Multidentate Di-N-heterocyclic carbene ligands for transition metal catalyzed hydrogenation reactions
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Chapter 5
Cooperative Lutidine-based Tridentate tzNHC Ru(II) Complexes for Catalytic Ester Hydrogenolysis

Abstract
In this chapter the development of CNC and CNN pincer ligands bearing tzNHCs is described as an expansion to the library of cooperative lutidine-derived ligands. Coordination of these ligands via transmetallation of the respective Ag(I) complexes led to [(L)Ru(H)(CO)(PPh$_3$)] complexes displaying rare facial coordination of the tridentate ligand. The Ru and Pd complexes exhibit the expected reactivity (reversible deprotonation/dearomatization) of the benzylic “arm”. The ruthenium complexes were active in catalytic ester hydrogenation at 100 °C in the presence of minimally 20 mol% of KOtBu. The sterically congested tBu-benzoate ester was converted considerably faster than the methyl analogue. Although transesterification of the substrate to the tert-butyl ester may play a role, the reason for the requirement of the critical minimum amount of KOtBu (≥20 mol%) remains unknown. Furthermore, potentially active CNC Ru hydride species have been elucidated by NMR spectroscopy under near-catalytic conditions.

Soraya N. Sluijter, Ties J. Korstanje, Jarl Ivar van der Vlugt and Cornelis J. Elsevier, *manuscript in preparation.*
5.1 Introduction

In Chapter 3 heteroditopic di-NHC ruthenium catalysts have been described that are active in the hydrogenation of ketones and imines. However, these catalytic systems were not able to reduce non-activated esters, which are more challenging substrates than ketones, in satisfactory yields. The hydrogenation, formally called hydrogenolysis, of carboxylic esters leading to alcohols (Scheme 1) is more difficult compared to ketones because the C=O double bond is a weak electrophile that is stabilized by resonance.

Ester hydrogenation is an industrially important transformation as it is commercially used to produce several alcohols from esters.\(^1\)\(^2\) Furthermore, interesting biomass feedstocks such as vegetable fats and oils contain many ester functionalities. Considering the depletion of fossil fuels, ester hydrogenation may therefore become an even more important transformation. In industry, non-selective heterogeneous catalysts (typically based on copper chromite) are used at high pressures and temperatures to perform this reaction.\(^3\) Hence, a more selective and environmentally friendly homogeneous replacement of these catalysts is desirable. Early reports on such catalysts for the hydrogenation of esters required additives, harsh conditions and/or were only suitable for activated esters.\(^4\)\(^–\)\(^6\)

Our group was among the first to convert esters to alcohols at reasonable temperature and pressure (100 °C and 70 bar) using a homogeneous ruthenium Triphos catalyst (Triphos = 1,1,1-tris(diphenylphosphinomethyl)ethane; Scheme 1).\(^7\)\(^–\)\(^9\) In the last decade, much progress has been made in ester hydrogenolysis catalyzed by well-defined transition metal complexes.\(^10\) Even first-row transition metals have now been successfully applied in this transformation.\(^11\)\(^–\)\(^15\) Several
breakthroughs can be attributed to the emergence of metal-ligand cooperativity (MLC) in the homogeneous catalysis field. As explained in the introductory chapter, MLC can create alternative catalytic pathways as the ligand participates actively in the process.

Although the mechanisms for ester hydrogenation have hardly been unequivocally proven,\textsuperscript{16,17} a plausible catalytic cycle for ester hydrogenation catalyzed by a cooperative Ru hydride complex is depicted in Scheme 2.\textsuperscript{18,19} Addition of $\text{H}_2$ to the dearomatized pincer complex leads to the formation of a trans-dihydride species. In the following step the first hydride transfer to the stabilized ester carbonyl leading to a hemi-acetal, is generally considered to be rate-limiting. To facilitate this step electron-rich ligands can be employed to enhance the nucleophilicity of the hydride towards the substrate. The hemi-acetal, unstable under the reaction conditions, subsequently splits in the first alcohol product and an aldehyde, which is then hydrogenated to produce the second alcohol product. Alternatively, an outer-sphere bifunctional mechanism could be operative as shown by Morris et al.\textsuperscript{20} On the basis of DFT calculations, another pathway involving direct $\text{H/OR}$ metathesis was proposed by Hasanayn and Baroudi.\textsuperscript{21}

\textbf{Scheme 2:} Proposed catalytic cycle of the hydrogenation of esters to alcohols using MLC.
The first example of an ester hydrogenation catalyst making use of MLC by deprotonation/dearomatization (Scheme 1) was the PNN Ru catalyst developed by the group of Milstein.\textsuperscript{18} Notably, the PNP Ru analogue was significantly less active, which was attributed to the lack of a hemilabile donor, which likely hampers substrate (pre-)coordination.\textsuperscript{18} By replacing the phosphine donor in the PNN design for a more electron-rich NHC moiety, Song \textit{et al.} were able to increase the rate of the reaction (Scheme 1).\textsuperscript{22} The CNN complex reported by Milstein in 2011 was slightly more active than its predecessor as well (Scheme 1). The lutidine-based CNC Ru pincer complex (Scheme 1) reported very recently by Pidko \textit{et al.} hydrogenated methyl benzoate and other esters in the presence of KOMe (C/B/S = 1/20/200) at 50 bar H\textsubscript{2} pressure and a relatively low temperature of 70 °C in 4 hours.\textsuperscript{23} The same group recently demonstrated that the cooperativity of the deprotonated NHC-based CNC is more pronounced compared to its phosphine analogue, which was attributed to a combination of electronic properties and flexibility of the larger CNC chelate.\textsuperscript{24}

In this chapter we describe the development of CNC and CNN pincer ligands bearing 1,2,3-triazolylidenes, which are envisioned to be an expansion to the library of cooperative lutidine-derived ligands. The corresponding Ru(II) complexes have been synthesized and characterized and applied in catalytic ester hydrogenolysis. The ability of these ruthenium complexes and the related [(CNN)PdCl] compound to undergo deprotonation/dearomatization has been studied. As described, a correlation between electron-density and catalytic ester hydrogenation activity has been observed previously: the PNP ligand leads to a less active catalyst than CNC ligand (C = imidazole-2-ylidene). It is therefore hypothesized that the more electron-rich tzNHC donors on our ligands may accordingly lead to enhanced activity, due to an expected increase of hydricity of the Ru-hydride.

5.2 Synthesis of the CNC and CNN ligands

The desired CNC ligand was efficiently synthesized in two steps (Scheme 3). First, 2,6-bis(bromomethyl)pyridine was converted to ditriazole 1 in high yields following a one-pot multicomponent tandem azidination and CuAAC procedure published by Crowley and Bandeen.\textsuperscript{25,26} As the \textit{in situ} prepared azide reacts with the terminal alkyne, handling of potentially dangerous azides could be circumvented and cumbersome work-up was avoided.

Second, N3 of the triazole was methylated using 2 equivalents of (Me\textsubscript{3}O)BF\textsubscript{4} leading to CNC ligand 2 (Scheme 3). The formation of the compound was confirmed by a downfield shift of the triazole peak to 9.19 ppm and the methyl resonance at 4.22 ppm in the \textsuperscript{1}H NMR spectrum.
We were also interested to obtain the CNN analogue 3, because the potential hemilability of the triazole moiety might have a positive effect on the catalytic ester hydrogenolysis.\(^{18}\) When only one equivalent of methylating agent was used, a mixture of starting material, mono- and bis-methylated product was obtained. The three different species could easily be separated by column chromatography (DCM : acetone = 1:1), providing access to the CNN pincer ligand (Scheme 3).

Although the yield of ligand 3 is low (34\%), this procedure allowed for recovery of the starting material 1 as well as isolation of ligand 2. Ligand 1, 2 and 3 have been characterized by multinuclear NMR spectroscopy and HR-MS. In contrast to ligands 1 and 2, the \(^{1}\text{H}\) and \(^{13}\text{C}\) NMR spectra of 3 indicated a non-symmetric structure with distinct signals for all hydrogen and carbon atoms.

### 5.3 Synthesis of CNC Ag(I), Pd(II) and Ru(II) complexes

**Synthesis of the CNC metal complexes**

Initial attempts to coordinate symmetric ligand 2 to ruthenium by direct deprotonation of the triazolium fragments using various bases (KOTBu, KHMD5 and 2-tert-butylimino-2-diethylamino-1,3-dimethylperhydro-1,3,2-diazaphosphorine; BEMP) in the presence of several precursors ([RuCl\(_2\)(MeCN)\(_4\)], [RuCl(CO)(H)(PPh\(_3\))\(_3\)], [RuCl\(_2\)(PPh\(_3\))\(_4\)] and [Ru(p-cym)(CO)Cl\(_2\)]) were unsuccessful.\(^ {327}\) Therefore, we turned to the Ag(I)-transmetalation route, which previously proved suitable for the heteroditopic Ru(II) NHC complexes in Chapter 3.
Silver(I) complex 4 could be obtained by stirring the CNC ligand 2 in the presence of \( \text{Ag}_2\text{O} \) in MeOH for two days (Scheme 4).\textsuperscript{28} The formation of the desired complex was confirmed by the disappearance of the triazolium hydrogen in the \(^1\text{H}\) NMR spectrum. In contrast to the other silver(I) di-NHC complexes described in this thesis, mass spectrometry pointed to a mononuclear structure in this case. Apparently, the structure of ligand 2 allows the two tzNHC groups to coordinate to the silver center in a linear fashion.

![Scheme 4: Synthesis of Ag(I) complex 4, Ru(II) complex 5 and Pd(II) complex 6.](image)

The silver complex was subsequently transmetalated following a procedure published by Suárez \textit{et al.},\textsuperscript{29} by stirring 4 with [RuCl\((\text{CO})(\text{H})(\text{PPh}_3)_3\)] in THF at 55 °C for 2 days (Scheme 4) to produce [Ru(CNC)(CO)(H)(PPh\(_3\))BF\(_4\)], complex 5. Remarkably, the CNC ligand was coordinated in a facial (fac) coordination mode to the ruthenium center, as was evident from the \(^1\text{H}\) and \(^{13}\text{C}\) NMR spectra. The inequivalent sides of the ligand gave rise to separate signals for all hydrogen and carbon atoms. Most indicative were the distinctive signals for both triazolylidene carbons at 172.2 (\(\^2J_{\text{CP}} = 7.2\) Hz, \textit{cis} to PPh\(_3\)) and 164.9 ppm (\(\^2J_{\text{CP}} = 75.7\) Hz, \textit{trans} to PPh\(_3\)) in the \(^{13}\text{C}\) NMR spectrum. The carbonyl ligand was also detected as a doublet in the \(^{13}\text{C}\) NMR spectrum at 208.5 ppm (\(\^2J_{\text{CP}} = 14.8\) Hz) and it gave rise to a CO vibrational band at 1926 cm\(^{-1}\) in the IR spectrum. The hydrido and PPh\(_3\) ligands were observed as a doublet at -7.04 (\(\^2J_{\text{PH}} = 28.9\) Hz) and a singlet at 46.7 ppm in the \(^1\text{H}\) NMR and \(^{31}\text{P}\{^1\text{H}\}\) NMR spectrum, respectively. These data are consistent with the only previous report of a \textit{fac}-CNC Ru complex by Suárez.\textsuperscript{12} Interestingly, Triphos is also known to adopt a facially coordination mode to octahedral Ru centers in our previously reported active ester hydrogenation system.\textsuperscript{30}
Most lutidine-based pincer complexes, including those with more flexible six-membered chelate rings, adopt a meridional (mer) conformation. However, a recent DFT and experimental study has shown that for [Ru(PNP)(PhCOO)$_2$] the fac coordination mode was significantly more stable (yet inactive in direct insertion of CO$_2$ into the C-H bonds of arenes). To gain insight in the reason for fac coordination in our case, we performed DFT calculations. The mer conformation turned out to be more thermodynamically favorable by 2.2 kcal/mol at the BP86/def2-TZVP level (Figure 1). This points to the fac configuration being the kinetic product, produced by these specific reaction conditions. Attempts to obtain the mer analogue synthetically have not been successful to date (combinations of various bases mentioned above or Ag(I) complex and several ruthenium precursors ([RuCl$_2$(MeCN)$_4$], [RuCl(CO)(H)(PPh$_3$)$_3$], [RuCl$_2$(PPh$_3$)$_3$] and [Ru(p-cym)(CO)Cl$_2$]) in various solvents (THF/DCM/MeCN) and temperatures (25-70 °C).

**Figure 1:** Computed DFT (BP86/def2-TZVP) structures of Ru CNC complexes with meridional (left) and facial (right) coordination. Hydrogen atoms, except for hydride and CH$_2$, are omitted for clarity.

In Pd(II) complex 6, which could be obtained by transmetalation of the Ag(I) complex 4 with [Pd(PhCN)$_2$Cl$_2$] in 92% yield (Scheme 4), planar coordination of the ligand 2 was observed. The square planar complex was characterized by multinuclear NMR spectroscopy and HR-MS. In CD$_2$Cl$_2$ the hydrogens of the linker were split in the $^1$H NMR spectrum (AB system centered at $\delta_A$ 6.10 and $\delta_B$: 5.98 ppm; $^3$J$_{HH}$ = 15 Hz) and the tzNHC carbon was found in the expected range at 168.0 ppm in the $^{13}$C NMR spectrum.

**Dearomatization/deprotonation of complexes 5 and 6**

The deprotonation/dearomatization abilities of the complexes were investigated next (Scheme 5). The benzylic position of both complex 5 and 6 could be deprotonated with one equivalent of KOTBu, marked by a characteristic color change to dark red.
The $^1$H NMR spectra of the symmetric CNC Pd(II) 6 and non-symmetric dearomatized CNC* Pd(II) complex $6'$ are depicted in Figure 2. Upon deprotonation of the benzylic arm, dearomatization of the pyridine ring occurred, characterized by an upfield shift for the pyridine hydrogens (5.92-4.93 and 6.45-5.70 ppm) and the appearance of the vinylic protons (5.52 and 6.27 ppm for $5'$ and $6'$, respectively) in the $^1$H NMR spectra. The complexes were not very stable upon dearomatization and could consequently not be completely characterized. The deprotonation/dearomatization reaction was reversible, as addition of hydrochloric acid (1 M in dioxane) led to rearomatization of the pyridine ring (Scheme 5).

**Scheme 5:** Reversible deprotonation/dearomatization of CNC complexes. 5: $ML_n = Ru(CO)H(PPh_3)_3$ and 6: $ML_n = PdCl$.

The $^1$H NMR spectra of the symmetric CNC Pd(II) 6 and non-symmetric dearomatized CNC* Pd(II) complex $6'$ are depicted in Figure 2. Upon deprotonation of the benzylic arm, dearomatization of the pyridine ring occurred, characterized by an upfield shift for the pyridine hydrogens (5.92-4.93 and 6.45-5.70 ppm) and the appearance of the vinylic protons (5.52 and 6.27 ppm for $5'$ and $6'$, respectively) in the $^1$H NMR spectra. The complexes were not very stable upon dearomatization and could consequently not be completely characterized. The deprotonation/dearomatization reaction was reversible, as addition of hydrochloric acid (1 M in dioxane) led to rearomatization of the pyridine ring (Scheme 5).

**Figure 2:** $^1$H NMR spectra of CNC Pd complex 6 (top; in CD$_2$Cl$_2$) and the deprotonated 6' (bottom; in THF-d$_8$). Pyridine hydrogens of 6' are assigned by letters (a-e; see Scheme 5) and solvents are marked by “x”.

**Synthesis of Ag(I) and Ru(II) CNN metal complexes**

[Ru(CNN)(CO)(H)(PPh$_3$)$_3$] complex 7 was synthesized in the same way as complex 5 via the silver transmetalation route from ligand 3 (Scheme 6). The formation of the carbene was indicated by the disappearance the triazolium hydrogen in $^1$H NMR and by CSI-HR-MS, which indicated the presence of the [(CNN)$_2$Ag]$^+$ ion, suggesting that two ligands are coordinated to one silver atom in 7.
Transmetalation to the Ru complex 8 proceeded smoothly in the same manner as for 5 using \([\text{RuCl}(\text{CO})(\text{H})(\text{PPh}_3)_3]\). Again, NMR spectroscopy pointed to facial coordination of the ligand. Compared to complex 5, the hydrido and PPh\(_3\) ligand both appeared as upfield signals at -13.0 ppm (\(J_{\text{PH}} = 28\) Hz, cis to PPh\(_3\)) and 40.9 ppm in the \(^1\text{H}\) NMR and \(^{31}\text{P}\{^1\text{H}\}\) NMR spectrum, respectively. The upfield shift of the former is in agreement with the hydride in trans position to the weak-field triazole ligand.\(^{35}\) In the \(^{13}\text{C}\) NMR spectrum, the large coupling of the tzNHC carbon (166.0 ppm; \(J_{\text{CP}} = 76.9\) Hz) with the phosphorus atom indicates that the NHC is located trans to the PPh\(_3\) ligand. The CO stretching frequency of 8 of 1949 cm\(^{-1}\) in the IR spectrum is higher than for 5. We correlate this value to the reduced electron density on the metal center (triazole is a weaker donor than a triazolylidene) of complex 8 compared to 5.

5.4 Ruthenium Catalyzed Ester Hydrogenolysis

*Ruthenium catalyzed hydrogenolysis of esters*

The application of 5 in the catalytic hydrogenolysis of esters was initially studied using methyl benzoate as the substrate, following the protocol as described by Beller and co-workers.\(^{36}\) When applying 30 mol% of KOTBu full conversion was observed within 6 hours at 100 °C under 50 bar of H\(_2\) pressure in 1,4-dioxane (Table 1). The reaction time as well as the catalyst loading could be reduced to 2 hours and 0.75 mol%, respectively, without a decrease in yield (Table 1, entries 2-4). At lower pressure (5 bar) the system also converted methyl benzoate, albeit significantly slower (entries 5 and 6). The amount of base, on the other hand, proved to be crucial. The concentration could be reduced to 20 mol% (entry 2), but when 10 mol% of base was added (entry 3), only traces of benzyl alcohol were detected. Beller et al. also reported a sharp decrease in conversion at lower base concentrations (<20 mol%), but did not provide any explanation for this critical concentration of base.\(^{36}\) The experiments described below are conducted with 20 mol% of KOTBu, whereas the role of the base is investigated further in the next paragraph.
Table 1: Methyl benzoate hydrogenolysis catalyzed by complex 5.

\[
\text{H}_2, \quad \text{Cat. 5,} \quad 
\begin{array}{c}
\text{KOTBu} \\
1,4\text{-dioxane} \\
100 ^\circ \text{C}
\end{array}
\rightarrow 
\begin{array}{c}
\text{OH} + \text{MeOH}
\end{array}
\]

<table>
<thead>
<tr>
<th>t (h)</th>
<th>p (bar)</th>
<th>mol% KOtBu</th>
<th>Conv. (%)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>50</td>
<td>30</td>
<td>100</td>
</tr>
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<tr>
<td>5</td>
<td>2</td>
<td>50</td>
<td>20</td>
<td>33</td>
</tr>
</tbody>
</table>

Conditions: 0.5 mmol methyl benzoate, 1.5 mol% (entry 1) or 0.75 mol% of 5, indicated amount of KOTBu, pressure and reaction time in 1,4-dioxane at 100 °C. Conversion and yield were determined by GC analysis with p-xylene as internal standard.

The substrate scope was expanded beyond methyl benzoate. The aliphatic ester n-butyl benzoate could be hydrogenated by complex 5 as well under the same reaction conditions (Table 2, entry 1). Longer alkyl chains did not provide a problem either: methyl stearate was nearly completely reduced to octadecanol within 2 hours (entry 2).

Methyl oleate, which contains both a carbon-carbon double bond and ester functionality, was subsequently tested in the ester hydrogenolysis catalyzed by 5 to test the chemoselectivity of the system (Table 2, entry 3). Almost full conversion of the unsaturated fatty carboxylic ester and formation of both the saturated and unsaturated product in a 2.6 : 1 ratio was observed. This indicates that the ester functionality is hydrogenated first. Saudan et al. reported this selectivity to a larger extent for their system, in which the double bond was only minimally affected (<99:1 ratio). They found that the ester reduction path is kinetically favored over the olefin hydrogenation. The triglyceride triolein was also converted, but many (often unidentified) products, including octadecanol (~5%) and oleyl alcohol (~4%), were detected using GC analysis.
The hydrogenation of the cyclic ester γ-valerolactone led to a moderate yield of 1,4-pentanediol (Table 2, entry 4). Carboxylic acids were incompatible with the system (entry 5 and 6), as even the activated acid trifluoroacetic acid (TFA) was not converted at all. This is probably due to the acid functionality neutralizing the base that is needed for the reaction, which was observed by a color change of the catalytic mixture from the characteristic bright orange to yellow upon addition of the substrate. As expected the methyl ester of TFA was completely converted to trifluoroethanol (entry 7). When phenyl benzoate was used as substrate no benzyl alcohol was detected on the GC, instead some transesterification products (tert-butyl benzoate and benzyl benzoate) were observed. This might be explained by the acidity of the formed phenol, neutralizing the required base.

### Table 2: Substrate scope for hydrogenation catalyzed by complex 5.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Conv. (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Product</th>
<th>Yield (%)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>93</td>
<td>HO</td>
<td>93</td>
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<td>C&lt;sub&gt;6&lt;/sub&gt;H&lt;sub&gt;17&lt;/sub&gt;OH</td>
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<td>0</td>
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<td>8</td>
<td>17</td>
<td>HO</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>100</td>
<td>HO</td>
<td>100</td>
</tr>
</tbody>
</table>

Conditions: 0.5 mmol ester, 0.75 mol% 5, 20 mol% of KOTBu, stirred under 50 bar H<sub>2</sub> in 1,4-dioxane at 100 °C for 2 hours. a.) Conversion and yield were determined by GC analysis with p-xylene as internal standard (entries 1-5 & 9) or by <sup>19</sup>F NMR spectroscopy using 1,3-bis(trifluoromethane)benzene as internal standard (entry 6 & 7).
Last but not least, the sterically hindered tert-butyl benzoate was hydrogenated to benzyl alcohol within 2 hours (Table 2, entry 9). In fact, we found that this substrate was converted significantly faster than methyl benzoate. This finding is very remarkable, as very few ester hydrogenation catalysts are known to convert this substrate.\textsuperscript{19,37}

The role of KOtBu in the hydrogenolysis of esters

Catalyst 5 showed good activity in the hydrogenolysis of aryl esters, but only when 20 mol% of KOtBu was used (Table 1, entry 2 and 3). Also for alkyl esters the base dependence was apparent (93% conversion of methyl butyrate to n-butanol using 20 mol% KOtBu vs 4% using 10 mol%). It has been previously observed that base can be required or have a tremendous accelerating effect on the rate of catalytic hydrogenolysis of esters,\textsuperscript{15,17,36,38} yet the role of the base has hardly been investigated.\textsuperscript{*}

To obtain more insight in the role of the base in catalytic ester hydrogenolysis, we tested different bases (KOH, KHMDS, K\textsubscript{2}CO\textsubscript{3}). None of these were beneficial for the reaction and notably, even different batches of KOtBu led to varying results.

The amount of base (10 or 20 mol%) and catalyst (1.5 mol% or 0.75 mol%) was varied, leading to full conversion at 20 mol% KOtBu, whereas only traces of product (<2%) were observed for both catalyst loadings when 10 mol% base was applied. This indicates that 20 mol% base is required with respect to the ester and not the catalyst. For the reduction of \(N\)-benzylideneaniline (100% conversion to benzylaniline after 2 hours under 5 bar hydrogen pressure at 100 °C) no excess of KOtBu with respect to the substrate was necessary. These observations, together with the remarkable activity of complex 5 for tert-butyl benzoate led us to investigate whether transesterification to this substrate induced by KOtBu plays a role.

Stirring methyl benzoate with 20 mol% of KOtBu at 100 °C (without catalyst) led to formation of 8% tert-butyl benzoate, whereas with 10 mol% only traces (~1%) were observed. Thus, transesterification followed by hydrogenation of tert-butyl benzoate could be a plausible explanation for the need for 20 mol% of KOtBu. From Table 3 it becomes apparent that tert-butyl benzoate is hydrogenated significantly faster than the corresponding methyl ester (entry 1 and 2). Furthermore, methyl benzoate showed no conversion when KHMDS was applied as base, whereas the tert-butyl analogue was fully converted (entry 3 vs entry 5).\textsuperscript{†}

\textsuperscript{*} Exceptions include Milstein and co-workers, who recently proposed a mechanism for Co-catalyzed ester hydrogenation involving the enolate form of the ester, which is only present (in equilibrium with the ester) under basic conditions.\textsuperscript{15} This mechanism is not suitable for our system, as this mechanism was based on the fact that the Co-catalyst did not convert “non-enolizable” esters (e.g. methyl benzoate and methyl trifluoracetate), whereas complex 5 does. According to Bergens et al. the base facilitates substitution of the alkoxide for H\textsubscript{2} on the metal through deprotonation of the NH group in their proposed mechanism.\textsuperscript{38}
Table 3: Catalytic hydrogenation of methyl vs tert-butyl benzoate with complex 5.

Unfortunately, decreasing the amount of base for the substrate tert-butyl benzoate did result in a large decrease of conversion (Table 3, entry 6). Thus, although transesterification seems to play a role in the hydrogenation of esters with 5, it does not fully explain the need for the critical amount of base.

The effect of possible vacant sites on Ru in the hydrogenolysis of esters

The previously developed NHC Ru ester hydrogenation pre-catalysts either bear a halide co-ligand that is abstracted during the deprotonation of the benzylic arm on the ligand or, in case of the complexes that are viable at low hydrogen pressure, contain a CNN motif with a hemilabile nitrogen donor. Complex 5, on the other

Remarkably, the yield of several entries containing the same conditions differ significantly, such as entry 1 vs entry 4 in Table 3 vs previous results from Table 1. These experiments were performed with different batches of complex 5. We therefore suspected these differences in activity of the pre-catalyst to be due to trace impurities in complex 5 that are not visible in the NMR spectra. Such an impurity could be silver salts that are still present after transmetallation. In control experiments wherein AgCl or AgBF₄ (1 mol%) was added to the catalytic mixture, no benzylalcohol was formed at all. Fluctuations in activity between different batches of 5 are consequently attributed to the presence of trace amounts of silver. Comparisons are made between experiments performed with the same batch of catalyst throughout the entire chapter.
hand, is completely coordinatively saturated, which might initially prevent it from entering the catalytic cycle. Hence, we attempted to create a vacant site on complex 5. When trimethylamine N-oxide (Me$_3$NO; excess) was added to a solution of the complex in CD$_2$Cl$_2$ in order to remove the carbonyl ligand as CO$_2$, the $^{31}$P NMR spectrum exhibited a peak at 27 ppm, characteristic for free Ph$_3$P=O. This indicates that the phosphine instead of the carbonyl moiety of 5 is oxidized and subsequently dissociates. The corresponding $^1$H NMR spectrum was unclear, presumably due to instability of the resulting unsaturated complex. Next, we added this reagent as an additive to the catalytic mixtures in ester hydrogenation trials (Table 4).

**Table 4:** The influence of additives on the catalytic hydrogenation of methyl benzoate.

<table>
<thead>
<tr>
<th>Additive</th>
<th>t(h)</th>
<th>P (bar)</th>
<th>mol% KOTBu</th>
<th>Conv (%)</th>
<th>Yield (%)</th>
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<td>4</td>
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<td>50</td>
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</table>

Conditions: 0.5 mmol ester, 0.5 mol% of 5, 0.5 mol% of Me$_3$NO for entry 2-4, indicated amount of KOTBu and H$_2$ pressure in 1,4-dioxane at 100 °C for 2 hours. The yield and conversion was determined by GC analysis with p-xylene as internal standard.

The addition of Me$_3$NO (0.5 mol%) led to slightly increased yield (Table 4, entry 1 vs 2). Interestingly, use of this additive allowed for the reduction of the amount of KOTBu to 10 mol% without significant loss in yield (entry 3), yet when the amount of base was lowered to 2 mol% no reaction occurred (entry 4). Increasing the amount of Me$_3$NO did not improve the results.

Complex 8, bearing the CNN motif with the potentially hemilabile triazole donor, could result in a vacant site on the Ru center upon decoordination of this moiety. In Table 5 the results of complex 8 vs complex 5 in methyl and tert-butyl benzoate hydrogenation have been compiled. As no significant differences between the conversion of the two pre-catalysts was observed, we conclude that either the 1,2,3-triazole donor is more strongly bound than anticipated (hence not displaying

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104
hemilability) or this feature does not play a critical role in the rate determining step of this catalytic reaction.

**Table 5:** Catalytic hydrogenation of methyl vs tert-butyl benzoate with complex 5 and 8.

<table>
<thead>
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<th>Yield (%)</th>
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<td>5</td>
</tr>
<tr>
<td>4</td>
<td>tBu</td>
<td>8</td>
</tr>
</tbody>
</table>

| Conditions: 0.5 mmol ester, 0.75 mol% of catalyst, 20 mol% of KOTBu, 50 bar H₂ in 1,4-dioxane at 100 °C for 2 hours. The yield was determined by GC analysis with p-xylene as internal standard.

### 5.5 NMR Investigations of Complex 5 under Near-Catalytic Conditions

To gain more insight in the catalytically active species, ^1^H NMR investigations were performed. A solution of complex 5 in THF-d₈ was studied under near-catalytic conditions (20 equiv. of KOTBu, 5 bar of H₂) in a J. Young pressure tube. At room temperature, the dearomatized complex 5' was present in solution according to the ^1^H NMR spectrum (Scheme 5). After the tube was warmed at 100 °C for 2 hours, a mixture of products was detected by NMR spectroscopy at room temperature. In the ^31^P NMR spectrum four peaks were visible at 59.6, 22.9, 14.9 and -5.5 ppm, the latter being characteristic for free PPh₃. The hydridic region of the ^1^H NMR spectrum is depicted in Figure 3 and suggests the presence of three hydride-containing Ru complexes (~1:1:1 ratio).

The doublet at -6.90 ppm has a large coupling constant Jₚ₄ of 122 Hz, which according to proton-coupled ^31^P NMR spectroscopy couples with the resonance at 23 ppm in the ^31^P spectrum. These values are in agreement with mutual trans arrangement of the hydride and PPh₃ and they compare well with those reported by Milstein et al. for a similar [(CNN)Ru(CO)H(PPh₃)] complex. Since the phosphine and hydride ligand are attached trans to each other, the CNC ligand consequently must be coordinated in a mer fashion, which leads to the proposed
structure of 5A in Figure 3. Apparently, fac-mer isomerization of the flexible CNC chelate, for instance via a five-coordinated Ru species, is possible under these conditions. Attempts to induce this isomerization thermally without base were unsuccessful.

Figure 3: Proposed structures (top) and hydride region of $^1$H NMR spectrum (bottom) of complexes formed from 5 and KOrBu under 5 bar H$_2$ after 2h at 100 °C.

$^1$H-$^1$H COSY combined with $^1$H($^{31}$P) NMR spectroscopy indicated that the hydride signals at -11.77 and -15.09 ppm (d, $^2J_{HH}$ = 8.4 Hz) belong to a Ru cis dihydride bearing no phosphine ligand (5B in Figure 3). The remaining two signals in the hydride region at -7.53 (1H) and between -8.67 and -9.11 ppm (2H) belong to complex 5C, which gives rise to the peak at 59.6 ppm in the $^{31}$P NMR spectrum. Based on integration and $^1$H-$^1$H COSY, $^1$H($^{31}$P) and $^{31}$P($^1$H) spectra and the observed patterns, which are indicative of an ABMX spin system, this species presumably concerns the trihydride species fac-5c (Figure 3). The peak at 14.9 ppm in the $^{31}$P NMR spectrum could not be assigned.

When the H$_2$ pressure was released, the mixture of species converted to the mer- and fac-ruthenium complexes 5A and 5’ in a ratio of approximately 2:1, which confirms that either 5B or 5C contain a mer coordinated CNC ligand, assuming that no fac-mer isomerization occurs at room temperature. However, more data (preferably single crystal X-ray diffraction) are required to verify the exact stereochemistry around the metal centers of 5B and 5C.

When applying 10 equivalents of KOrBu and H$_2$ to 5 the same species were observed in solution, albeit in a slightly different ratio (5A : 5B : 5C = 1.5 : 2 : 1).
These NMR experiments provide initial insight in the potential structure of the active species during the catalytic hydrogenation of esters. Additionally, access to the meridional coordination mode of ligand 2 has been found.

5.6 Conclusions

Novel lutidine-derived CNC and CNN pincer ligands 2 and 3 bearing tzNHCs have been developed. The ligands could be conveniently synthesized using a one-pot multi-component reaction followed by methylation of the triazole ring. Coordination of these ligands via transmetalation of the corresponding Ag(I) complex led to the rare fac-[(L)Ru(H)(CO)(PPh₃)] complexes 5 and 8. According to DFT calculations this facial coordination mode is thermodynamically less stable than the mer form and presumably forms as the kinetic product under the reaction conditions. Planar coordination of the tridentate ligand was observed in the symmetric [(CNC)Pd(II)Cl] complex 6, which was also obtained via transmetalation. All complexes showed the expected (reversible) deprotonation/dearomatization reactivity upon addition of one equivalent of KOTBu.

The ruthenium complexes 5 and 8 were active pre-catalysts in the hydrogenolysis of a range of aromatic and aliphatic esters at 100 °C in the presence of 20 mol% KOTBu. Surprisingly, the sterically congested tBu-benzoate ester was converted more rapidly than the methyl analogue. Although transesterification of the substrate to the tert-butyl ester may play a role, the exact reason for the critical minimal amount of KOTBu remains unknown in spite of near-catalytic and high pressure in situ NMR spectroscopic investigations. Nevertheless, more insight in potentially active Ru hydride species in the catalytic ester hydrogenolysis reaction was obtained by these experiments.

5.7 Experimental

All reactions were carried out using standard Schlenk techniques under an atmosphere of dry nitrogen. Solvents were dried and distilled according to standard methods. Methyl benzoate was degassed and dried over 4 Å molsieves. All other chemicals were purchased from commercial suppliers and used without further purification. The NMR spectra were recorded on Varian Mercury 300 MHz, Bruker DRX Avance 300 and Bruker AMX 400 MHz spectrometers. ¹⁹F NMR was used to confirm the (non-coordinating nature of the) BF₄⁻ anion (-152 ppm). ¹H-¹H COSY and/or ¹H-¹³C HSQC NMR spectroscopy was used to assign the signals of several compounds. High resolution mass spectrometry was performed on a Bruker MicrOTOF-Q (ESI⁺) GC analysis for esters was performed on a Thermo Scientific Trace GC Ultra equipped with a Restek RTX-200 column (30 m x 0.25 mm x 0.5 μm). Temperature program: Initial temperature 50 °C, hold for 4 min, heat to 130 °C with 30 °C/min, hold for 2 min, heat to 250 °C with 50 °C/min, hold for 9 min.
Inlet temperature 200 °C, split ratio of 60, 1 mL/min carrier flow, FID temperature 250 °C. GC analysis for fatty esters and benzoic acid was performed on a Thermo Scientific Trace GC Ultra equipped with a Restek Stabilwax-DA column (30 m x 0.25 mm x 0.25 μm). Temperature program: initial temperature 40 °C, heat to 175 °C with 6 °C/min, heat to 250 °C with 50 °C/min, hold for 18 minutes. Inlet temperature 280 °C, split ratio of 40, 1.5 mL/min carrier flow, FID temperature 250 °C. Conversion of trifluoroacetic acid and methyl trifluoroacetate were determined by \(^{19}\)F NMR spectroscopy using 1,3-bis(trifluoromethane)benzene as internal standard.

**Synthesis of 3,3-[pyridine-2,6-diylbis(methylene)]bis(4-para-tolyl-1,2,3-triazole);** 1. To a solution of 2,6-bis(bromomethyl)pyridine (397 mg, 1.5 mmol) in DMF/H\(_2\)O (7.5 mL, 4:1) was added NaN\(_3\) (205 mg, 3.1 mmol), para-tolylacetylene (357 mg, 3.1 mmol), Na\(_2\)CO\(_3\) (159 mg, 1.5 mmol), CuSO\(_4\).5H\(_2\)O (150 mg, 0.6 mmol) and sodium ascorbate (238 mg, 1.2 mmol). The reaction mixture was stirred at room temperature for 16 h, after which the suspension was poured into an EDTA/NH\(_4\)OH solution (100 mL, 0.5 M). The product was extracted with dichloromethane (3 x 15 mL) and washed with water (2 x 50 mL) and brine (50 mL). The organic phase was dried over MgSO\(_4\) and concentrated in vacuo to yield the product as a white solid (480 mg, 1.1 mmol, 76%). \(^1\)H NMR (300 MHz, CDCl\(_3\)) \(\delta\) 7.85 (s, 2H, NC\(_\text{H}C\)), 7.75-7.65 (m, 6H, Pyr-C\(_\text{H}\), T ol-C\(_\text{H}\)), 7.22 (m, 8H, Pyr-C\(_\text{H}\), T ol-C\(_\text{H}\)), 5.71 (s, 4H, C\(_\text{H}_2\)), 2.40 (s, 6H, T ol-C\(_\text{H}_3\)); \(^{13}\)C NMR (75 MHz, CDCl\(_3\)) \(\delta\) 155.0 (C\(_q\)), 139.0 (Pyr-C\(_\text{H}\)), 138.3 (C\(_q\)), 136.1 (C\(_q\)), 129.8 (T ol-C\(_\text{H}\)), 127.7 (C\(_q\)), 125.9 (T ol-C\(_\text{H}\)), 122.2 (pyr-C\(_\text{H}\)), 120.1 (tz-C\(_\text{H}\)), 55.51 (C\(_\text{H}_2\)), 21.51 (C\(_\text{H}_3\)). MS(EI\(^{+}\)) for C\(_{25}\)H\(_{23}\)N\(_7\): m/z calculated 421.2009 [M]\(^{+}\), observed 421.2013.

**Synthesis of 3,3-[pyridine-2,6-diylbis(methylene)]bis(3-methyl-4-para-tolyl-1,2,3-triazolium) bistetrafluoroborate;** 2. Meerweins’ salt ((Me\(_3\)O)BF\(_4\), 137 mg, 0.92 mmol) was added to a solution of ligand 1 (155 mg, 0.37 mmol) in dichloromethane (10 mL) and the reaction mixture was stirred at room temperature for 16 h. A few drops of methanol were added to quench the reaction. The precipitate was collected on a glass frit and washed with small amounts of DCM and Et\(_2\)O, yielding the product as a white solid (185 mg, 0.30 mmol, 81%). \(^1\)H NMR (300 MHz, DMSO-d\(_6\)) \(\delta\) 9.19 (s, 2H, NC\(_\text{H}C\)), 8.08 (t, \(J_{\text{HH}}\) = 7.8 Hz, 1H, Pyr-CH\(_3\)), 7.70 (d, \(J_{\text{HH}}\) = 7.8 Hz, 2H, Pyr-CH\(_3\)), 7.54 (d, \(J_{\text{HH}}\) = 8.0 Hz, 4H, Tol-CH\(_3\)), 7.37 (d, \(J_{\text{HH}}\) = 8.0 Hz, 4H, Tol-CH\(_3\)), 6.07 (s, 4H, C\(_\text{H}_2\)), 4.22 (s, 6H, N-CH\(_3\)), 2.40 (s, 6H, Tol-CH\(_3\)); \(^{13}\)C NMR (75 MHz, acetonitrile-d\(_3\)) \(\delta\) 152.6, 144.2, 143.4 (C\(_q\)), 140.7 (pyr-CH\(_3\)), 131.0, 130.1 (T ol-CH\(_3\)), 124.9 (Pyr-CH\(_3\)), 120.1 (C\(_q\)), 58.2 (N-CH\(_3\)), 39.6 (N-CH\(_3\)), 21.5 (CH\(_3\)). MS(CSI\(^{+}\)) for C\(_{27}\)H\(_{29}\)N\(_7\)BF\(_4\): m/z calculated 538.2513 [M-BF\(_4\)]\(^{+}\), observed 538.2482.
Synthesis of 3,3-[pyridine-2,6-diylbis(methylene)](4-para-tolyl-1,2,3-triazolyl)
(3-methyl-4-para-tolyl-1,2,3-triazolium) tetrafluoroborate; 3. Meerweins’ salt
((Me₃O)BF₄, 126 mg, 0.85 mmol) was added to a solution of ligand 1
(360 mg, 0.85 mmol) in DCM (30 mL) and the reaction mixture was
stirred at room temperature for 16 h. A few drops of methanol were
added to quench the reaction. After the solvent was removed under
reduced pressure, the product was purified by column chromatography (SiO₂, DCM:acetone
= 1:1) yielding the product (151 mg, 0.29 mmol, 34%) as a white powder.1H NMR (300 MHz,
DMSO-d₆) δ 9.10 (s, 1H, tz-CH), 8.48 (s, 1H, tz-CH), 8.00 (t, 3JHH = 7.7 Hz, 1H, Pyr-CH), 7.63
(d, 3JHH = 8.1 Hz, 2H, Tol-CH), 7.60 – 7.53 (m, 3H, Pyr-CH and Tol-CH overlapping), 7.46
(d, 3JHH = 7.7 Hz, 1H, Pyr-CH), 7.40 (d, 3JHH = 7.9 Hz, 2H, Tol-CH), 7.17 (d, 3JHH = 7.8 Hz, 2H,
Tol-CH), 6.05 (s, 2H, CH₂), 5.75 (s, 2H, CH₂), 4.18 (s, 3H, N-CH₃), 2.43 (s, 3H, CH₃), 2.32 (s,
3H, CH₃); 13C NMR (101 MHz, DMSO-d₆) δ 155.1, 151.9, 146.3, 142.4 (C₆), 141.5 (Pyr-CH),
138.9, 137.1 (tz-CH), 129.8 (Tol-CH), 129.3 (Tol-CH), 129.2, 129.1 (Tol-CH), 127.7, 124.9 (Tol-
CH), 122.4, 122.4 (Pyr-CH), 121.7, 119.5 (C₆), 56.8, 54.0 (CH₃), 38.9 (N-CH₃), 21.0, 20.8 (CH₃).
MS(CSI) for [C₆H₆N₆]⁺; m/z calculated 556.2250 [M-BF₄]⁺, observed 556.2323.

Synthesis of [Ag(CN)]BF₄; 4. Ag₂O (87 mg, 0.3 mmol) was added to a
solution of ligand 3 (95 mg, 0.15 mmol) in MeOH (10 mL) in a Schlenk
flask charged with 4Å molsieves. The resulting suspension was stirred for
2 days at room temperature during which it changed color to pale grey/
brown. The mixture was filtered over Celite (to obtain good yields the
filtrate was thoroughly flushed with MeOH and acetone) and dried in
vacuo yielding the product (87 mg, 0.13 mmol, 90%) as a pale yellow solid. The compound
was stored under nitrogen and with exclusion of light. 1H NMR (300 MHz, acetone-d₆) δ
7.93 (t, 3JHH = 7.7 Hz, 1H, Pyr-CH), 7.55 (d, 3JHH = 7.7 Hz, 2H, Pyr-CH), 7.47 (d, 3JHH = 7.8, 4H,
Tol-CH), 7.23 (d, 3JHH = 7.8 Hz, 4H, Tol-CH), 5.84 (s, 4H, CH₂), 4.09 (s, 6H, N-CH₃), 2.44 (s,
6H, CH₂); 13C NMR (75 MHz, acetone-d₆) δ 155.3, 149.8, 148.3, 140.8, 130.5, 129.9, 125.8
(Ar-C), 60.7 (CH₂), 37.9 (N-CH₃), 21.3 (CH₃). MS(CSI) for [C₂₇H₂₉AgN₇]⁺; m/z calculated
556.1379 [M-BF₄]⁺, observed 556.1342 and for [C₂₇H₂₉AgN₇]⁺; m/z calculated 558.1379 [M-
BF₄]⁺, observed 558.1377.

Synthesis of [Ru(OC)(H)(PPh₃)(CN)]BF₄; 5. A mixture of silver complex
4 (78.2 g, 0.12 mmol) and [RuHCl(CO)(PPh₃)₂] (115 g, 0.12 mmol) in
THF (8 mL) was heated at 55 °C for 2 days. The resulting pale brown
suspension was filtered, evaporated to dryness and extracted with
MeOH (2 × 5 mL). The solvent was evaporated, and the product was
obtained by precipitation from DCM with Et₂O as pale beige powder
(76.2 mg, 0.08 mmol, 68%). IR v(CO) 1926 cm⁻¹; 31P 1H NMR (162 MHz, CDCl₃) δ 46.7;
1H NMR (400 MHz, CD₂Cl₂) δ 7.94 (t, 3JHH = 7.7 Hz, 1H, Pyr-CH), 7.76 (d, 3JHH = 7.5 Hz, 1H,
Pyr-CH), 7.58 – 7.12 (m, 16H, PPh₃ & Pyr-CH), 6.97 (d, 3JHH = 2.8 Hz, 4H, Tol-CH), 6.90 (d, 3JHH
AB system centered at δ A, 5.51 (d, 3J H-H = 15.7 Hz, 1H, CH3) & δ B: 4.82 (d, 3J H-H = 15.7 Hz, 1H, CH3), 3.73 (s, 3H, N-CH3), 3.60 (s, 3H, N-CH3), 2.46 (s, 3H, Tol-CH3), 2.40 (s, 3H, Tol-CH3), -7.04 (d, 3J P-H = 28.9 Hz, 1H, Ru-H): 13C NMR (101 MHz, CD2Cl2) δ 208.51 (d, 3J CP = 14.8 Hz, Ru-CO), 172.2 (d, 3J CP = 7.2 Hz, C tzNHC), 164.9 (d, 3J CP = 75.7 Hz, C tzNHC) 155.4 & 155.2 (Pyr-C), 148.7 (Pyr-CH), 148.3 (d, J CP = 7.1 Hz, PPh3-C), 139.6 (d, J CP = 6.0 Hz, PPh3-CH) 138.1 (Pyr-CH), 136.7 (d, J CP = 38.0 Hz, PPh3-CH), 136.2, 134.3, 133.7, 133.5, 132.61, 131.8, 131.1, 130.2 (Tol-CH), 129.4 (Tol-CH), 129.3, 129.2, 129.1, 128.9, 128.4 (d, J CP = 7.7 Hz, 6 CH arom, PPh3), 128.3, 128.1, 128.0, 127.9, 127.4, 127.4, 125.3, 125.1, 125.0, 124.3, 124.1, 61.5 (CH3), 58.3 (CH3), 37.0, 36.8 (N-CH3), 21.4, 21.1 (Tol-CH), MS(CSI^+) for C46H43N7OPRu: m/z calculated 842.2323 [M-H-BF4]+ observed 842.2333.

Synthesis of [Pd(CNC)(Cl)]BF4: 6. To a solution of complex 4 (75 mg, 0.12 mmol) in MeCN (7 mL) was added [Pd(NCPh)2Cl2] (45 mg, 0.12 mmol) and the resulting mixture was stirred for 2 h. The resulting suspension was filtered over Celite and the solvent was removed under reduced pressure. The product was precipitated from DCM with pentane to obtain the product as a yellow solid (72 mg, 0.11 mmol, 92%). 1H NMR (300 MHz, acetone-d6) δ 8.40 (t, 3J J = 7.8 Hz, 1H, Pyr-CH), 8.22 (d, 3J J = 7.8 Hz, 2H, Pyr-CH), 7.61 (d, 3J J = 7.9 Hz, 4H, Tol-CH), 7.24 (d, 3J J = 7.9 Hz, 4H, Tol-CH), 6.26 (s, 3H, CH3), 4.16 (s, 6H, N-CH3), 2.35 (s, 6H, CH3); 1H NMR (300 MHz, CD2Cl2) δ 8.27 (d, 3J J = 7.7 Hz, 1H, Pyr-CH), 7.97 (d, 3J J = 7.7 Hz, 2H, Pyr-CH), 7.48 (d, 3J J = 7.8 Hz, 4H, Tol-CH), 7.29 (d, 3J J = 7.8 Hz, 4H, Tol-CH), AB system centered at δ A, 6.10 (d, 3J H-H = 15.1 Hz, 1H, CH2); & δ B: 5.98 (d, 3J H-H = 14.8 Hz, 1H, CH2), 4.02 (s, 6H, N-CH3), 2.42 (s, 6H, CH3); 13C NMR (75 MHz, CD2Cl2) δ 168.0 (C tzNHC), 154.2, 148.3, 146.5 (Cq), 142.5 (Pyr-CH), 140.9 (Cq), 130.9, 129.4 (Tol-CH), 127.24 (Pyr-CH), 123.7 (Cq), 59.38 (CH3), 37.65 (N-CH3), 21.61 (CH3). MS(CSI^+) for C27H27CIN7Pd: m/z calculated 590.1058 [M-BF4]^+ observed 590.1012.

General procedure for deprotonation/dearomatization of complexes: To a solution of the CNC complex (1 equiv.) in THD-d8 was added KOTBu (1 equiv.) upon which an immediate color change to dark-red was observed.

[[(CNC)Ru(CO)(H)(PPh3)]]; 5+. Dark-red solution. Low stability of the complex prevented its isolation and full characterization. 31P{1H} NMR (162 MHz, THF-d8) δ 55.3; 1H NMR (300 MHz, THF-d8) δ 7.74 – 7.04 (m, 19H, PPh3 & 4H Tol-CH), 6.93 (d, 3J H-H = 7.8 Hz, 2H, Tol-CH), 6.64 (d, 3J H-H = 7.7 Hz, 2H, Tol-CH), 6.12 (d, 3J H-H = 13.1 Hz, 1H, CH2), 5.90 (d, 3J H-H = 8.0 Hz, 1H, Pyr-CH), 5.57 – 5.43 (m, 2H, CH and Pyr-CH overlapping), 5.13 (d, 3J H-H = 13.1 Hz, 1H, CH2), 4.90 (d, 3J H-H = 8.8 Hz, 1H, Pyr-CH), 4.02 (s, 3H, N-CH3), 3.17 (s, 3H, N-CH3), 2.42 (s, 3H, Tol-CH3), 2.39 (s, 3H, Tol-CH3), -7.19 (d, 3J P-H = 21.9 Hz, 1H, Ru-H); 13C NMR (75 MHz, THF) δ 138.8 (Cq), 137.6 (d, J CP =12.1 Hz, PPh3), 134.8,
133.8, 133.7, 133.6, 133.4, 131.8 (d, $J_{\text{CP}} = 9.5$ Hz, PPh$_3$), 131.3, 130.6 (pyr-CH), 130.3, 129.4, 128.7, 128.4, 128.3, 128.2, 128.0, 127.5, 127.4 (d, $J_{\text{CP}} = 4.5$ Hz, PPh$_3$), 126.9, 126.7, 116.8 (Pyr-CH), 100.4 (Pyr-CH), 94.5 (CH), 64.1 (CH$_3$), 35.6 (N-CH$_3$, 34.5 (N-CH$_3$), 20.4 (Tol-CH$_3$), 20.3 (Tol-CH$_3$).

$[(\text{CNN})^+\text{Pd(}\text{Cl})]$: 6'. Dark-red solution. $^1$H NMR (300 MHz, THF-d$_8$) $\delta$ 7.44 (d, $J_{\text{HA}} = 8.0$ Hz, 2H, Tol-CH$_3$), 7.35 (d, $J_{\text{HA}} = 8.0$ Hz, 2H, Tol-CH$_3$), 7.15 – 7.01 (m, 4H, Tol-CH$_3$), 6.45 (dd, $J_{\text{HH}} = 9.0$, 6.1 Hz, 1H, Pyr-CH$_3$), 6.27 (s, 1H, CH$_3$), 6.10 (d, $J_{\text{HH}} = 9.0$ Hz, 1H, Pyr-CH$_3$), 5.70 (d, $J_{\text{HH}} = 6.2$ Hz, 1H, Pyr-CH$_3$), AB system centered at $\delta$ $\sim$ 5.28 (d, $J_{\text{HH}} = 14.2$ Hz, 1H, CH$_3$) & $\delta$ $\sim$ 5.11 (d, $J_{\text{HH}} = 12.7$ Hz, 1H, CH$_3$), 3.96 (s, 3H, 1H, NCH$_3$), 3.80 (s, 3H, NCH$_3$), 2.32 (s, 6H, CH$_3$).

**Synthesis of [Ag(CNN)]BF$_4$: 7.** This complex was synthesized in analogy to complex 4 from ligand 3. Pale beige solid (58 mg, 0.05 mmol, 78%) $^1$H NMR (300 MHz, methanol-d$_4$) $\delta$ 7.99 (s, 1H), 7.72 (t, $J_{\text{Hz}} = 7.7$ Hz, 1H, Pyr-CH$_3$), 7.43 (d, $J_{\text{HH}} = 7.9$ Hz, 1H, Pyr-CH$_3$), 7.34 (d, $J_{\text{HH}} = 8.0$ Hz, 2H, Tol-CH$_3$), 7.28 (d, $J_{\text{HH}} = 8.0$ Hz, 2H, Tol-CH$_3$), 7.20 (d, $J_{\text{HH}} = 7.9$ Hz, 1H, Pyr-CH$_3$), 7.16 (d, $J_{\text{HH}} = 7.8$ Hz, 2H, Tol-CH$_3$), 6.96 (d, $J_{\text{HH}} = 7.8$ Hz, 2H, Pyr-CH$_3$), 5.61 (s, 2H, CH$_3$), 5.38 (s, 2H, CH$_3$), 4.01 (s, 3H, N-CH$_3$), 2.45 (s, 3H, Tol-CH$_3$), 2.30 (s, 3H, Tol-CH$_3$); $^{13}$C NMR (101 MHz, methanol-d$_4$) $\delta$ 154.2, 154.1, 148.4 ($C_q$), 139.6 (Pyr-CH$_3$), 138.6 (Tol-CH$_3$), 138.2 (Tol-CH$_3$), 137.6, 131.3, 128.7, 129.1, 128.5, 128.9, 127.0, 124.9, 124.8, 124.5, 122.0, 121.8 ($C_q$), 47.9, 47.5 (CH$_3$), 36.2 (N-CH$_3$), 19.9 (Tol-CH$_3$), 19.7 (Tol-CH$_3$). MS(ESI$^+$) for C$_{52}$H$_{50}$AgN$_{14}$: m/z calculated 979.3390 [L$_2$Ag-BF$_4$]$^+$, observed 979.3445.

**Synthesis of [Ru(CO)(H)(PPh$_3$)(CNN)]BF$_4$: 8.** This complex was synthesized in analogy to complex 5 from Ag(1) complex 7 (0.5 equiv). Pale beige powder (23 mg, 0.025 mmol, 64%) IR ν(CO) 1949 cm$^{-1}$. $^{31}$P $^1$H NMR (162 MHz, CDCl$_3$) $\delta$ 40.9; $^1$H NMR (300 MHz, CD$_2$Cl$_2$) $\delta$ 8.59 (s, 1H, tz-CH), 7.90 (t, $J_{\text{HH}} = 7.7$ Hz, 1H, Pyr-CH$_3$), 7.78 – 7.64 (m, 4H, Tol-CH$_3$), 7.59 – 7.14 (m, 20H, Tol-CH$_3$, PPh$_3$ and Pyr-CH overlapping), 7.07 – 6.95 (m, 1H, Pyr-CH$_3$), 6.18 (d, $J_{\text{HH}} = 13.7$ Hz, 1H, CH$_2$), 6.07 (d, $J_{\text{HH}} = 15.4$ Hz, 1H, CH$_2$), 5.90 (d, $J_{\text{HH}} = 14.1$ Hz, 1H, CH$_2$), 4.82 (d, $J_{\text{HH}} = 15.8$ Hz, 1H, CH$_2$), 3.79 (s, 3H, CH$_3$), 2.60 (s, 3H, CH$_3$), 2.46 (s, 3H, CH$_3$), -12.96 (d, $J_{\text{HH}} = 27.9$ Hz, 1H, Ru-H); $^{13}$C NMR (101 MHz, CD$_2$Cl$_2$) $\delta$ 166.0 (d, $J_{\text{CP}} = 76.9$ Hz, C$_{\text{CNN}}$), 155.7 & 154.2 (Pyr-C$_q$), 148.5, 148.4, 139.8 (d, $J_{\text{CP}} = 3.7$ Hz, PPh$_3$), 138.4, 133.7, 133.6, 132.9, 132.8, 131.2, 129.7, 129.2, 129.1, 128.5, 128.5, 128.4, 128.3, 128.2, 127.1, 126.6, 125.7, 124.8, 124.4, 123.9 (tz-CH), 60.8 & 54.4 (CH$_3$), 36.6 (N-CH$_3$), 21.3 (Tol-CH$_3$), 21.0 (Tol-CH$_3$, Ru-CO not observed. MS(FD$^+$) for C$_{45}$H$_{42}$N$_7$OPT$_3$: m/z calculated 828.2204 [M$^+$]$^+$, observed 828.21537.
General procedure for catalytic ester hydrogenation reactions: The catalyst (3.75 μmol), KOtBu (11 mg, 0.1 mmol for 20 mol%), Me₃NO (if applicable, 1.9 mg) and the substrate (if solid; 0.5 mmol) were weighed in a 4 mL GC-vial with a septum screw-cap charged with a stirring bar under an N₂ atmosphere. Subsequently, p-xylene (23.2 μL), the substrate (if liquid; 0.5 mmol) and THF (2 mL) were added. A needle was used to puncture the cap and a set of four vials was placed in a stainless steel autoclave (200 mL) under argon gas. The autoclave was flushed 2 times with 10 bar of H₂ and then pressurized to the desired pressure (5 or 50 bar), after which it was placed in a preheated oil bath (140 °C; built-in thermometer indicated 100 °C as the internal temperature of the autoclave). After allowing the autoclave to warm up (approximately 30 min.) the mixture was stirred for 2h after which the autoclave was cooled in an ice bath and the pressure was released. The conversions were determined by GC analysis.

NMR experiment on the effect of possible vacant sites on Ru in the hydrogenolysis of esters. Trimethylamine N-oxide (Me₃NO; 5 mg, 0.07 mmol) was added to a solution of complex 5 (10 mg, 0.01 mmol) dissolved in CD₂Cl₂ (1 mL) under N₂ atmosphere and stirred for 18 hours. The resulting solution was characterized by NMR spectroscopy as is described in paragraph 5.5.

NMR experiments under near-catalytic conditions: Complex 5 (~20 mg) was dissolved in THF-d₈ (0.6 mL) and KOtBu was added (0, 10 or 20 equiv.) under nitrogen atmosphere. The mixture was transferred to a J.Y oung NMR pressure tube and pressurized with 5 bar H₂, after which a ¹H NMR spectrum was recorded. The tube was subsequently heated in an oil bath at 100 °C for two hours and analyzed by multinuclear NMR spectroscopy at room temperature.

5.7 References
(11) Korstanje, T. J.; van der Vlugt, J. I.; Elsevier, C. J.; de Bruin, B. 2015, manuscript submitted.


