Transition from automated to manual driving: What factors influence take-over time and performance?

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Transition of Control

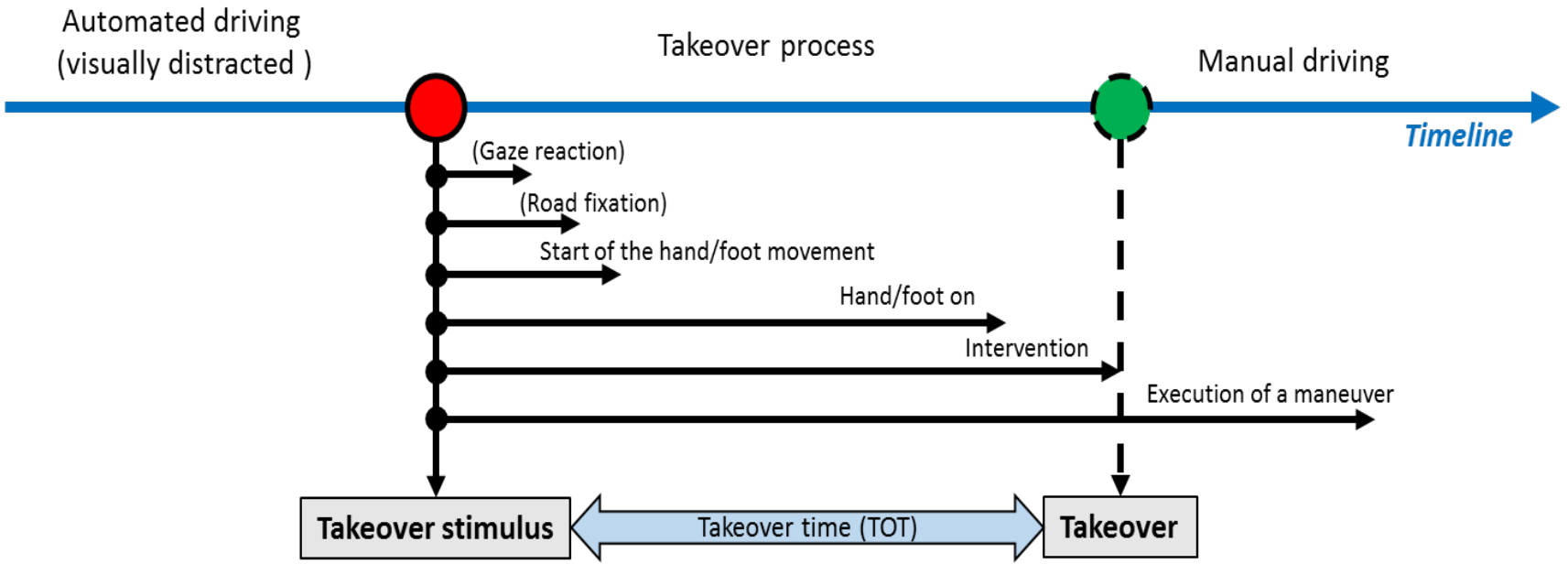
Big next step for higher levels of automation

Discussion within UN-ECE: How to design for these `transitions`?

Lu et al. (2016), McCall et al. (2019)

- Driver initiated or **System initiated**
- **Scheduled take-over of non-scheduled take-over**
- **Normal or Emergency situation**

Driver Take-over time (TOT)



ELSEVIER

Transportation Research Part F: Traffic Psychology and Behaviour

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Determinants of take-over time from automated driving: A meta-analysis of 129 studies

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Inclusion criteria

1) Transition to manual (after hands off and feet off)
2) Take-over performed by a human by braking, steering or pressing a button
3) Presence of a TOR or a critical event
4) Reported *mean* or *median* TOT
5) 4 or more studies available with this variable

Methods

1) “Between study” correlation analysis to examine the relationships between **study variables** and mean TOTs across the experimental conditions

2) “Within-study” evaluation of the effect when holding other variables constant

Situation-related
- Urgency
- Non-driving tasks
- Behaviour of other road users
- Traffic density
- …

Study specific
- Simulator fidelity
- Experiment design
- Instructions
- …

Driver-related
- Age
- Driver states
- Experience
- …

Vehicle/system-related
- Level of automation
- TOR modality
- …

Variables studied

1. Mean age of the participant group
2. Simulator fidelity (low, medium, high)
3. Level of automation (L2, L3+L4)
4. Modality of the NDT (visual/acoustic /motoric/cognitive)
5. Hand-held device
6. Modality of the TOR (visual, auditory and tactile)
7. Urgency (low, medium, high) and time budget to take over (e.g TTC)
8. Complexity of the driver response (low, medium, high)
9. Interaction with other road users during take-over process (binary)

129 studies included

126 car studies - 3 truck studies

520 mean TOT

4556 participants

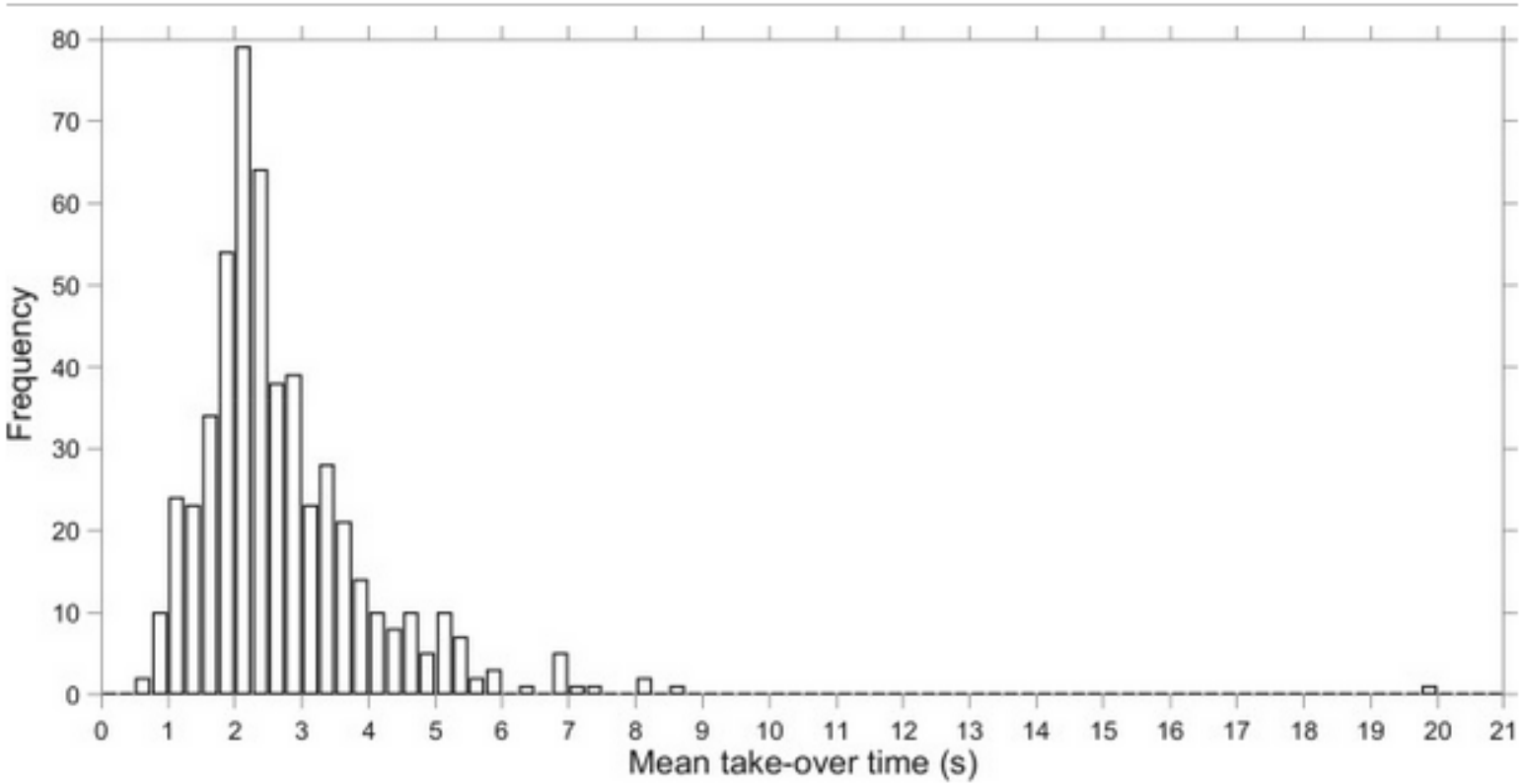
- 40 high-end simulators
- 84 mid/low fidelity driving simulators
- 3 on-road studies
- 2 test tracks

Results: Study set-up (combinations)

- Higher levels of automation: Explicit TOR + NDT + longer TTC
  → in line with the definition of SAE Levels of AD
- NDT: motor task often combined with visual – cognitive task with auditory
  → standardized tasks were frequently used (e.g. SURT, cognitive N-back)
- Visual + auditory TOR (auditory + vibrotactile hardly combined)
- Complex driver response + higher urgency and other road users
- Low fidelity simulators + younger participants

	1. AGE	2. SIM	3. LAD	4. TOR_V	5. TOR_A	6. TOR_VT	7. TOR_P	8. NDT_V	9. NDT_A	10. NDT_M	11. NDT_C	12. HAND	13. NDT_P	14. URG	15. DRE	16. IRU	17. TBTC	18. TBTB
1.AGE	-																	
2.SIM	.38	-																
3.LAD	-.07	.03	-															
4.TOR_V	.07	.26	.24	-														
5.TOR_A	.18	.18	.34	.35	-													
6.TOR_VT	-.21	-.30	.13	-.13	-.35	-												
7.TOR_P	.05	.08	.65	.40	.60	.11	-											
8.NDT_V	-.12	-.08	.30	.12	.08	.10	.19	-										
9.NDT_A	.04	-.17	.08	-.09	-.04	.07	.04	.03	-									
10.NDT_M	-.18	-.01	.28	.13	.07	.13	.18	.68	-.21	-								
11.NDT_C	-.09	-.21	.16	-.06	.01	.09	.10	.13	.27	.29	-							
12.HAND	-.05	.03	.21	.09	.10	.04	.11	.31	-.14	.24	-.12	-						
13.NDT_P	-.08	-.08	.34	.08	.08	.11	.22	.77	.36	.55	.33	.35	-					
14.URG	-.27	.01	-.16	-.04	-.14	.10	-.13	-.07	-.02	.12	.13	-.18	-.06	-				
15.DRE	-.10	.05	.06	.00	-.01	.09	-.01	.05	-.04	.17	.10	.00	.09	.52	-			
16.IRU	.12	.03	.08	.03	.01	-.06	.00	.01	-.07	.05	.16	.04	.02	.10	.46	-		
17.TBTC	-.17	-.30	.35	.13	.02	.20	.22	.09	.01	.02	-.03	.21	.17	-.61	-.12	-.01	-	

General overall results

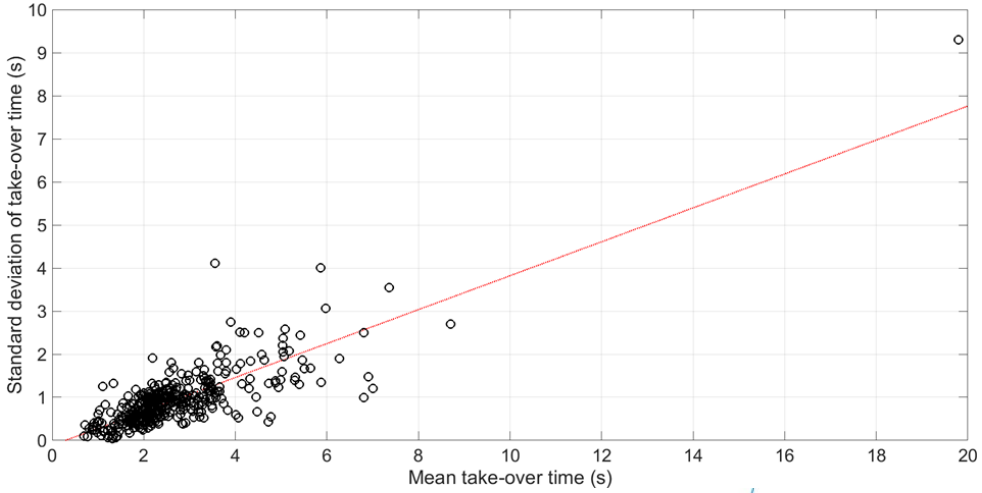


Results: between study

Urgency of the take-over scenario and HH device strongest correlations with the mean TOT

Weak correlation with modality of TOR or NDT

Strong correlation between mean and SD of TOT(r = .82)



Study variable	Correlation mean TOT with r	p	Study variable conditions	n	Average mean TOT (s)	SD mean TOT (s)
1. AGE	.22	.24	-	485	-	-
2. SIM	-.04	.02	0 (low fidelity)	81	2.67	2.39
			1 (medium fidelity)	268	2.84	1.33
			2 (high fidelity)	171	2.57	0.95
3. LAD	.15	.19	0 (L2)	62	2.14	1.17
			1 (L3 and above)	458	2.80	1.47
4. TOR_V	.04	.08	0 (no visual TOR)	160	2.63	1.75
			1 (with visual TOR)	360	2.77	1.29
5. TOR_A	.12	.12	0 (no auditory TOR)	84	2.33	1.00
					2.80	1.51
6. TOR_VT	-.11	-.10			2.79	1.50
			1 (with vibrotactile TOR)	73	2.35	0.99
7. TOR_P	.06	.06	0 (no TOR)	34	2.40	1.08
			1 (TOR present)	486	2.75	1.47
8. NDT_V	.13	.13	0 (no visual NDT)	204	2.49	1.12
			1 (the NDT is visual)	309	2.89	1.62
9. NDT_A	-.03	-.07	0 (no auditory NDT)	384	2.75	1.29
			1		2.67	1.88
10. NDT_M	-.01	-.04	0		2.74	1.27
			1 motoric manoeuvre)	224	2.72	1.67
11. NDT_C	-.05	-.11	0 (without highly cognitively demanding NDT)	385	2.78	1.28
			1 (with highly cognitively demanding NDT)	128	2.60	1.90
12. HAND	.30	.35				1.42
			the hands)	108	3.61	1.46
13. NDT_P	.11	.11	0 (no NDT present at the moment of TOR)	143	2.46	1.17
			1 (NDT present at the moment of TOR)	377	2.82	1.53
14. URG	-.44	-.42				
			0 (low response complexity)	108	3.43	2.21
15. DRE	-.16	-.07	1 (medium response complexity)	134	2.34	1.16
			2 (high response complexity)	253	2.66	1.04
16. IRU	.08	.14	0 (no interaction with other road user)	344	2.67	1.55
			1 (interaction with other road user)	141	2.93	1.24
17. TBTC	.53	.43	—	—	—	—
18. TBTB	.73	.31	—	—	—	—

TOR modality

NDT modality

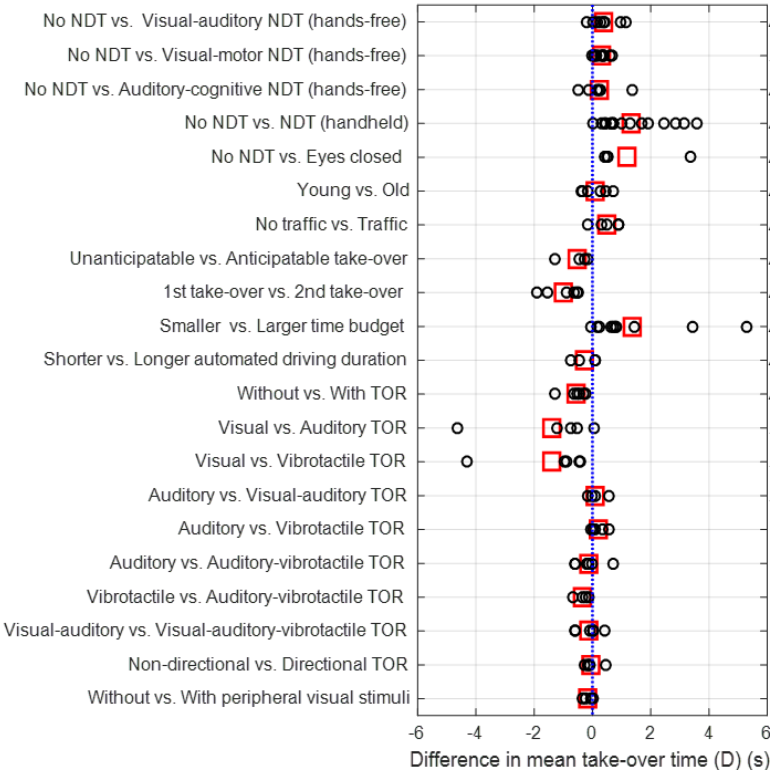
Hand holding a device

Urgency of the TO scenario

TO time budget

Results (within)

- NDT and TOR modalities most frequent independent variables, followed by urgency, traffic density and age.
- Urgency and hand-held device were found to have large effects (MDs ~ 1.3 s)
- Familiarization of TO scenario shortened mean TOT (MD = -1.0 s)
- Visual-only TOR led to substantially longer TOT (MDs < -1.4 s)
- Effect of age is weak (MD = .10 s)



Summary

1) Urgency has strong correlation with mean TOT

   → if there is more time to take over, drivers use more time to take over

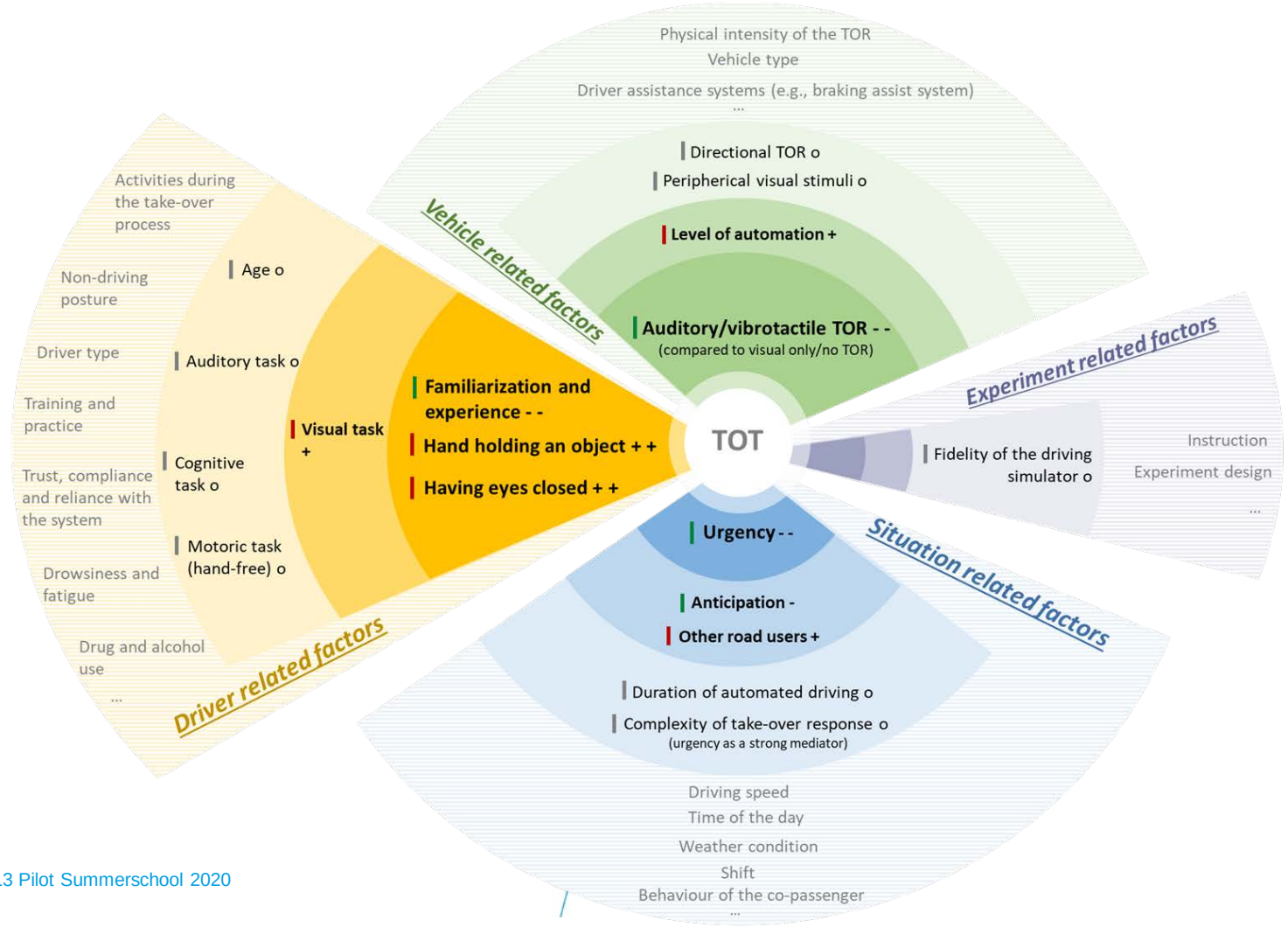
2) Non-driving related held-held task increases mean TOT

3) Modality of the non-driving related task (e.g., visual, auditory, motoric, or cognitive) showed small effects on TOT

4) Prior experience with take-overs has a strong effect

5) Drivers responded about equally quickly to vibrotactile, auditory, multimodal, or directional TORs (visual only slower!)

6) No consistent effect of age in the within-study analysis despite of the wide age variance (not controlled for trust..)


Physical intensity of the TOR
Vehicle type
Driver assistance systems (e.g., braking assist system)
...
Directional TOR o
Peripherical visual stimuli o
Level of automation +
Auditory/vibrotactile TOR - -
(compared to visual only/no TOR)
Vehicle related factors
Activities during the take-over process
Non-driving posture
Driver type
Training and practice
Trust, compliance and reliance with the system
Drowsiness and fatigue
Drug and alcohol use
...
Age o
Auditory task o
Cognitive task o
Motoric task (hand-free) o
Visual task +
Familiarization and experience - -
Hand holding an object + +
Having eyes closed + +
Driver related factors
TOT
Experiment related factors
Fidelity of the driving simulator o
Instruction
Experiment design
...
Urgency - -
Anticipation -
Other road users +
Situation related factors
Duration of automated driving o
Complexity of take-over response o
(urgency as a strong mediator)
Driving speed
Time of the day
Weather condition
Shift
Behaviour of the co-passenger
...

Limitations and further research

- Nearly all studies were conducted in driving simulators (minority high-end):
  - Relative instead of absolute validity?
  - Knowing to be in experiment
  - Almost all cars, limited number of truck studies
- The between-study analysis: correlational rather than causal
- Mean TOTs so individual participants' transition times could have been much longer: Collisions are outliers in the TOT distribution.
- This meta-analysis investigated take-over time, not take-over quality.

Thank you for your kind attention.

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