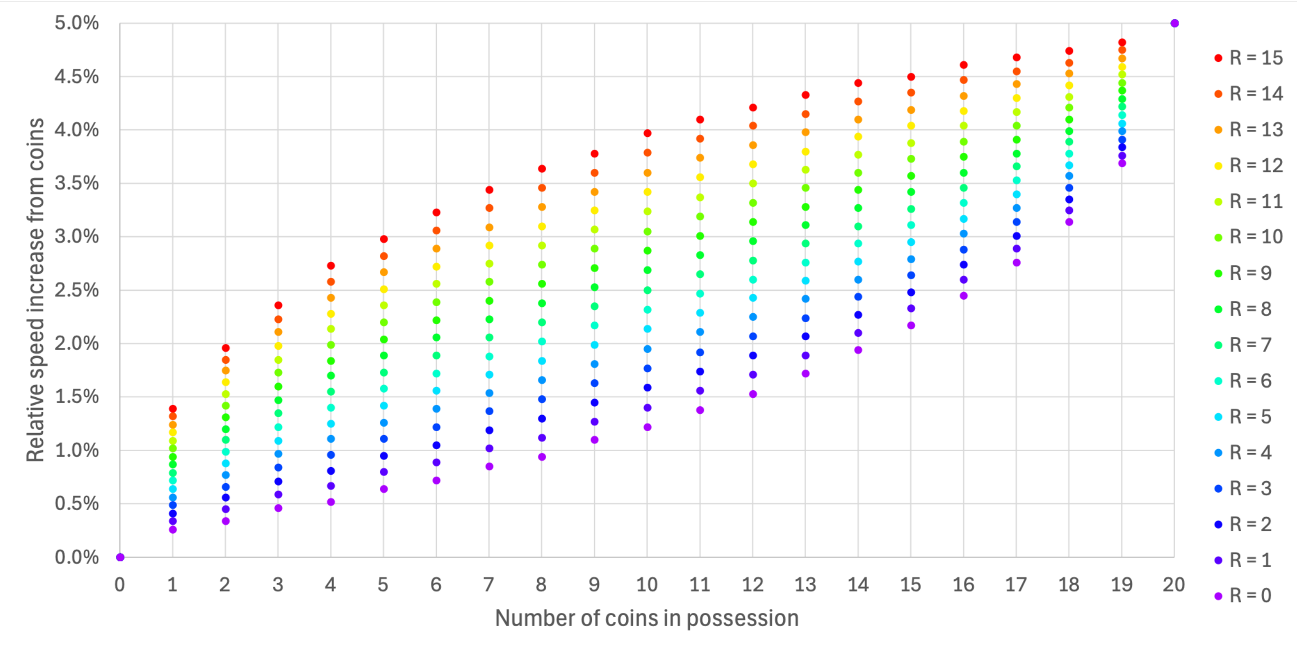

Figure 1. A simultaneous plot of $\boldsymbol{\varepsilon_{c,w}}$ vs the number of coins in possession for $\boldsymbol{R} \in \{15,14,13,\ldots,0\}$.

$\varepsilon = relative\ speed\ increase$

$s = speed\ attribute$
$c = number\ of\ coins\ in\ possession$
$R = coin\text{-}responsiveness\ attribute$
$t = terrain\ identifier$
(lowercase means specific and uppercase means averaged)

$$\varepsilon_{s,t} \approx 0.312\% \cdot s_t \tag{1}$$

$$\varepsilon_{s,t,c,w} = \varepsilon_t\left(1 + \varepsilon_{s,t}\right)\left(1 + \varepsilon_{c,R}\right) - 1 \tag{2}$$

$$\varepsilon_t = \begin{cases} 1, & t = smooth \\ 1, & t = grainy \\ 0.9, & t = water \\ 1, & t = RAW \end{cases} \tag{3}$$

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 55.52%, 16.30%, 7.94%, and 20.24% of all roads in Mario Kart World [1]. 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.

$$\varepsilon_{s,T,c,R} = 0.5552\varepsilon_{s,solid,c,R} + 0.1630\varepsilon_{s,grainy,c,R} + 0.0794\varepsilon_{s,water,c,R} + 0.2024\varepsilon_{13,RAW,c,R} \tag{4}$$

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 [1], and the mini-turbo attribute, which is a hidden attribute in the game, determines the duration of boosts from drifting and tricking [1, 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.

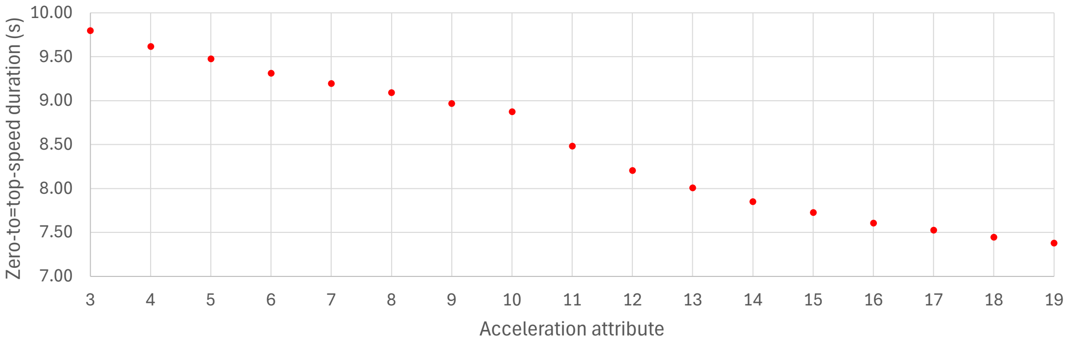

Figure 2. The zero-to-top-speed duration as the acceleration attribute increases from 3 to 19 points.

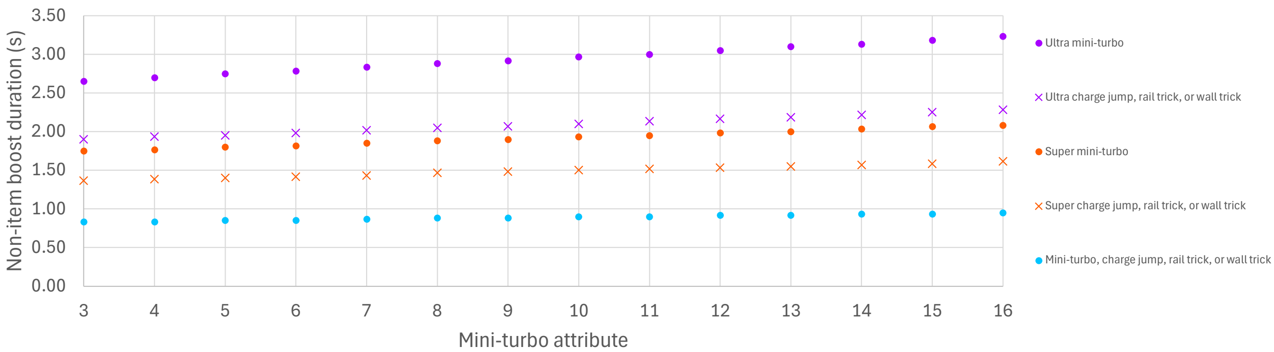

Figure 3. A simultaneous plot of the boost durations of the various drift and trick boosts (see legend).

Given that the frequency of zero-to-top-speed occurrences is once per race [1], 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.

$a = acceleration\ attribute$
$\tau = race\ duration\ (\mathrm{s})$
$\zeta = zero\text{-}to\text{-}top\text{-}speed\ duration\ (\mathrm{s})$
$\tau_1, \tau_2 = different\ race\ durations\ (\mathrm{s})$
$a_1, a_2 = different\ acceleration\ attributes$
$v = racer\ top\ speed\ (\mathrm{px\ s^{-1}})$
$\Delta x = racetrack\ distance\ (\mathrm{px})$

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

$$\therefore \tau_1 - \tau_2 = \frac{1}{2}(\zeta|_{a = a_1} - \zeta|_{a = a_2}) \tag{5}$$

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.

$\lambda = coin\ collection\ rate$ (min^{-1})
$\mu = coin\ dispossession\ rate$ (min^{-1})
$r = coin\ reset\ rate\ (i.e. frequency\ of\ races)$ (min^{-1})
$P = coin\ possession\ probabilities$

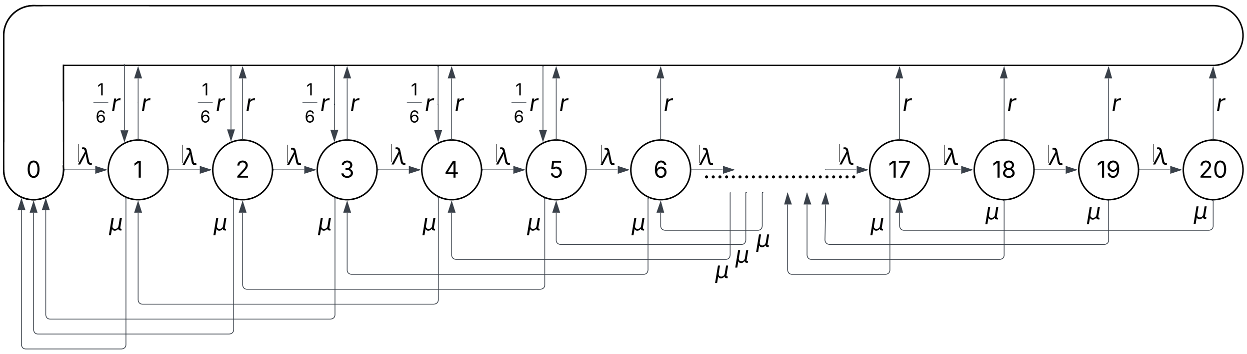

Figure 4. The Markov chain for coin possession in a 150cc Mario Kart World race.

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

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

$$for\ 1 \le c \le 5, \qquad \lambda P_{c-1} - \left(\lambda + \mu + \frac{5}{6}r\right)P_c + \mu P_{c+3} = 0 \tag{7}$$

$$for\ 6 \le c \le 17, \qquad \lambda P_{c-1} - (\lambda + \mu + r)P_c + \mu P_{c+3} = 0 \tag{8}$$

$$for\ 18 \le c \le 19, \qquad \lambda P_{c-1} - (\lambda + \mu + r)P_c = 0 \tag{9}$$

$$\lambda P_{19} - (\mu + r)P_{20} = 0 \tag{10}$$

$$and\ by\ definition \qquad P_0 + P_1 + P_2 + \cdots + P_{20} = 1 \tag{11}$$

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

$$-\left(\lambda+\mu+\frac{5}{6}r\right)\rightarrow d_1,\qquad -(\lambda+\mu+r)\rightarrow d_2,\qquad -(\mu+r)\rightarrow d_3,\qquad \left(\mu+\frac{5}{6}r\right)\rightarrow b_1,\qquad \frac{5}{6}r\rightarrow b_2$$

$$\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 \\
0 & \lambda & d_1 & 0 & 0 & \mu & 0 & 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 & 0 & \lambda & d_1 & 0 & 0 & \mu & 0 & 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 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 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 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 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 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 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 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 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 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_2 & 0 & 0 & \mu & 0 & 0 \\
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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 & 0 & \lambda & d_2 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda & d_3 & d_3 \\
1 & 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 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}
\tag{12}$$

3.2. Finding the rates

An hour-long YouTube video of Mario Kart World online gameplay uploaded by Shortcat [5] was watched. The occurrences of coin collections, coin dispossessions, 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 $\boldsymbol{\lambda}$, $\boldsymbol{\mu}$, and $\boldsymbol{r}$. 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 $\boldsymbol{\varepsilon_{s,T,c,w}}$ for all $1 \leq \boldsymbol{c} \leq 20$ 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 $\boldsymbol{E}$ was evaluated using Equations 12 and 13. Finding the optimal character-vehicle combinations then required identifying the combination with the highest $\boldsymbol{E}$ and all runners-up within 0.100% from the highest $\boldsymbol{E}$. ($\boldsymbol{\varepsilon_{nib}}$ was found through manual testing.)

$E = expected\ overall\ speed\ increase\ relative\ to\ the\ baseline$
$\overleftrightarrow{B} = non\text{-}item\ boost\ rate\ column\ matrix$ (min^{-1})
$\overleftrightarrow{T} = non\text{-}item\ boost\ duration\ column\ matrix$ (s)
$nib = non\text{-}item\ boost$
$\tau_{mean} = mean\ race\ duration$ (s)

$$\varepsilon_{s,T,c,w,a} \approx \left(1+\varepsilon_{s,T,c,w}\right)\left(1+\frac{1\ \mathrm{min}}{60\ \mathrm{s}}\varepsilon_{nib}\overleftrightarrow{B}^T\overleftrightarrow{T}\right)\frac{\tau_{mean}}{\tau_{mean}-\frac{1}{2}\left(\zeta|_{a=3}-\zeta\right)}-1 \tag{13}$$

$$E = \sum_{c=0}^{20} P_c \cdot \varepsilon_{s,T,c,w,a} \tag{14}$$

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 [5].

Total number of			Total racing time (min)	λ (min^{-1})	μ (min^{-1})	r (min^{-1})
Coins collected	**Dispossessions**	**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.

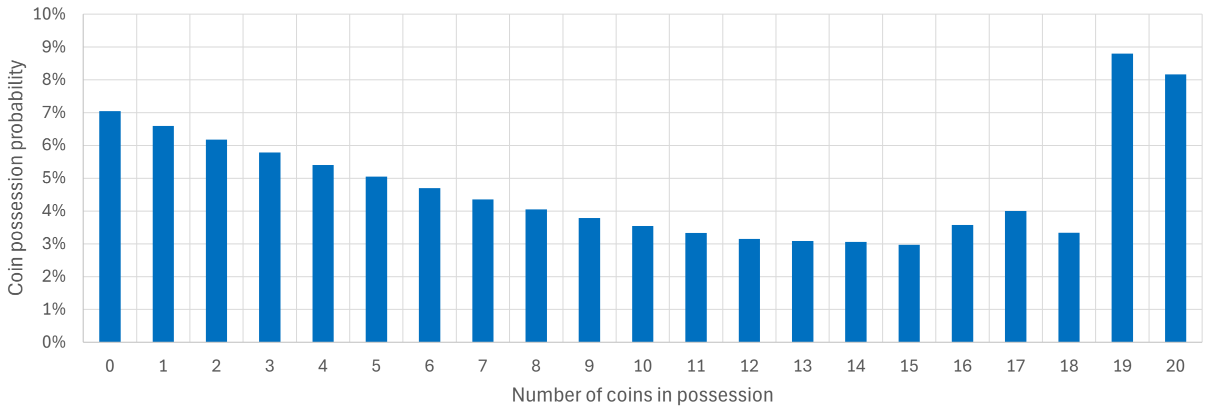

Figure 5. A bar chart of P_c versus c.

Then, the following non-item boost rates were found (Table 2). ε_{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^{-1})	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 combination was found to be a flyweight character (i.e. Swoop, Para-Biddybud, Baby Peach, or Baby Daisy) with the Reel Racer at $E_{max} \approx +9.247\%$, with viable alternatives at $E \geq E_{max} - 0.050\%$ being a flyweight character with the W-Twin Chopper or the Junkyard Hog, a solid-focused lightweight character (i.e. Nabbit or Toadette) with the Baby Blooper or the Junkyard Hog, a solid-focused middleweight character (i.e. Mario or Rocky Wrench) with the Baby Blooper, and a solid-focused heavyweight character (i.e. Wario or Wriggler) with the Reel Racer. Figure 5 shows their $\varepsilon_{s,T,c,w,a}$ 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	Coin-responsiveness	Handling			
	Solid	Grainy	Water					Solid	Grainy	Water	
Flyweight Reel Racer	11	11	11	12	9	6	12	13	13	13	+9.247
Flyweight W-Twin Chopper	10	10	10	13	10	5	13	14	14	14	+9.216
Flyweight Junkyard Hog	11	11	11	13	10	7	11	11	11	11	+9.228
Solid Lightweight Baby Blooper	12	6	6	14	12	6	12	18	12	12	+9.244
Solid Lightweight Junkyard Hog	13	12	12	11	9	9	9	11	9	9	+9.206
Solid Middleweight Baby Blooper	14	8	8	12	10	8	9	16	10	10	+9.217
Solid Heavyweight Reel Racer	17	16	16	6	5	12	4	9	7	7	+9.220

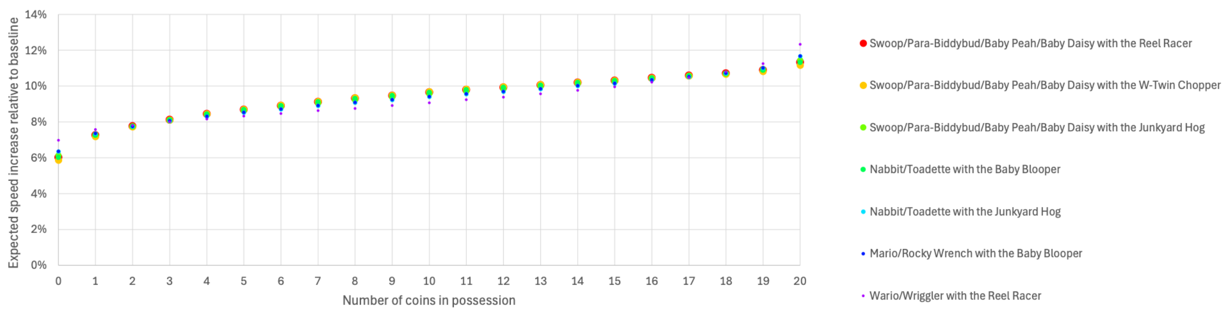

Table 4. A simultaneous plot of the $\boldsymbol{\varepsilon}_{s,T,c,R,a}$ versus $\boldsymbol{c}$ profiles of the optimal combinations and the viable alternatives.

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 balancing it with the coin-responsiveness attribute while maintaining a reasonable acceleration attribute at 12 or 13 points. The maximum speed strategy maximises progress while the racer is uninterrupted, whereas the maximum coin-responsiveness 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.

The Reel Racer was featured in both strategies as it offered 8 points of speed attribute for all non-RAW terrains and 3 points of coin-responsiveness attribute, being one of the most advantageous vehicles in maximising balancing the speed attribute with the coin-responsiveness attribute. The W-Twin Chopper, offering 7 points of speed attribute for all non-RAW terrains and 4 points of coin-responsiveness attribute, was paired only with the flyweight character class, since the benefits of increasing the coin-responsiveness 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.

5. CONCLUSION

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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